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# Ontology for smart 4D printed material systems and structures synergically applied with generative artificial intelligence for creativity promotion

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## Abstract

This study presents a versatile ontology for describing all kinds of smart or stimuli-responsive 4D printed material systems and structures. The different components of the ontology, namely: initial geometry and shape, shape-morphing principle(s), triggering stimuli, intermediate/final geometry and shape, 4D material and printing or additive manufacturing technology, are enumerated and classified. Accordingly, a codification system for schematically illustrating the actuation cycle of 4D printed material systems and structures, and shape-morphing devices in general, is proposed. The systematic application of the ontology to a relevant set of examples helps to demonstrate its utility and adaptability to many different types of 4D printed objects. It demonstrates that the ontology and codification schemes developed in this research can serve a comprehensive classification tool for the emergent field of 4D printing. It is the first ontology capable of representing the multiple actuation steps of complex 4D printed devices and actuators, in which several metamorphoses may be achievable, due to combinations of different shape-morphing principles and triggering stimuli. To this end, a single line of code is required. A glossary is provided to support its implementation and application. Besides, the usability of the ontology and related codification by a generative artificial intelligence (AI) for supporting engineering design tasks is explored and validated through a set of examples and an industrial use case. This work is expected to provide a universal language to facilitate the communication in the 4D materials and printing field, as well as a synergic generative AI-based methodology for creativity promotion linked to innovative smart 4D printed material systems and structures.

Keywords: 4D printing, smart materials, smart systems, shape memory materials, additive manufacturing, living matter

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## 1. Introduction

Shape-morphing materials and structures enable the creation of smart devices and systems with metamorphic abilities, which are capable of improved interactions with the environment by adapting their geometry, in some cases with reversible operation [1–4]. Shape-morphing regions within complex devices can serve also as actuators for performing extremely varied functions. These shape-shifting structures and devices are already making an impact in several industrial fields, from robotics to medicine, from architecture to inner design, from vehicles to space technology. Deployable satellite structures, adaptive furniture, environmental responsive façades, minimally invasive surgical tools, tissue engineering scaffolds and implants, to cite just a few, benefit from an implementation involving shape-morphing structures or shape-shifting components. In terms of size, applications range from large-scale systems for buildings, vehicles and machines, to micro-/nano-manipulators and micro-/nano-electro-mechanical-systems (MEMS/NEMS) [5–9].

Numerous design and manufacturing strategies allow for the development of shape-morphing systems. Smart or multifunctional materials, capable of responding in a controlled way to external stimuli, can be arranged as the active elements within shape-morphing structures [3–5]. Functionally graded materials (FGMs) or structures [6, 7] and metamaterials [8] may also have shape-shifting properties and can be used as driving elements for shape-morphing structures. Conventional hydraulic, pneumatic and electromagnetic actuators can be active elements within transformable structures and machines' subsystems [6, 10]. Special designs for creating structures that transform into mechanisms and vice versa can be also employed.

Many of the previously mentioned materials and geometrical configurations, leading to shape-morphing structures and devices, can be materialized employing additive manufacturing (AM) technologies. AM technologies, usually working following a layer-by-layer approach, enable the creation of complex-shaped objects, FGMs and structures, multi-material and multi-scale objects, and have helped to reinvent product development in many ways. Some AM technologies (and careful design procedures) can help to directly manufacture mechanisms (kinematic chains made of interconnected links, as basic units for mechanical systems and machines), mechanical metamaterials, functionally graded geometries, and even micro/nanomechanisms (and MEMS/NEMS), starting from a computer-aided design (CAD) file and avoiding a variety of time-consuming and demanding post-processes and assembly operations [11–13].

All these innovations synergize for empowering the field of shape-morphing (meta)materials, structures, devices and engineering systems in general. In fact, the AM of shape-shifting systems has been a research topic for almost two decades now. 3D printing with shape-memory materials, 3D printing of structures with inner mechanisms and 3D printing of graded structures and materials have also been reported.

These alternative or complementary routes, for achieving metamorphic structures and devices employing AM technologies, have been more recently integrated under the term four-dimensional printing or '4D printing' [1, 3, 9, 14–22]. The fact is that 4D printing is an emergent and rapidly evolving field, which still needs to be defined and structured, for increased industrial impacts.

In general, 4D printing uses the materials and techniques common from 3D printing, sometimes with slight adaptations, and generates components and devices that perform controlled geometrical changes over time. The transformation is usually enabled by special design features, by the use of digital or stimuli-responsive materials, by multi-material printing or even by actively producing deformation upon the part structure in a controlled way [1, 3, 9, 14–22]. Bioinspired design principles are employed in many cases [23–25], as well as graded materials and composites [26–28].

More recently, the creation of biohybrid systems [29–31], in which living cells perform as active elements, driving the motion of MEMS and micromachines, is also becoming a relevant R&D trend. In many ways, smart and living materials share several features, including the possibility of responding to external stimuli in a controlled way through morphological changes.

To better understand the field of 4D printing and analyze its potentials for the development of smart shape-morphing (meta)materials, structures, devices and systems, systematically describing and presenting the field, while exploring its boundaries can be a successful strategy connected to creativity promotion. In this creative exercise, it is relevant to start with an ontology or classification and codification scheme for the 4D printing field. Ontologies are schemes for classification, typically defining categories, properties and relationships between concepts data and entities, which help organize and index knowledge and research fields. Apart from classifying what already exists, ontologies and taxonomies (special hierarchical ontologies) can be used to foresee and organize what may still be developed or created, especially in the cases of ontologies and taxonomies dealing with novel research fields.

Different ontologies are being constructed for varied areas of materials science and engineering, including 4D printing, for which already a taxonomy and an ontology have been recently proposed [1, 15]. Other nascent areas in materials science and engineering, like the field of engineered living materials, whose dynamic properties have direct connections with 4D printed devices and shape-morphing structures, are also benefiting from the organizational impact of ontologies and taxonomies [29, 30]. Soft-robotics actuators, obtained by AM procedures in many cases, are also being classified [31]. Despite the above-mentioned pioneering studies, 4D printing still lacks a complete ontology capable of considering geometries, shapes, shape-morphing principles, triggering stimuli, applicable manufacturing technologies and usable raw materials. Some of the referred schemes mainly focus on soft materials, shape-memory polymers and alloys and single-step actuators, which are too limited considering

the vast potential of 4D printing. Furthermore, existing codification schemes for 4D printing do not usually consider shape-morphing actuators, which benefit from several actuation metamorphoses. Additionally, novel generative artificial intelligence (AI) resources combined with ontological frameworks and codification schemes may support radical innovation and automated discoveries in the field, which constitutes an unexplored synergy presented for the first time in this work.

Consequently, this study aims at exploring the concept of 4D printing in depth and introducing the most versatile and useful ontology to provide a codification scheme that is already supporting our team in the exploration of functional principles and concepts for better approaching different smart devices in varied projects. Through this abstraction process, creativity has been fostered, as we have worked through an exploratory cycle linked to the development of the ontology and codification scheme, followed by a contraction cycle, through which the ontology and codification have been applied to different particular use cases. The next section presents the proposed ontology and classification scheme, for which relevant pioneering studies have served of inspiration [1–3, 9, 14–17, 29–33], before illustrating its utility through the classification of 54 examples of 4D printed shape-morphing actuators responding to a wide set of stimuli. Besides, the usability of the ontology and related codification by a generative AI for supporting engineering design tasks is explored and validated through a comprehensive set of examples and thanks to the development of a complete industrial use case: the design of a 4D printed shape-memory cardiovascular stent. Finally, a discussion on current challenges and future research proposals is provided. Throughout the study, reference to the tables A1–A5, providing as annexed glossary for the ontology with a description of the supporting codification, will be made.

## 2. Ontology and codification scheme for 4D printed material systems and structures

Detailed below, the different categories for the proposed ontological framework for 4D printed material systems and structures, and the rationale for the codification scheme are presented. Compared to existing related studies, to the authors' best understanding, present ontology and codification scheme for 4D printing and their application for creativity promotion stand out for the following reasons:

- The presented ontology provides one of the most comprehensive collection of geometries, shapes, shape-morphing principles and triggering stimuli considered in any of the existing examples of classifications dealing with 4D printing as a field of study and with 4D printed actuators as the direct result of such research field.
- Important breakthroughs from an ongoing project from our team, such as multi-material printing and the use of biodegradation (BIODEG) as shape-morphing triggering stimuli, are considered both in the ontology and in the codification scheme, which is quite unique.
- The conceived codification scheme includes a unique set of codes that can present, in a single code line, the whole life cycle (the different actuation steps) of a 4D printed material or component or shape-morphing actuator, detailing and codifying all its shape changes with their respective triggering stimuli along the actuator's life.
- Both the ontology and the codification consider 4D printed materials or components or shape-morphing actuators capable of performing multiple actuation steps, as compared to existing reference that deal typically with single step actuators.
- Above all, according to our best knowledge, for the first time the employment of an ontology and codification scheme for 4D printed materials and shape-morphing components is employed for training a generative AI and for taking benefit from such innovative resources as creativity promotion tool. The understanding of the ontology and codification scheme by the generative AI is illustrated, its applicability for generating ideas about geometries (even with visual representations), materials and printing technologies along the development of new actuators is exemplified, and a complete industrial design use case involving a set of constructive dialogues with the generative AI is provided.

### 2.1. Ontology

The main categories employed for constructing this 4D printing ontology are detailed below, before presenting the codification scheme in the following section 2.2. The glossary of the Annex, summarized in tables A1–A5, acts as an essential companion to this section 2.

**Geometries and shapes:** geometrical dimensions and shapes are fundamental features required for classifying 4D printing as a field and for categorizing 4D printed actuators as research outcomes. In the proposed ontology, 0D, 1D, 2D, 3D and 4D geometrical dimensions are considered, following the usual engineering concept for one-, two- and three-dimensional objects. For example, a 1D object has two dimensions c.a. one order of magnitude smaller than the other one, while a 2D planar object has one dimension c.a. one order of magnitude smaller than the other two. 4D objects evolve with time, while 0D objects have all dimensions one order of magnitude smaller than a conventional 3D body (e.g. particles). As regards shapes, the glossary of the Annex presents, in table A1, the common shapes (cubes, domes, spheres, plates, bars, springs...) that 4D printed objects or shape-morphing actuators can adopt in their different actuation steps. The change from one shape to another is connected to the shape-morphing principles detailed below, which constitute another essential taxonomic group for the proposed classification scheme.

**Shape-morphing principles (geometrical evolutions):** shape-morphing principles in 4D printing are related with the geometrical evolutions that the actual printed shape-morphing actuators undergo during the shape-shifting/morphing stages. The way in which an actuator evolves from one geometrical dimension and shape to another is illustrated by terms such as: folding, bending, rolling, buckling, shrinking, expanding,

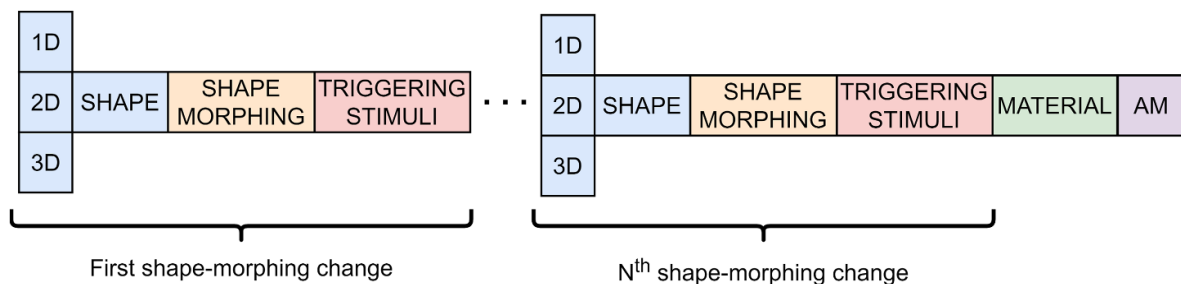
**Table 1.** Summary of gathered shape-morphing principles or geometrical evolutions. Different examples of shape-morphing principles, usually employed from promoting transformations across the considered geometrical dimensions, are gathered and presented in form of symmetric matrix.

	0D	1D	2D	3D
0D	Topographical change Expanding/ contracting Swelling/ deswelling	Mechanism Metamaterial Self-assembly	Mechanism Metamaterial	Swelling/deswelling Blossoming Origami Kirigami Self-assembly
1D	Mechanism Metamaterial Self-assembly	Stretching/compressing Topographical change Twisting/untwisting Helixing/unhelixing	Folding/unfolding Bending/straightening Rolling/unrolling Buckling/debuckling Bistable Multistable Mechanism Metamaterial Auxetic Textile	Expanding/contracting Stretching/compressing Swelling/deswelling Twisting/untwisting Helixing/unhelixing Origami Kirigami
2D	Mechanism Metamaterial	Folding/unfolding Bending/straightening Rolling/unrolling Buckling/debuckling Bistable Multistable Mechanism Metamaterial Auxetic Textile	Expanding/contracting Topographical change Twisting/untwisting Mechanism Metamaterial Auxetic Textile Self-assembly	Swelling/deswelling Folding/unfolding Bending/straightening Rolling/unrolling Curving/flattening Bistable Multistable Origami Kirigami Blossoming Mechanism Metamaterial Auxetic Textile
3D	Swelling/deswelling Blossoming Origami Kirigami Self-assembly	Expanding/contracting Stretching/compressing Swelling/deswelling Twisting/untwisting Helixing/unhelixing Origami Kirigami	Swelling/deswelling Folding/unfolding Bending/straightening Rolling/unrolling Curving/flattening Bistable Multistable Origami Kirigami Blossoming Mechanism Metamaterial Auxetic Textile	Swelling/deswelling Topographical change Twisting/untwisting Hierarchical Origami Kirigami Kusadama Mechanism Metamaterial Auxetic Textile Self-assembly

to cite a few. Other more complex shape-morphing principles/strategies, like those based on origami/kirigami/kusadama or those relying on bistable and multistable structures or kinematic chains and mechanisms, are also noteworthy, as they help to empower the shape-morphing abilities of the 4D printed actuators. In many cases such principles are reversible, which is also considered in the proposed scheme. Table 1 below summarizes such shape-morphing principles, trying to provide the most comprehensive set existing in the literature for this field of research. Table A2 in the Annex lists them

comprehensively with the codes associated with the codification scheme.

**Triggering stimuli:** the stimuli that trigger and help to control the shape-morphing ability of 4D printed mechanisms are also fundamental in a classification or organizational scheme for the field. It is a common practice to classify actuators by means of their driving principles. Common stimuli for sparking the geometrical evolutions of smart 4D printed devices include changes in environmental conditions, like



**Figure 1.** General codification scheme for 4D printed material systems and structures.

temperature or humidity; external mechanical actions upon the devices' structures, like force, pressure, vibration or acoustic actions; electromagnetic stimuli, chemical and biological actions, among many others. Table A3 in the Annex enumerates all the triggering principles that the authors have been able to review in the literature and provides a coding scheme. As already advanced, special relevance is the triggering by BIODEG, which is not usually considered in 4D printing reviews, and opens new horizons in fields including biomedical practice, as it may contribute to minimal invasion, improved ergonomics and enhanced healing processes based on biodegradable smart devices.

**Materials:** as happens with available technologies for 4D printing, the portfolio of materials capable of being additively processed and applicable to the development of shape-morphing actuators is continuously increasing. Most studies and reviews dealing with the field of 4D printing concentrate on the printing of shape-memory polymers and shape-memory alloys (SMAs), which lead to actuators triggered by temperature changes. However, other relevant materials like biomedical alloys, carbon-based materials, ceramics and composites, which can lead to other kinds of shape-morphing actuators triggered by a wide set of stimuli, are often neglected. These need to be considered for the proposed 4D printing ontology and are also listed in the glossary of the Annex (table A4).

**Technologies:** the family of AM technologies is continuously receiving more members, and the related achievable precision, resolution, repeatability and manufacturing volumes keep on increasing, as required for high-performance and impactful industrial applications. The glossary of the Annex (table A5) provides a comprehensive recapitulation of AM technologies following commonly accepted families and representative technologies. Such collection, which is also codified, even if not being totally complete and probably requiring periodic updates (for example new bioprinting and 4D bioprinting resources are currently under development), proves an adequate compromise for the purposes and timely nature of this study.

## 2.2. Codification scheme and practical examples

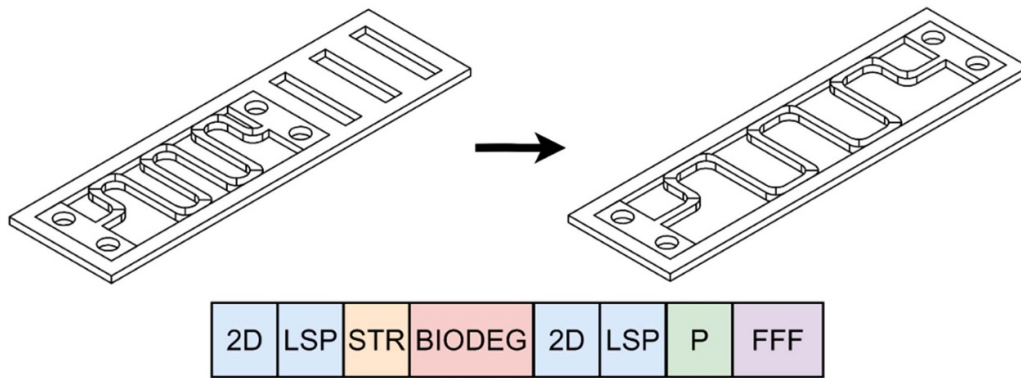
Now that the boundaries of 4D printing as a field of study are clearer, thanks to the implemented ontology, section 2.2 is devoted to providing a straightforward codification scheme

for working with 4D printed actuators. Furthermore, it aims to systematically foster creativity through semantic combinations. The term actuator is employed here as a generalization of shape-morphing material, structure, device or system, although in most cases actuators are constitutive elements of even more complex engineering systems. It is necessary to point out that our codification tries to illustrate, in a single line of code, the whole metamorphoses of smart 4D printed actuators, in a way that contributes to organize the field of study. Groups of acronyms or symbols, each one representing a specific state of the actuator, are joined. Each of the groups includes an indication of the geometrical dimension and of the general shape of the actuator in a certain state. Between blocks, the shape-morphing principles and triggering stimuli are indicated. In this way, multiple actuation steps can be easily described, detailing the actuator' whole life cycle. Finally, the code line ends with an indication about the raw materials and technologies employed for manufacturing the actuators, as schematically presented in figure 1.

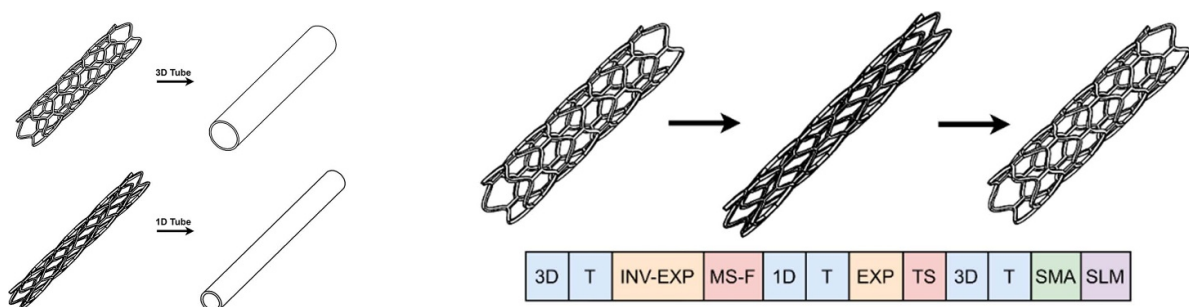
As advanced, the glossary of the Annex provides a list of geometries, shapes, shape-morphing principles (or geometrical evolutions), triggering stimuli, materials and technologies that constitute the key features for classifying smart shape-morphing actuators. Explanations and symbols are provided as an initial attempt to create a universal language for 4D printing. To illustrate the codification, three examples from very different types of smart printable structures are provided in the following pages in figures 2–4.

The first case (figure 2) is linked to a linear actuator, with the shape of a planar spring (2D & LSP) and capable of stretching (STR), once the BIODEG as triggering principle of an external framework takes place. It is manufactured using a polymer (P) by fused filament fabrication (FFF). It represents the first conceptual demonstrator for a distraction device, which will be transformed into solutions for craniosynostosis and skin expansion (EXP). Different combinations of codes and symbols can be employed to illustrate its life cycle and metamorphoses, as shown in the images of the figure.

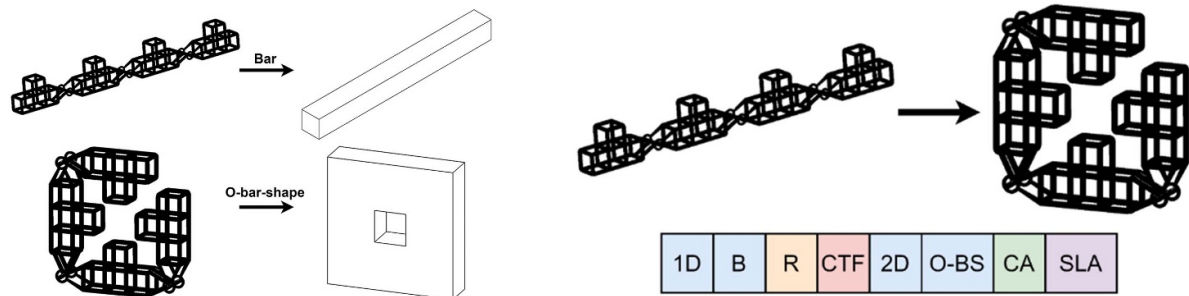
The second case (figure 3) deals with a stent for cardiovascular pathologies, a field in which smart materials and 4D printing can have a very relevant impact. In the specific case of the illustrative example, the stent is manufactured using a SMA by selective laser melting (SLM). The presented shape-shifting steps are connected to the shape-memory training, in which the initial stent with tubular shape (3D T) is compacted



**Figure 2.** Codification scheme application example: linear spring with stepped actuations triggered by biodegradation of surrounding frameworks. Geometrical evolution and codifications are presented.



**Figure 3.** Codification scheme application example: shape-memory stent concept with geometrical changes triggered by mechanical and thermal stimuli. Geometrical evolution and codifications are presented.



**Figure 4.** Codification scheme application example: 4D printed micromechanism actuated by cell traction force of cultured cells, as concept for living micromachine. Geometrical evolution and codifications are presented.

(INV-EXP) by means of a radially applied force (MS-F) to reach a unidimensional temporary shape with cross-section diameter c.a. one order of magnitude lower than its length. Subsequently, radial EXP is achieved by heating (TS, as triggering principle). The three shapes are represented in the codification, with two shape-morphing steps in between with different triggering principles: mechanical and thermal stimuli respectively.

The case (figure 4) presents a 4D printed chassis, in which living cells can be cultured for reaching an innovative living material or living micromachine. In this case, cell traction force (CTF) is the triggering stimulus for producing a shape-shift from an initial unidimensional structure towards a final two-dimensional shape, thanks to the rotation of different parts of the chassis.

### 3. Application of the ontology to a collection of 4D printed material systems and structures

Once that the ontology and related codification schemes have been described and illustrated through the examples of figures 2–4, it is important to analyze its versatility and, to some extent, its universality for univocally describing smart shape-morphing materials, structures, actuators, devices, systems in general, enabled thanks to the application of 4D printing principles. In a way, the ontology classifies these engineering systems, but also the whole 4D printing scientific-technological realm. It gives an idea, not only of what already exists, but of what could be developed through synergic research and co-creation methods, which will be illustrated in following sections by employing generative AI resources.

With this purpose, a brief review of recently published studies dealing with 4D printed shape-morphing actuators has been performed. Several scientific documents published along the last decade have been gathered and organized [28–57]. Most families of usable materials, such as polymers, ceramics, alloys and composites, both passive and with shape-morphing and shape-memory properties, have been represented in the gathered collection. Regarding AM technologies, capable of producing 4D printed geometries, relevant examples have been included, like FFF, stereolithography, digital light processing, SLM, direct ink jetting, binder jetting, drop on demand or laminated object manufacturing, to cite a few. Both very simple shapes, including bars, plates and springs, as well as complex flower-like structures, scaffolds and metamaterials, have been taken into account. In terms of shape-morphing triggers, a wide range of examples using mechanical, electromagnetic, chemical, and biological stimuli has been explored.

After gathering these relevant examples of 4D printed shape-morphing actuators, the ontology has been systematically applied to all of them, codifying their life cycle (metamorphoses) considering initial geometry and shape, shape-morphing, triggering principle, final geometry and shape, material and printing technology. Actuating life cycles involving more than one metamorphosis are also included. In those cases, different coding lines codify the different stages of actuation. The result is summarized in table 2, which provides a brief description of the considered 4D printed actuators and classifies them providing a codification of their morphological lifecycle. The different references are also listed, to facilitate colleagues finding the original publications and checking the actual geometries, shapes and properties of the different actuators.

A remarkable feature of the ontology and codification is that, even without checking the photographs of the different classified actuators in the seminal publications, it is already possible to imagine the described metamorphoses just by reading a single text line. The abstraction power of this codification and its potential for creativity promotion should not be neglected. Arguably, in the future, it may be possible to combine these blocks of text to conceptually design complex shape-morphing systems, emulating the use of letters for representing verbal communication. This and other possibilities are discussed in the following sections, which also present current challenges and some ongoing research lines and directions of study.

The codification should be read with the support of the annexed glossary and tables A1–A5.

#### 4. Generative AI-driven coding and design of 4D printed material systems and structures

The integration of AI tools is driving a new era of ideation and prototyping, enabling designers to explore and iterate on design concepts more broadly and creatively. Generative AI technologies, such as ChatGPT, are starting to transform design and manufacturing processes. In AM, ChatGPT has

streamlined G-code generation, which is essential for controlling 3D printers and ensuring high-quality results, by adjusting printing parameters in real time and significantly reducing the trial-and-error phase [76]. ChatGPT has also supported the design of 3D printed wrist-hand orthoses, suggesting procedures that include 3D scanning of the patient's anatomy and generating visual representations through DALL-E, demonstrating its versatility for specific design needs [77]. Additionally, ChatGPT has shown its ability to optimize design, planning and material selection in 4D printing, promoting more sustainable and efficient practices. In 4D printing, which uses materials that change properties over time, AI may enhance the process by aiding in the selection of materials that respond to specific stimuli, improving the adaptability and durability of printed structures [78].

This section presents an innovative approach for the coding and design of 4D printed material systems and structures using generative AI tools (i.e. ChatGPT). The ontology acts as a communication tool with ChatGPT, supporting the conceptual design phase and the selection of materials and manufacturing processes. The interaction with ChatGPT is carried out through 'prompts', textual instructions that allow for constructive dialogues. The first prompt establishes the context and role for the AI, which is crucial for helping ChatGPT to understand the coding from an engineering perspective.

In our exploratory journey for establishing synergies between the ontology and codification and the generative AI technology, the initial prompt was as follows:

*"You are an engineer specializing in coding shape-morphing actuators. To support your work, you have developed an ontology that outlines the entire life cycle of these actuators, including details on their shape, shape-morphing principles, triggering stimuli, materials, and technologies. Attached, you will find several Word documents, each serving a specific purpose:*

*1. Ontology.docx: This document provides a comprehensive description of each component within the ontology.*

*2. Tables A1–A5: These tables offer detailed definitions for each component involved in the coding process.*

*3. Codification of 4D printed actuators.docx: This document provides a list of examples of different 4D printed material systems and structures encoded with the ontology.*

*Please review these documents thoroughly. After analyzing the provided information, could you confirm whether you understand the ontology and its coding?"*

In response, the generative AI (ChatGPT) briefly described each component of the ontology and demonstrated an 'understanding' of the coding and its applicability by looking at



**Table 2.** Application of the proposed ontology for 4D printed actuators with 54 examples of application demonstrating its utility and versatility.

Description of 4D printed actuator	Ontology application										Reference
	Geometry	Shape	Shape-morphing principles	Triggering stimuli	Geometry	Shape	Material	AM technology	AM technology	Reference	
Ni-Ti gripper responsive to thermal stimuli	2D	U-BS	INV-BE	MGS	1D	B	SMA	SLM	[34]		
Light-fueled rolling robot	2D	PL	KI	LS	3D	T	P	LOM	[35]		
Multimaterial 4D printed homogeneous auxetic lattice	2D	PL	AUX	TS	2D	PL	MT(P + CO)	DIW	[36]		
Multimaterial 4D printed heterogeneous auxetic lattice	2D	PL	CU	TS	3D	D	MT(P + CO)	DIW			
Droplet network composed of two strips of droplets of different osmolarities	1D	B	BI	MO	2D	C-BS	MT(G + G)	DOD	[37]		
Flower-shaped network folding spontaneously into a hollow sphere	2D	STAR-BS	INV-BLO	MO	3D	S	G	DOD			
Hydrogel disk with 15% honeycomb filler that rolls into a tube	2D	DK	R	TS	3D	T	G	DIW	[38]		
Self-folding string of letters 'FBK'	1D	B	F	TS	2D	FBK-BS	SMMT(SMP + P)	FFF	[39]		
Self-opening box	3D	C	O	TS	2D	PL	SMMT(SMP + P)	FFF			
Helix formed by the gel sheet under the action of thermal stimuli	2D	PL	HE	TS	3D	T	G	DLP	[40]		
Raster structure that changes shape after water absorption	2D	PL	SW	MO	3D	PL	P	DIW	[41]		
Ring column that changes shape after water absorption	2D	RG	SW	MO	3D	T	P	DIW			

(Continued.)

Table 2. (Continued.)

Description of 4D printed actuator	Ontology application									
	Geometry	Shape	Shape-morphing principles	Triggering stimuli	Geometry	Shape	Material	AM technology	Reference	
Herringbone tessellation origami <sup>a</sup>	3D	T	INV-STR	MS-F	2D	DK	SMP	FFF	[42]	
Full entubulation of 4D nerve guidance conduit via a 'thermomechanical programming' shape transformation	2D	DK	STR	TS	3D	T				
	2D	PL	R	TS	3D	T	SMP	SLA	[43]	
Single cylindrical tube manufactured with a kirigami structure for a bifurcation stent <sup>a</sup>	3D	T	KI	MS-ST	3D	U-BS	SMP	FFF	[44]	
	3D	U-BS	KI	TS	3D	T				
Self-folding of CLP (crossed layers of parallels) unit cell	2D	PL	O	MS-F	3D	C	P	FFF	[45]	
Self-folding regular icosahedron under light stimuli	2D	PL	O	LS	3D	S	P	DLP	[46]	
2D multi-stable metamaterials assembled by snapping segments	2D	PL	MTS	TS	2D	PL	MT(CO + P)	BJ + FFF	[47]	
	3D	C	MTS	MS-F	3D	C	MT(CO + P)	BJ + FFF		
3D multi-stable metamaterials assembled by snapping segments	3D	SP	UHE	MS-F	1D	CY	P	DIW	[48]	
	1D	CY	HE	TS	3D	SP				
3D microspiral capable of memorizing a 1D linear shape and recover its original form after the application of thermal stimuli <sup>a</sup>	3D	P-BS	F	MS-ST	3D	C	SMP	DLP	[49]	
	3D	C	UF	TS or LS	3D	P-BS				

(Continued.)

Table 2. (Continued.)

Description of 4D printed actuator	Ontology application										Reference
	Geometry	Shape	Shape-morphing principles	Triggering stimuli	Geometry	Shape	Material	AM technology	Reference		
Self-folding box <sup>a</sup>	3D	C	O	MS-ST	2D	PL	SMCO	DIW	[50]		
Horseshoe-shaped element that becomes linear when stimulated by heat <sup>a</sup>	2D	PL	O	TS	3D	C					
	1D	B	BE	MS-ST	2D	U-BS	SMCO	DIW			
The sequential drive of the multi-material	2D	U-BS	STRA	TS	1D	B					
Archimedean chord in a dome due to heating	2D	DK	CUR	TS	3D	D	MT(CO + CO)	DIW	[51]		
Film which, when heated, turns into a twisting column	2D	PL	TW	TS	3D	CY	G	DIW	[52]		
Porous structure composed of rectilinear printing paths alternating 90° with respect to the previous layer that contracts due to thermal stimuli	2D	PL	CONT	TS	2D	PL	G	DIW			
Complex flower morphology generated by 4D biomimetic printing	2D	STAR-BS	INV-BLO	MO	3D	S	P	DIW	[53]		
4D printing of ceramics with the design of bending configuration	2D	B	BE	TS	3D	U-BS	CE	DIW	[54]		
4D ceramic printing with shape-shifting design on a helical ribbon	2D	B	HE	TS	3D	T	CE	DIW			
4D ceramic printing with shape-shifting design on a saddle surface	2D	PL	CUR	TS	3D	PL	CE	DIW			
Auxetic structures exhibiting shrinkage in both length and width under applied magnetic fields	2D	PL	AUX	MGs	2D	PL	CO	DIW	[55]		

(Continued.)

Table 2. (Continued.)

Description of 4D printed actuator	Ontology application									
	Geometry	Shape	Shape-morphing principles	Triggering stimuli	Geometry	Shape	Material	AM technology	Reference	
Self-folding of a single strand into a three-dimensional cube.	1D	CY	F	MO	3D	C	MT(P + P)	JET	[56]	
2D to 3D shape transformation of a flat flower-like structure	2D	DK	INV-BLO	TS	3D	S	SMP	FFF	[57]	
Butterfly shape moves its wings under magnetic field actuation.	2D	PL	BE	MGS	3D	C-BS	CO	DIW	[10]	
4D-printed electroactive smart gripper	2D	U-BS	BE	TS	2D	U-BS	SMCO	DIW	[58]	
A ring that transforms into a wavy structure	2D	RG	CUR	TS	3D	T	SMMT(SMP + P)	BJ	[59]	
4D printing of shape-memory scaffolds <sup>a</sup>	3D	CY	COMP	MS-ST	2D	DK	SMP	DLP	[60]	
Shape-shifting specimen composed of an arrangement of out-of-plane bending elements	2D	DK	STR	TS	3D	CY	SMP	FFF	[61]	
Flat structure that self-assembles with a mechanical stimulus to form a three-dimensional mechanism.	3D	T	STRA	TS	2D	PL	SMP	FFF	[61]	
Water-responsive flower	2D	PL	SFA	MS-ST	3D	D	MT(P + P)	JET	[62]	
Tunable Octet lattice <sup>a</sup>	3D	DK	INV-BLO	MO	3D	S	G	DLP	[63]	
	3D	C	COMP	TS + MS-ST	3D	C	SMP	FFF	[13]	
	3D	C	STR	TS	3D	C				

(Continued.)

Table 2. (Continued.)

Description of 4D printed actuator	Ontology application										Reference
	Geometry	Shape	Shape-morphing principles	Triggering stimuli	Geometry	Shape	Material	AM technology	Reference		
4D printed Poly(1-lattice)/(FeCl <sub>3</sub> -TA/MgO) composite scaffolds	3D	C	STR	LS-NIR	3D	C	SMCO	DIW	[64]		
Bistable shape-changing bar	1D	B	BS	TS	2D	U-BS	SMCO	FFF	[65]		
Reprogrammable soft manipulator	3D	C	TW	MS-ST	3D	C	P	FFF	[66]		
Asymmetrical flat composite sheet	2D	PL	BE	TS + MS-ST	3D	C-BS	SMCO	LAM	[67]		
Micro-textured printed plate with shape-morphing pillars	2D	PL	TC	TS	2D	PL	P	SLA	[68]		
DNA-like structure	2D	PL	HE	TS	3D	T	SMP	FFF	[69]		
Reversible meta-sandwiches <sup>a</sup>	2D	PL	COMP	MS-ST	2D	PL	SMMT(SMP + P)	FFF	[70]		
Reversible bistable actuator <sup>a</sup>	2D	PL	STR	TS	2D	PL					
Uniform honeycomb lattice structure <sup>a</sup>	2D	Y-BS	BS	MS-ST	2D	M-BS	SMP	FFF	[71]		
Magneto-electroactive flat actuator	2D	M-BS	BS	TS	2D	Y-BS	SMP	FFF	[72]		
Self-bending gripper <sup>a</sup>	3D	C-BS	COMP	MS-ST	3D	M-BS	SMP	FFF	[73]		
	3D	M-BS	STR	TS	3D	C-BS					
	2D	PL	F	MGS	3D	C	SMCO	FFF	[74]		
	2D	U-BS	UB	TS + MS-ST	2D	V-BS	SMP	FFF	[75]		
	2D	V-BS	B	TS	2D	M-BS					
	2D	M-BS	B	TS	2D	U-BS					
	2D	DK	INV-BLO	TS	3D	S	SMP	FFF	[75]		
Self-morphing flower-shaped structure	2D	PL	HE	TS	3D	T	SMP	FFF			
Self-rolling helix	2D	PL	HE	TS	3D	T	SMP	FFF			

<sup>a</sup>Two or more metamorphoses.

**Table 3.** Application of the ontology for coding 4D printed material systems and structures by a generative AI (ChatGPT in our case) .

Description of 4D printed actuator (input)	Ontology code (output)
Shape-memory polymer arch with temperature-responsive curving	2D/PL/CUR/TS/3D/CY/SMP/SLA
Hydrogel strip that swells and folds with moisture	1D/B/SW/MO/2D/PL/G/DIW
Biodegradable scaffold with multi-stable folding mechanism	3D/SP/MTS/BIODEG/3D/C/SMP/FFF
Magnetically actuated ring that twists into a helix	2D/RG/TW/MGS/3D/HE/CO/SLM
Light-responsive composite disk that bends	2D/DK/BE/LS-V/3D/CY/P/DLP
Thermo-mechanical shape-memory tube that expands	1D/T/EXP/TS/3D/T/SMA/LENS
Humidity-responsive gel sphere that flattens	0D/S/FLAT/MO/2D/PL/G/DIW
pH-responsive polymer plate that buckles	2D/PL/BU/pH/3D/T/P/NPJ
Mechanical pressure activated multi-material spring	3D/SP/COMP/MS-F/3D/SP/MT/CDLP
Biodegradable gel dome that collapses	3D/D/CONT/BIODEG/2D/DK/G/DLP

**Table 4.** Prompts used in the conceptual design and optimization process of 4D printed material systems and structures and shape-morphing actuators in general.

Prompt	Outcomes
Third prompt <i>Thank you very much. As a 4D printing engineer, you are the best. Could you provide me with descriptions of how to design actuator(s) with the following encoding(s), including geometric and material aspects based on the selected additive manufacturing technology, ensuring that the actuator(s) are able to change shape as desired?</i>	table 5
Fourth prompt <i>Could you help me select the appropriate materials needed to achieve the desired shape change for each of the provided cases?</i>	table 6
Fifth prompt <i>Could you provide a separate visual representation for each designed actuator based on the coding provided above?</i>	table 7

the table with the coded examples (table 2). Furthermore, it encouraged questions related to the ontology or coding.

To validate its comprehension and ability to apply it, the next instruction was: *'Now, after analyzing all the information provided, could you use the ontology to code ten different 4D printed material systems and structures, ensuring they are distinct from the previously provided examples?'*.

The answer is summarized in table 3. These ten examples show that ChatGPT is capable of correctly coding shape-morphing actuators, after having been trained with the basic documents and tables that conform the ontology and codification.

However, the most interesting aspect of this section is the demonstration of how ChatGPT can be used as a tool to stimulate designers' creativity by exploring geometries that precisely change shape with the defined triggering stimuli, as discussed below. Once the ontology was provided to ChatGPT, the design process followed a structured approach guided by a series of prompts, which are presented in table 4 in our wish to provide good practices for interacting with these resources in the fields of 4D printing and shape-morphing actuators. These prompts guided (or mentored) the generative AI to provide detailed recommendations on several critical aspects of 4D smart actuator design, including geometry, material selection and manufacturing processes. ChatGPT's ability to interpret coding and provide insightful design suggestions underlines its potential as an effective design tool for engineers and researchers.

To illustrate this, ChatGPT was given four different codifications, each representing a different actuator design. Based

on these code lines, ChatGPT was asked to generate specific design recommendations. The results, shown in tables 5–7, demonstrate the capabilities of ChatGPT in several areas:

- **Design recommendations** (table 5): chatGPT provides detailed suggestions for the geometry and shape of each actuator based on the provided coding, addressing the specific requirements of shape-morphing actuators. It suggests features such as hinge-like structures or thin sections for smooth folding and unfolding, as well as embedded patterns or material gradients to induce controlled bending. These suggestions highlight ChatGPT's understanding of complex geometric requirements and its ability to offer feasible design solutions tailored to the intended behavior of each actuator.

In addition, AI considers the interaction of the actuators with external stimuli such as temperature or magnetic fields. For example, it proposed the design of a cylindrical tube that unfolds into a flat plate when heated, demonstrating its ability to ensure smooth transitions between initial and final shapes in response to external triggering stimuli.

- **Material selection** (table 6): chatGPT provides valuable recommendations for materials that not only support the desired shape-morphing functionality but are also compatible with the proposed manufacturing techniques. For example, for heat-responsive actuators, it suggested shape-memory polymers with precise transition temperatures that allow shape change when heated. Similarly, for moisture-responsive actuators, it recommended hydrogels

**Table 5.** From the codification to the description of 4D printed material systems and structures using a generative AI (ChatGPT). Remarkable proposals and advices given by the generative AI are highlighted in bold.

Ontology code (input)	Description (output)
3D/T/UF/TS/2D/PL/SMP/FFF	<ul style="list-style-type: none"> <li>Initial geometry and shape: create a cylindrical tube with specific dimensions that allow for smooth unfolding. The tube should be hollow with uniform wall thickness for even heat distribution.</li> <li><b>Material selection: select an SMP that has a transition temperature suitable for the application. Ensure the polymer has good flexibility and shape memory characteristics.</b></li> <li>Shape morphing principle: <b>integrate hinge-like features or thin sections</b> along the length of the tube that facilitate controlled unfolding when heated.</li> <li>Triggering stimuli: ensure the SMP is responsive to a specific temperature range, which will trigger the unfolding mechanism.</li> <li>Resulting geometry and shape: upon heating, the tube unfolds into a flat plate. Design the <b>fold lines</b> to control the final shape accurately.</li> <li>Manufacturing process: use a 3D printer capable of FFF to print the tube. Ensure precise control over the extrusion process to maintain uniform wall thickness and hinge features. <b>Post-processing might include slight reheating to ensure the hinges function properly during actuation.</b></li> </ul>
2D/DK/CUR/MS-ST/3D/D/MT(A + P)/FFF	<ul style="list-style-type: none"> <li>Initial geometry and shape: design the disk with a <b>thickness gradient</b> that promotes curving. Thicker regions should resist deformation more than thinner ones, enabling controlled curvature when stressed. Introduce <b>stress-relaxation zones in the disk structure (e.g. perforations or grooves)</b> to guide the curving process precisely</li> <li>Material selection: use a SMA like Nitinol for its excellent stress-strain response and ability to return to pre-defined shapes after deformation. Select flexible polymer such as thermoplastic polyurethane or a SMP that complements the alloy' behavior under mechanical strain.</li> <li>Shape morphing principle: curving implies a smooth deformation, such as rolling the disk edges upward or downward, depending on the stimuli.</li> <li>Triggering stimuli: this means external forces, tension, or <b>programmed stress-relaxation properties</b> in the materials will initiate the curving process.</li> <li>Resulting geometry and shape: the final dome shape is achieved through a combination of material strain recovery and geometric programming, where the alloys expand and polymers flex into the desired curvature.</li> <li>Manufacturing process: employ a <b>dual-extrusion FFF printer</b> to deposit the alloy-polymer combination. Print the <b>polymer as the outer layer and the alloy as an embedded mesh or skeleton within the disk</b>. Use precise <b>infill patterns to preprogram stress zones</b> that will guide the transition from disk to dome.</li> </ul>
2D/U-BS/BS/MGS/1D/B/A/FFF	<ul style="list-style-type: none"> <li>Initial geometry and shape: create a flat U-shaped bar with bistable properties, allowing it to snap between two stable states.</li> <li>Material selection: choose a magnetically responsive alloy that can maintain bistable behavior.</li> <li>Shape morphing principle: incorporate bistable elements in the U-shaped bar that allow it to transition to a straight bar under magnetic stimuli.</li> <li>Triggering stimuli: <b>embed magnetic particles or use a magnetically responsive alloy to facilitate shape change under magnetic fields.</b></li> <li>Resulting geometry and shape: the U-shaped bar snaps into a straight bar configuration when exposed to a magnetic field.</li> <li>Manufacturing process: use a 3D printer capable of FFF to print the U-shaped bar. Ensure precise control over the extrusion process to achieve the desired bistable properties. <b>Post-processing may include magnetization to enhance the magnetic response.</b></li> </ul>
2D/PL/O/MO/3D/C/G/DIW	<ul style="list-style-type: none"> <li>Initial geometry and shape: create a flat plate with <b>predefined fold lines</b> to facilitate origami-like folding.</li> <li>Material selection: select a <b>gel that responds to moisture by swelling and becoming flexible, enabling folding.</b></li> <li>Shape morphing principle: design the plate with precise fold lines and sections that fold into a cube upon moisture exposure.</li> <li>Triggering stimuli: ensure the gel material is sensitive to moisture and swells appropriately to initiate folding.</li> <li>Resulting geometry and shape: the plate folds into a cube when exposed to moisture.</li> <li>Manufacturing process: use DIW to print the plate with precise fold lines and <b>ensure even distribution of the gel material</b>. Optimize the printing process to achieve the desired flexibility and folding behavior. Post-process to ensure the gel's moisture responsiveness is optimized for actuation.</li> </ul>

**Table 6.** Generative AI (ChatGPT) proposals for innovative geometries, materials and manufacturing resources for the development of innovative codified actuators. Remarkable proposals and advices provided by the generative AI are highlighted in bold.

Ontology code (input)	Description (output)
3D/T/UF/TS/2D/PL/SMP/FFF	<p>Material selection:</p> <ul style="list-style-type: none"> <li>• Polyurethane SMP: known for its excellent shape memory properties and responsiveness to heat.</li> <li>• Polycaprolactone (PCL): has a low transition temperature and good biocompatibility.</li> <li>• Polylactic Acid (PLA): commonly used in FFF and has shape memory capabilities when blended or modified.</li> </ul> <p>Considerations:</p> <ul style="list-style-type: none"> <li>• Transition Temperature: <b>ensure the SMP selected has a transition temperature suitable for the application.</b></li> <li>• Flexibility and Strength: <b>the material should be flexible enough to fold and unfold without breaking.</b></li> <li>• Printability: must be compatible with FFF technology, ensuring smooth extrusion and layer adhesion.</li> </ul>
2D/DK/CUR/MS-ST/3D/D/MT(A + P)/FFF	<p>Material selection:</p> <ul style="list-style-type: none"> <li>• Nickel-Titanium (NiTi) Alloy: known for its excellent shape memory properties. Provides <b>high fatigue resistance</b> and durability for repeated actuation cycles.</li> <li>• Alternative Alloys: <b>stainless steel particles blended into a filament may be used if NiTi is unavailable.</b></li> <li>• Thermoplastic Polyurethane (TPU): offer flexibility and resilience, ideal for applications requiring durability and <b>wear resistance</b>.</li> </ul> <p>Considerations:</p> <ul style="list-style-type: none"> <li>• Material Compatibility: <b>ensure NiTi and TPU/SMP bond well during printing</b> or assembly to avoid delamination during shape morphing.</li> <li>• Printability: <b>NiTi may need to be integrated post-printing or pre-treated for hybrid printing process.</b></li> <li>• Flexibility and Strength: materials must withstand mechanical stress without cracking or delaminating. TPU or SMPs with good elastic are essential.</li> </ul>
2D/U-BS/BS/MGS/1D/B/A/FFW	<p>Material selection:</p> <ul style="list-style-type: none"> <li>• Magneto-Responsive Alloys (e.g. Fe-Ga Alloy): exhibits large magnetostriction and is responsive to magnetic fields.</li> <li>• Iron-Nickel (Fe-Ni) Alloy: provides magnetic properties and bistable characteristics.</li> <li>• Terfenol-D (Terbium-Dysprosium-Iron Alloy): known for its magnetostrictive properties, though more challenging to print.</li> </ul> <p>Considerations:</p> <ul style="list-style-type: none"> <li>• Magnetic Responsiveness: the material must respond efficiently to magnetic fields.</li> <li>• Bistable Properties: ensure the material can snap between stable states.</li> <li>• <b>Printability: must be compatible with FFF, possibly requiring a filament with embedded magnetic particles.</b></li> </ul>
2D/PL/O/MO/3D/C/G/DIW	<p>Material selection:</p> <ul style="list-style-type: none"> <li>• Hydrogel: such as Polyacrylamide or Poly(N-isopropylacrylamide) (PNIPAM), which swell and change shape in response to water.</li> <li>• Alginate Gel: biocompatible and responsive to moisture.</li> <li>• Chitosan Gel: natural polymer gel that responds to moisture and has good mechanical properties.</li> </ul> <p>Considerations:</p> <ul style="list-style-type: none"> <li>• Moisture Responsiveness: <b>ensure the gel swells adequately and uniformly.</b></li> <li>• Mechanical Integrity: the gel should maintain structural integrity when folding.</li> <li>• Printability: must be compatible with DIW, ensuring smooth extrusion and layer build-up.</li> </ul>

like polyacrylamide or chitosan, which swell when water is absorbed to achieve the desired folding effect.

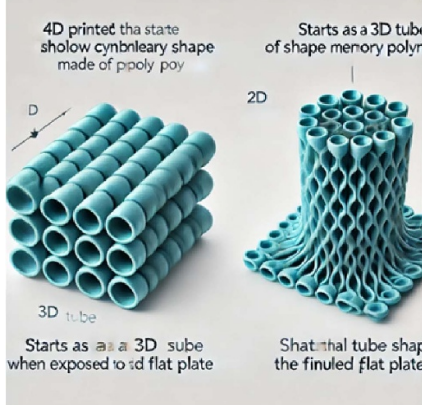
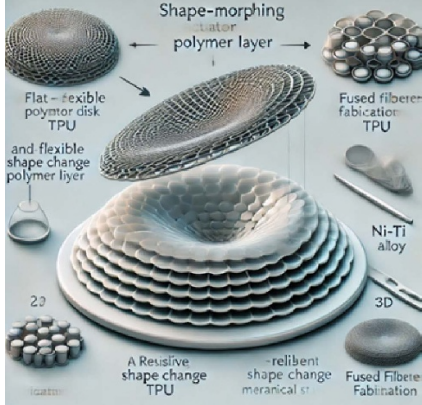
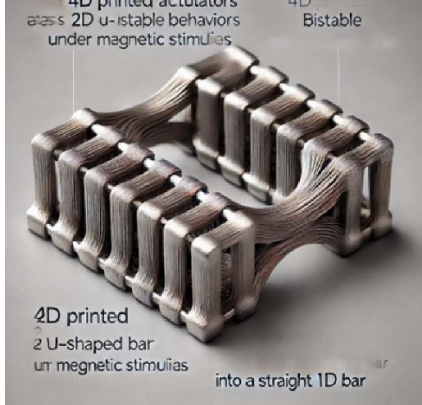
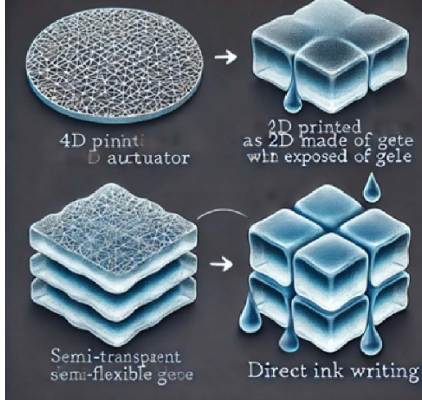
In the multimaterial case, ChatGPT is able to define optimal combinations, such as a rigid material that is a metal capable of withstanding cyclic loading, like nitinol, and a flexible polymer that complements the mechanical behavior under deformation, like TPU. In addition, it identifies synergies between these materials by proposing configurations that optimize both structural strength and flexibility at key

application points. The use of metal-loaded filaments is also suggested, respecting the defined combination of materials.

What stands out is the personalized nature of ChatGPT's recommendations. It carefully considers key factors such as flexibility, strength and response to external stimuli to ensure that materials are well suited to the specific shape transformations required. It also considers the printability of the materials, suggesting those that are compatible with AM techniques such as FFF or Direct Ink Writing



**Table 7.** Visual representations of innovative coded actuators produced by ChatGPT and DALL-E as generative AIs.

Ontology code (input)	DALL-E representation (output)
3D/T/UF/TS/2D/PL/SMP/FFF	 <p>4D printed the state show low cylindrical shape made of poly poly</p> <p>Starts as a 3D tube when exposed to a flat plate</p> <p>Starts as a 3D tube of shape memory polymer</p> <p>2D</p> <p>3D tube</p> <p>Starts as a 3D tube when exposed to a flat plate</p> <p>Starts as a 3D tube of shape memory polymer</p> <p>2D</p> <p>Starts as a 3D tube when exposed to a flat plate</p>
2D/DK/CUR/MS-ST/3D/D/MT(A + P)/FFF	 <p>Shape-morphing actuator polymer layer</p> <p>Flat - flexible polymer disk TPU</p> <p>and flexible shape change polymer layer</p> <p>Fused fiber fabrication TPU</p> <p>Ni-Ti alloy</p> <p>2D</p> <p>3D</p> <p>A Resilient shape change TPU</p> <p>Resilient shape change mechanical stress</p> <p>Fused Fiber Fabrication</p>
2D/U-BS/BS/MGS/1D/B/A/FFF	 <p>4D printed actuators as 2D bistable behaviors under magnetic stimuli</p> <p>4D Bistable</p> <p>4D printed 2 U-shaped bar under magnetic stimuli</p> <p>into a straight 1D bar</p>
2D/PL/O/MO/3D/C/G/DIW	 <p>4D printed actuator</p> <p>2D printed as 2D made of gel when exposed of gel</p> <p>Semi-transparent semi-flexible gel</p> <p>Direct ink writing</p>

- (DIW), ensuring precise processing and high-quality results.
- **Manufacturing process suggestions** (tables 5 and 6): chatGPT's design process goes beyond material selection, providing valuable insights into the manufacturing process and tailoring its recommendations to the capabilities of different 3D printing technologies. For the multimaterial actuator, it encourages the use of a dual extruder FFF printer to produce strategic infill patterns for accurate pre-programming of stress zones. In addition to recommending appropriate manufacturing techniques, ChatGPT considers post-processing steps to improve actuator performance. For example, it recommends reheating hinge-like features in certain designs to ensure proper functionality during shape-morphing. For magnetic materials, it suggests post-manufacturing magnetization to improve responsiveness to magnetic fields. This careful attention to the manufacturing process ensures that actuators meet design specifications and perform reliably in real-world applications.
  - **Visual representations** (table 7): in addition to its written outputs, ChatGPT's integration with DALL-E supports the design process by generating conceptual visual representations. While not as detailed as CAD models, these images may provide engineers with starting points for visualizing actuators and their shape-morphing behavior. By providing insight into the basic geometry and transformation processes, these visual sketches serve as a valuable tool for further refinement and inspiration. By combining both descriptive text and preliminary illustrations, ChatGPT supports a more holistic design approach. Designers can use these visualizations to better understand the physical form and function of their concepts, ensuring a smoother progression from the initial idea towards a detailed CAD model and a fully realized prototype.
  - **Creative problem-solving and adaptability**: one of ChatGPT's most notable contributions is its ability to offer creative alternatives when traditional approaches may not meet the design requirements. For example, in one design where shape-morphing through unfolding was required, ChatGPT suggested an innovative solution involving a helix-to-flat transition. This alternative not only met the design criteria, but also introduced a novel approach that could inspire new engineering concepts. This highlights ChatGPT's ability to think beyond conventional solutions and propose inventive designs that stimulate new ideas.
- Furthermore, ChatGPT's adaptability is demonstrated by its ability to suggest different stimuli to achieve similar results. In one case, it offered several material options based on the type of stimulus, suggesting that either magnetic or mechanical strain could trigger the desired shape change. This flexibility in its design approach allows AI to provide engineers with multiple pathways to achieve their goals, enhancing the overall creative process.

It is also interesting to highlight how the codification, which includes initial and final geometries based on primitives such as cubes, cylinders, rings, domes and springs, among others,

can inspire even more complex geometries (as seen in the results from table 7). These geometries meet the requirements of shape-shifting functionality based on the triggering stimuli and the selected manufacturing technologies.

Summarizing, the generative AI is able to operate with the ontology and codification provided, to codify textual descriptions of smart actuators, to describe codified shape-morphing systems, to support with materials selection tasks and to advise with manufacturing options for codified actuators and to generate conceptual design proposals, including inspirational images showing the actuation process on the basis of adequately codified smart materials systems and structures.

## 5. Application of generative AI to the design and manufacturing of a 4D cardiovascular stent




To further illustrate the potentials of synergically employing the codified ontology with generative AI resources an industrial use case linked to a shape-morphing cardiovascular medical device is presented here. Indeed, the designs and manufacturing of a coronary stent that changes shape in response to mechanical stimuli, following the life cycle '3D/T/INV-EXP/MS/1D/T/EXP/MS/3D/T/A/SLM', represents an advanced case of 4D printing and demonstrates how generative AI can assist in the design process. The code line for this actuator describes the various transformations the coronary stent undergoes, starting as a three-dimensional tube (3D/T), which transitions to a one-dimensional shape (1D/T) due to radial compression (INV-EXP/MS). Upon releasing the stored energy (EXP/MS), the stent returns to its initial form (3D/T). The proposed device can be fabricated from an alloy (A) using the SLM process.

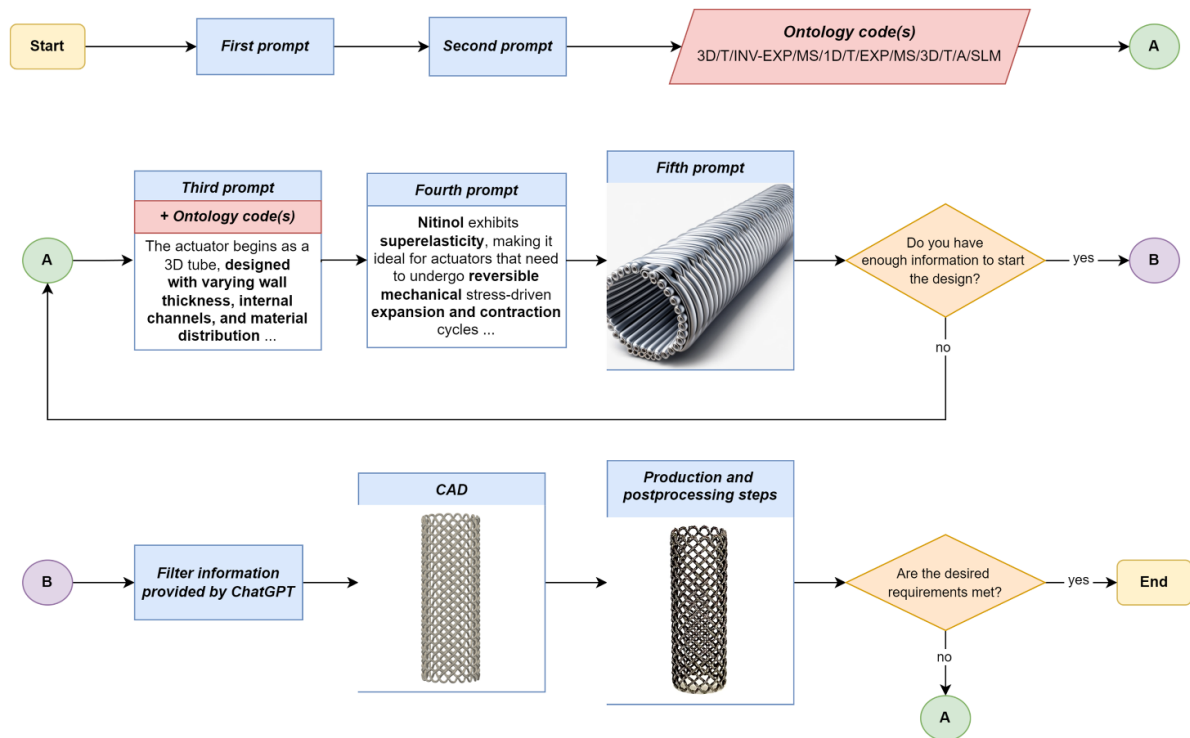
ChatGPT was introduced to the first two prompts to re-explain the use of the ontology and validate its understanding. Subsequently, the ontology code was defined, which is attached after the third prompt. Finally, the other three prompts were then used to guide the design of the desired actuator (table 4). To assess the consistency of ChatGPT's responses, the process was repeated three times as a proposed good practice, both to obtain a wider variety of ideas and to verify the variability of solutions provided by the generative AI.

The related key results are summarized in table 8 and the whole design process is schematically illustrated in figure 5.

Upon comparing the three iterations, authors observed similarities in the outcomes, such as the use of nitinol, the smart nickel titanium family of alloys, which is compatible with the defined manufacturing process, and the need for flexible or stretchable regions to allow the stent's radial contraction and EXP. In the second and third iterations, other materials, such as Co-Cr and titanium alloys, shape-memory and elastomeric polymers, and even hydrogels, were suggested to achieve the desired shape changes. Notably, in the case of hydrogels, ChatGPT recommended that DIW would be the most appropriate production process, demonstrating its ability to creatively and reliably bridge the gap between materials and manufacturing techniques.

**Table 8.** Iterative outcomes of the generative AI during the design of a cardiovascular stent: three constructive dialogues are presented.

Input	Output 1	Output 2	Output 3
Third prompt	<p>The actuator begins as a 3D tube, <b>designed with varying wall thickness, internal channels, and material distribution</b> to allow for inverted expansion. <b>Internal stress points or flexible regions</b> can be introduced to ensure morphing behavior, with <b>features like variable thicknesses or spiral designs</b> enabling contraction under external stress. <b>Selective laser melting (SLM)</b> provides precise control over the structure, <b>ensuring accurate internal features and mechanical properties. Surface finish and post-processing are critical</b>, especially for high-stress environments where smooth surfaces and precise tolerances are required.</p>	<p>This can be applied in situations where repeated expansion and contraction are required, such as in <b>pumps or soft robotics</b>. The shape change is triggered by mechanical forces like <b>stress, pressure, or external deformation</b>. This type of actuator is particularly useful in <b>medical devices</b>, where precise control of expansion and contraction is essential, or in <b>soft robotics</b>, where flexible and reversible actuators are needed.</p>	<p>The actuator begins as a 3D hollow tube with a <b>well-defined diameter and thickness</b> to withstand the mechanical forces it will encounter. Using SLM, the tube can be manufactured with precise dimensions and <b>complex internal structures, ensuring it remains lightweight yet strong enough to handle mechanical stress</b>. During actuation, the tube transitions into a 1D structure, likely through elongation or significant contraction, which may require <b>flexible or stretchable sections in its design</b>.</p>
Fourth prompt	<p>Mechanical stress responsiveness: <b>nitinol exhibits superelasticity, making it ideal for actuators that need to undergo reversible mechanical stress-driven expansion and contraction cycles</b>. Compatibility with SLM: <b>nitinol is suitable for SLM technology, as SLM can precisely fabricate intricate shapes and internal structures</b> from Nitinol powder. This ensures high-quality, detailed manufacturing of the 3D tubular structure.</p>	<p>Materials used for tubes in both 3D and 1D configurations must <b>offer flexibility</b> for deformation under stress and have <b>excellent recovery properties</b>. Mechanical forces trigger the shape changes, so the materials need to allow for deformation and recovery. <b>NiTi</b> is ideal for cyclical morphing due to <b>its ability to return to its original shape after stress</b>, making it suitable for <b>biomedical applications</b> like stents and grippers. <b>Elastomeric polymers</b>, such as TPU or silicone, provide softer, <b>more flexible deformations</b> with less force compared to metals. <b>Hydrogels, which can expand or contract with stress</b>, are suited for biocompatible applications but are usually used in Direct Ink Writing (DIW), not SLM.</p>	<p><b>Shape-memory polymers (SMPs)</b> offer a <b>lighter, more flexible alternative to metals</b>, capable of contracting and returning to their original state when triggered by mechanical or thermal stimuli. <b>Ni-Ti (Nitinol)</b> is the preferred shape-memory alloy for its compatibility with SLM, providing <b>excellent shape recovery, fatigue resistance, and biocompatibility, ideal for medical applications</b>. Cobalt-chromium (Co-Cr) alloys are suitable for SLM when <b>corrosion resistance or biocompatibility</b> is needed, offering strength and durability in harsh environments. <b>Titanium alloys</b> are widely used in aerospace and medical devices due to their <b>lightweight, high strength, and biocompatibility</b>.</p>
Fifth prompt	 <p><b>3D Tubular Actuators</b> designed with inverted expansion and internal channels. The diagram shows a cross-section of a tubular structure with internal channels and a spiral design. Labels include: <b>3D Tubular Actuators</b>, <b>Inverted Expansion</b>, <b>Internal Channels</b>, <b>Spiral Design</b>, <b>Shape Memory Alloy</b>, and <b>Direct Ink Writing (DIW)</b>.</p>	 <p><b>3D Tubular Actuators</b> designed with self-expansion and internal channels. The diagram shows a cross-section of a tubular structure with internal channels and a spiral design. Labels include: <b>3D Tubular Actuators</b>, <b>Self-Expansion</b>, <b>Internal Channels</b>, <b>Spiral Design</b>, <b>Shape Memory Alloy</b>, and <b>Direct Ink Writing (DIW)</b>.</p>	 <p><b>3D Tubular Actuators</b> designed with self-expansion and internal channels. The image shows a 3D tubular structure with internal channels and a spiral design. Labels include: <b>3D Tubular Actuators</b>, <b>Self-Expansion</b>, <b>Internal Channels</b>, <b>Spiral Design</b>, <b>Shape Memory Alloy</b>, and <b>Direct Ink Writing (DIW)</b>.</p>



**Figure 5.** Generative AI-aided design and manufacturing process of a shape-morphing cardiovascular stent involving the interaction with ChatGPT and the employment and application of the developed ontology and codification. Printed nitinol prototype courtesy of IMDEA Materials Institute.

In addition, the iterations defined certain geometric characteristics, such as varying wall thicknesses, creating internal channels, spiral designs, and correctly defining key parameters like wall thickness and the diameter of the tubular structure. Surprisingly, after the first iteration, the AI suggested potential industrial applications for the actuator in fields like medical device design or soft robotics mechanisms. Consequently, the information provided in each iteration complements the others, all following the same goal of designing the stent.

Based on the visual representations of the actuator provided in response to the fifth prompt, significant changes were observed between iterations. In the first image, intertwined helical fibers are visible, showing how these fibers close over time, resulting in the 1D/T that enables the stent to be inserted into the corresponding artery via a catheter. In the second image, transverse strands are depicted, allowing the mechanism's dimensional change in height, meaning the EXP and contraction occur longitudinally rather than radially, in response to the triggering stimulus. In the third image, the intertwined strands of the stent are more explicitly visible, supporting the idea from the first image of designing a stent based on spiral intertwining, creating a flexible structure capable of shape-morphing when activated.

From these results, the authors concluded that superelastic nitinol is the most suitable material for this application due to its biocompatibility, fatigue resistance, and ability to return to its original shape while withstanding the diameter variations the stent will undergo throughout its metamorphosis.

Additionally, as ChatGPT suggested, post-processing the stent will be necessary to ensure a smooth and defect-free surface finish, a crucial aspect in medical devices. Regarding geometric design, the interwoven spirals that enhance the structure's flexibility were considered. As a result, the design is carried out in CAD software, allowing the STL file to be exported and imported into the corresponding slicer for manufacturing using the SLM process, which allows the precise creation of complex structures as conceptual preliminary prototypes.

Figure 5 summarizes the whole process, showing how, from the actuator's codification (in this case, the coronary stent), a series of textual and visual recommendations for its design, material selection, and manufacture are generated. These help to filter ideas, define requirements, design the actuator using CAD software, and fabricate it with the selected process and material. Other ideas provided by ChatGPT in different iterations may be useful for designing other related actuators or alternative solutions with various shape changes, triggering stimuli, materials, and manufacturing processes.

It is important to clarify that this is only a conceptual test, allowing designers to brainstorm using the ontology as a means of communication with the AI. In this case, an iterative brainstorming process is recommended since, as seen in this example, the information provided by ChatGPT is complementary across various iterations. To validate the AI-generated design, computational simulations, mechanical testing, and *in vivo* and *in vitro* tests can be conducted to confirm its biocompatibility and clinical efficacy, ensuring that the final

product not only meets medical requirements but also provides a durable and safe solution for patients with cardiovascular diseases.

Indeed, with the current state of the art, according to our experience with the interactions with the generative AI, the combined employment of the ontology (and its codification) and generative AI tools are interesting from the point of view of creativity promotion, mainly for the conceptual design stage of the engineering design cycle. Once a codification for a possible 4D printed actuator is provided to the trained generative AI, it is possible to ask for materialization proposals, as exemplified in section 4 and summarized mainly in the outputs from tables 5 and 6. In those outputs, the generative AI makes specific references to aspects like strength, response to stimulus, and printability, providing concrete examples of usable materials, designs and manufacturing options, even without having been provided with materials properties.

In fact, those properties are already available to the AI, which searches for them within the general documentation already forming part of its 'cultural background'. However, at the current state of development of generative AI tools, even if vast information about materials properties may be available from the documentation employed for training (potentially the whole documentation from the world wide web), we still believe that the transition from the visual representations and conceptual descriptions provided as outputs by the AI towards the final reliable design of a functional shape-morphing device should be still carried out by experienced engineers, acting as quality control warrants.

## 6. Discussion, current challenges and future proposals

First, it is important to highlight the versatility and utility of the developed ontological framework and related codification scheme for classification and description purposes. It is true that most of the examples found in the brief review (and classified in table 2) deal with a single metamorphosis: one initial shape and one final shape with a shape-morphing process in between. However, as illustrated in the example of figure 3 and in 10 of the 54 examples of table 2, the ontology and codification are perfectly adequate for dealing with 4D printed shape-morphing actuators capable of numerous shape-morphing steps or metamorphoses. A single line of code is enough to describe the whole actuation lifecycle, which includes all the geometrical transformations of the material, structure or device.

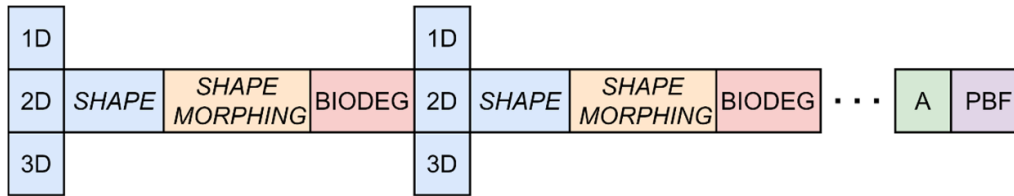
Regarding creativity promotion in the 4D printing arena, counting with this comprehensive ontology and codification can prove extremely rewarding, especially if combined with generative AI tools for fostering innovative solutions. Apart from the already presented synergies with generative AIs, by means of example, figure 6 provides a general codification scheme applied to innovating 4D printed families of multi-stepped actuators triggered by BIODEG, manufactured using biodegradable alloys using powder-bed laser fusion. If the different boxes 'shape' and 'shape morphing' are methodically

combined using the possibilities listed in tables A.1 and A.2 from the annexed glossary, an extremely varied set of potentially viable solutions should be obtained for BIODEG - triggered shape-morphing metallic actuators. To this end, generative algorithms may be also applied in the future.

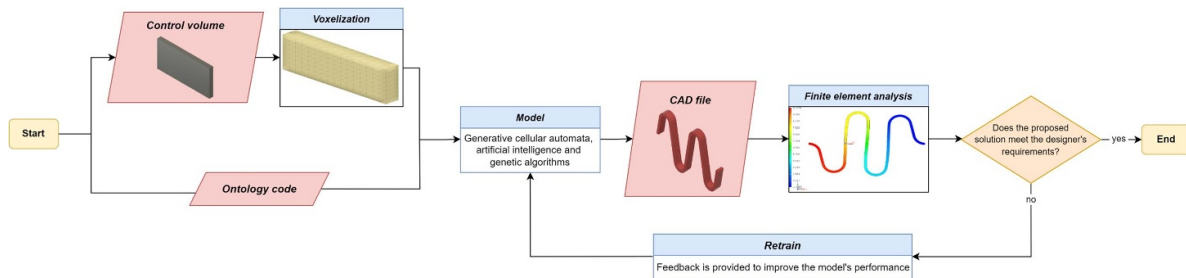
Interestingly, the elements of the ontology can be employed as building blocks, to foster innovation in the 4D printing field, motivating researchers to search for potentially useful combinations of geometries, shapes, shape-morphing principles, triggering stimuli, materials and printing technologies, and, hence, additionally increase the already vast field of application for 4D printed shape-morphing devices. For this purpose, the progressive incorporation of the building blocks of this or similar ontologies, to the set of design operations within CAD modeling software, in connection with algorithmic design approaches, can constitute a relevant step forward. Counting on specific finite elements that adequately describe the shape-morphing of different printable materials, because of the applicable triggering stimuli, is hence essential. Linking these elements to the building blocks of the ontology can support the straightforward development of viable shape-morphing systems.

Considering other future research proposals and directions of study, authors foresee an automated discovery of novel families and subfamilies of smart shape-morphing 4D printed actuators, which will be nurtured by properly combining the three types of self-organizing artificial system: cellular automata, AI (generative adversarial networks and reinforcement learning) and genetic algorithms to emulate and amplify the designer' thinking and creativity [79].

In our view, with the proposed ontology and symbolic codification provided, the first step to deciphering the genome of shape-morphing systems has been already taken [80]. The integration of both proposals, CAD/CAE modeling and artificial systems, is necessary for discovering new smart 4D printed structures. Therefore a generative cellular automaton could be employed, in which the lattice geometry would be univocally related to a control volume imported by the designer, which could be divided into voxels because they allow to arrange the material in any distribution and evaluate their behavior straightforwardly [81]. The information of the shape-morphing steps and their corresponding triggering stimuli would feed the automata, whose rules would be set by an AI based on: 1) the laws of 4D printing [82], 2) the selected AM technology linked to the proposed materials and 3) their distribution. The result would be a CAD file built from the combination of the voxels in the final distribution, supplied by the automata, together with a simulation to verify if the result fits the desired metamorphoses. In addition, the designer could provide feedback to improve the model's performance based on previous experiences and experiments, for fine-tuning purposes. Eventually, the role of the designer will become that of a quality inspector evaluating if the proposed solutions meet the defined requirements (as schematically presented in figure 7). The additional integration of generative AI to the innovation cycle will also transform the role of the designer, including the need for training in ways of interacting with the AI (providing successful prompts) and an additional role as creativity



**Figure 6.** Codification scheme applied to innovating 4D printed families of multi-stepped actuators triggered by biodegradation, manufactured using biodegradable alloys employing powder-bed fusion.



**Figure 7.** Codification scheme applied to innovating 4D printed families of multi-stepped 4D printed actuators.

promotion mentor and validator of artificially proposed solutions.

## 7. Conclusions

A versatile and useful ontology, with universal ambition, for describing all kinds of smart 4D printed material systems and structures has been presented. The different components of the ontology, namely: initial geometry and shape, shape-morphing principle(s), triggering stimuli, intermediate/final geometry and shape, material and 4D printing or AM technology, have been described, and a codification scheme for accordingly describing the life cycle of 4D printed material systems and structures has been provided. The systematic application of the ontology to a set of 54 relevant examples has helped to illustrate its utility and adaptability to many different types of 4D printed devices.

In our view, the ontological framework and codification scheme developed constitute one of the most comprehensive classification tools for the emergent field of 4D printing, thanks to incorporating several geometries, shapes, shape-morphing principles, triggering stimuli, materials and technologies not covered by previous examples of taxonomies and ontologies for smart and 4D printed materials and structures, as has been discussed and referred.

Besides, it is the first ontology capable of representing (in a single line of code) the whole lifecycle of complex 4D printed devices and actuators, in which several metamorphoses may be achievable, due to combinations of different shape-morphing principles and triggering stimuli. A glossary is provided as Annex, to support its implementation and application, and authors are available for fruitful discussions oriented to modifying, completing and improving the proposed ontology with the global aim of organizing this continuously evolving and fascinating field of study.

To the authors' best knowledge, for the first time, an ontology of smart 4D printed materials systems and structures has been combinedly employed with a generative AI tool and their synergic utility validated, as an extremely powerful means for creativity promotion in the engineering design of smart materials and structures.

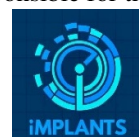
## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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### Conflict of interest

Authors declare no conflicts of interest.

### Declaration of AI and AI-assisted technologies in the writing process

The authors acknowledge the use of generative AI as part of the research methods, as the study deals with a design methodology based on constructive dialogues with a generative AI using the developed ontology and codification scheme as training and mentoring resources. Whenever AI-generated content has been employed within the text, it has been mentioned and highlighted by placing the content in double quotation marks or as a block quote within tables indicating the content as output.

## Annex. Glossary for the proposed ontology

**Table A1.** Geometries, dimensions and common shapes in shape-morphing & 4D printed actuators.

Common shapes	Geometrical dimensions	Abbreviation
Cube	0D, 3D	C
Bar	1D, 3D	B
Plate	2D, 3D	PL
Cylinder	1D, 3D	CY
Elliptical cylinder	1D, 3D	ECY
Tube	1D, 3D	T
Disk	2D	DK
Ring	2D	RG
Sphere	0D, 3D	S
Dome	3D	D
Spring	3D	SP
Serpentine spring	1D, 2D	SSP
Torsion spring	2D, 3D	TSP
Letter-bar-shape	2D, 3D	–BS (U-BS)
Letter-cylinder-shape	2D, 3D	–CYS (O-CYS)
Letter-tube-shape	3D	–TS (Y-TS)

**Table A2.** Shape-morphing principles classified according to achieved geometrical evolution.

Shape-shifting behaviors/types	Other names	Definitions [1, 2]	Abbreviation	Abbreviation v.2
Expansion/contraction [1]	Encapsulation/scaling [2]	Mechanical expansion according to two preferred directions	EXP	EXP/CONT
Swelling/deswelling	Dilation	Three-dimensional expansion through specific volume increase	SW	SW/DSW
Stretching/compressing [2, 3]	Shrinkage, deformation [3]–	Mechanical expansion according to a preferred direction	STR	STR/COMP
Folding/unfolding [1]		Folding is a localized deformation with sharp angles within a narrow hinge area [1]	F	F/UF
Bending/straightening [1]		Bending is the overall deformation leading to a smoother curvature [1]	BE	BE/STRA
Rolling/unrolling [1]		Rolling occurs when continuous force is applied, is a motion in which the shape rotates more than 360° on its axis [1]	R	R/UR
Curving/flattening [1]	Waving, curling [2], wrinkling, creasing [1], snapping [2]	Curving is the amount of curvature that deviates from a flat surface of a geometric object [1]	CUR	CUR/FLAT
Topographical change [1]	Pitting, corrosion	Surface topography represents a local/micrometer deviation of the surface from a flat plane [1]	TC	TC
Twisting/untwisting [1]	Torsion	Twisting is dominated by stretching in the plane [1]	TW	TW/UTW
Helixing/unhelixing [1]	Coil, spiral [4, 5], spiral [6]	Helix is the type of smooth space deformation with curves occurring in the 3D space [1]	HE	HE/UHE
Buckling/debuckling [1–3]		Buckling is characterized by sudden sideways failure of structural members under high compression stress [1]	BU	BU/DBU
Hierarchical [1]		Mechanism that has several shape shifting types	H	H
Bistable (Multistable)		Structure that has two (or multiple) stable equilibrium positions within the range of motion [7]	BS (MTS)	BS (MTS)
Origami		Origami structure can only change its shape by folding	O	O
Kirigami		Kirigami structure can change its shape by folding and cutting	KI	KI
Kusadama		Kusama involves folding several sheets into identical modules that are then assembled to form a structure	KU	KU
Mechanism (kinematic chain)		Multi-body systems and kinematic chains with kinematic joints	MECHA	MECHA
Metamaterial		Metamaterials are structures rationally designed to enable functionality not found in natural materials [2]	META	META
Auxetic (special family of metamaterials)		It consists of a structure that expands when stretched and contracts when compressed [8]	AUX	AUX
Textile		Textile structure is composed of fibers that are intertwined with each other	TE	TE
Blossoming		This mechanism that allows the unfolding of petal-like structures while maintaining structural integrity	BLO	BLO
Self-assembly		Structures assemble themselves and grow from interconnectable units	SFA	SFA



**Table A3.** General scheme of stimuli for actuating smart materials and structures, following [17] with modifications for its adequate adaptation to the proposed codification scheme.

Families of triggering principles	Specific triggering principles or stimuli	Definitions/comments/quotations from references	Abbreviation
Physical stimuli: Transform the chain dynamics or internal atomic packing arrangements of stimuli-responsive materials, resulting in shape-shifting behavior [18, 19].	Mechanical stimuli  Force/stress/pressure  Movement [21]/Vibration  Strain/ Deformation	<p>The materials can deform under the influence of a mechanical force. Also, the internal stress-triggered shape change is driven by the incorporation of the ‘stress-relaxation’ phenomenon during the material manufacturing process [20].</p> <p>‘A tunable, locally resonant structural waveguide is proposed and demonstrated for active vibration bandgap switching and elastic-wave manipulation between 1000–4000 Hz based on 3D printed building blocks of zinc-neutralized poly(ethylene-co-methacrylic acid) ionomer’ [22].</p> <p>Mechanical-responsive materials with versatile responsiveness and high-end precision detect various regimes of pressure or strain at different positions on the human body during physical activities [23].</p> <p>A defined strain can be applied to seeded cells during shape recovery and provide dynamic instructions to the scaffold shape [24].</p>	MS-F   MS-V   MS-ST
	Fluidic stimuli	<p>‘We demonstrate the passive control of viscous flow in a channel by using an elastic arch embedded in the flow. Depending on the fluid flux, the arch may ‘snap’ between two states—constricting and unconstricting—that differ in hydraulic conductivity by up to an order of magnitude’ [25]</p>	FS
	Acoustic stimuli (acoustic field)	<p>Naiyf <i>et al</i> [26] explore the intersection of tunable acoustic structures and additive manufacturing by 4D printing a metamaterial element whose acoustic response can be locally, actively tuned via resistive heating. Contrary to existing, thermally tunable structures, which rely on ambient heating for elastic modulation, the 3D printed structure presented here can be precisely controlled to selectively soften or stiffen only desired areas of the structure.</p>	AS
	Electromagnetic stimuli (EM-fields) in some cases with the electrical aspects more presents, in others with the magnetic ones more present	<p>Electric fields have the capability of manipulating cells to predefined positions or orientating cells in particular directions, these phenomena are known as galvanotaxis and electro tropism respectively [19]. Nevertheless, if the applied electric current is too high, it can cause cell death, localized heating, and membrane rupture [18].</p> <p>Electricity is also an indirect stimulus, as it has been proved to show heating effect due to the resistive nature of material through which it passes [17].</p> <p>‘The shape recovery was actuated as a result of induction heating in the presence of alternating magnetic field’ [19]. Furthermore, magnetic field frequency must be in the medical safety range (50–100 kHz) to circumvent the raised temperature that may hurt the body tissue [18, 27]. Also, shape-shifting can be realized using magnetic forces, with magnetic dipoles [19].</p> <p>Magnetism-responsive materials have been widely used to design and fabricate various actuation devices due to their excellent mechanical response to an external MF, including magnetic force and torque [20].</p> <p>The magnetic field is an direct and indirect stimulus that can bring deformation in the structure [17].</p>	ES       MGS

(Continued.)

Table A3. (Continued.)

Families of triggering principles	Specific triggering principles or stimuli	Definitions/comments/quotations from references	Abbreviation
	Thermal stimuli (heat)	Heat transfer is a direct stimulus. The changes in the shape of these materials are mainly due to two mechanisms: the shape change effect (SCE) or the shape memory effect (SME). In the case of SCE materials, the deformation is proportional to the stimulus applied. The bilayer structure uses the SCE mechanism [17]. A typical 4D structure usually results from the change of molecular structure, anisotropic nature, or different swelling behaviors with the variation of temperature [20].	TS
	Light stimuli (special case of EM stimuli)	The application of light-responsive materials, by selecting specific wavelength, can be characterized into two models: one is the direct light-induced SME, and the other is the indirect effect, whose principal mechanism of action is the photothermal SME (the heat generated from absorbed light) [16, 17, 19]. Moreover, photo-activated materials are limited, generating responses at a particular wavelength [18].	LS-NIR LS-UV LS-V
Chemical stimuli: Variations in physiological situations such as a change in pH or ionic concentrations are usually crucial symptoms for distinguishable kinds of diseases, like cardiovascular system illnesses, infections and cancers; therefore, interpreting them as critical aims of consideration when designing and developing chemical-responsive materials [9, 19].	pH	4D structures shift when the ratio of $H^+/OH^-$ ions in an aqueous solution are varied. The mechanism was attributed to the electrostatic repulsion [16, 20]. *pH responsive materials are capable of swelling, shrinking, dissociation or degradation upon change in environmental pH, attributed to either protonation of ionizable groups or degradation of acid-cleavable bonds [19].	pH
	Ionic concentration	Shape morphing could be realized through changing salt concentration. Despite relatively little research on material's response to ionic concentration, it is important to note that physiological electrolytes level can be a critical indication for various diseases [19].	ION
	Biodegradation Solvent (dissolution mechanics [3])	The solvent-induced stimulus is relatively easy because a 4D construct can achieve the shape transformation or functional transformation only through immersion into a solvent such as water [20]. This mechanism was demonstrated by Kokkinis <i>et al</i> [28] in the field of bioprinting. In this mechanism, a printed structure is immersed in an appropriate solvent (ethyl acetate), based on the studied polymer structures. A change in shape occurs as a result of the loss of some non-crosslinked polymers when the structure is immersed in the solvent [3].	BIODEG
	Humidity/Moisture	Printed structures change their shape when they absorb water and recover their original shape after drying [16]. For liquid-responsive materials, transformation is designed such that differential swelling of the different compartments occurs in spatially and temporally dependent manner [18, 19].	MO

(Continued.)

Table A3. (Continued.)

Families of triggering principles	Specific triggering principles or stimuli	Definitions/comments/quotations from references	Abbreviation
Biological stimuli: In the human body, biological processes often rely on feedback-controlled communication involving biological small molecules or bio-macromolecules such as glucose, enzymes, nucleic acids, polypeptides, and proteins [18, 19]. All play a significant role in controlling the normal mechanism and functioning of organs. Therefore, recognizing these important parameters and biomaterials that respond to biological stimuli are essential for the better performance of 4D printing technology [9].	Biological scavenging	Enzymatic degradable materials are also of significant interest in the field of tissue regeneration because implants made of these materials can be broken down and removed naturally from the body after they have fulfilled their functions [19]. However, weak mechanical strength, slow response time, and hydrolysis can cause degradation, and swelling/de-swelling cycles are essential considerations when estimating the material's usage and life span [18].	BIOSCA
	Cell traction force [16]	Living materials incorporating cells within synthetic chassis, with the cells acting mechanically upon the chassis and moving them.	CTF
	Enzymes [16, 18] Glucose [18] Proteins [18] Polypeptides [18] Nucleic acids [18]	Shape-shifting processes at molecular level.	NANO

**Table A4.** Common families of materials and shape memory [3, 9, 14] materials, with which shape-morphing systems and 4D printed actuators can be created.


Family	Materials	Abbreviation
Common materials	Alloys	A
	Polymers	P
	Composites	CO
	Multimaterials	MT <sup>a</sup>
	Ceramics	CE
	Gels	G
	Carbons	CA
Shape memory (SM) materials	Alloys	A (SMA)
	Polymers	P
	Composites	CO
	Multimaterials	MT <sup>a</sup>
	Ceramics	CE
	Gels	G
	Carbons	CA

<sup>a</sup> When defining 4D printed actuator that is multimaterial, the component materials are added as follows: MT(CE+P+...).

**Table A5.** The ontology and codification scheme, as regards additive manufacturing technologies, is based on the 7-family division commonly accepted [16], with some minor modifications. The table below includes the glossary of selected relevant additive manufacturing technologies for the proposed ontology and codification scheme.

Technology	AM process	Abbreviation	Reference
Material extrusion EXT	Fused filament fabrication	FFF	[15, 16]
	Direct ink writing	DIW	[15]
Material jetting JET	Nano particle jetting	NPJ	[15]
	Drop on demand	DOD	[15]
Vat polymerization VAT	Stereolithography	SLA	[15, 16]
	Continuous direct light processing	CDLP	[15, 16]
	Digital light processing	DLP	[15, 16]
Binder jetting BIN	Binder jetting	BJ	[16]
	Inkjet head printing		
Powder bed fusion PBF	Multi jet fusion	MFJ	[16]
	Electron beam melting	EBM	[15, 16]
	Selective laser melting	SLM	[15, 16]
	Selective laser sintering	SLS	[15, 16]
Direct energy deposition DED	Laser engineered net shaping	LENS	[15, 16]
	Laser metal deposition	LMD	[15]
	Cold metal transfer	CMT	[15]
	Rapid plasma deposition	RPD	[15]
	Electron-beam additive manufacturing	EBAM	[16]
Sheet lamination LAM	Laminated object manufacturing	LOM	[15, 16]
	Solid foil polymerization	SFP	[15]
	Ultrasonic additive manufacturing	UAM	[15]

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