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CRITICAL REVIEW

Research on imminent enlargements of smart materials and structures towards novel 4D printing (4DP: SMs-SSs)

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Abstract

Smart structures of 4D printing are perhaps interdisciplinary research area with significant development and applicability future. The cornerstone of 4D printing is smart materials. When a stimulus is put in front of this structure, it changes into a different structure. This article initially provides a succinct insight of the aforementioned 4DP: SMs-SSs: 4D printing (4DP) technology imminent enlargements of smart material's (SMs) prospective to physique smart structure (SSs). Investigation into 4D printing has pulled in phenomenal enthusiasm. The research work of 4DP: SMs-SSs has stimulated promising future. The paper discusses smart materials and their potential towards mainstream 4D printing for smart constructions (4DP: SMs-SSs). Cursory research write-up on smart materials associated 4D printing approaches to process them based on adaptability to stimuli, fabrication, control mechanisms, multi physics modeling, and existing as well as emerging functionalities. Indeed, innovative structural initiatives could perhaps inspire new paradigms for stimulate positive structures. Novelty structures are being thoroughly researched, and new ideas will be incorporated. Programmability, reactivity toward and adaptability to their circumstances, and automation are all functionality of 4D-printed items. The article's conclusion is that 4DP: SMs that can create intelligent/smart structures (SSs) will even trigger a massive era of construction material. This article shows an insight into how quickly technology is changing, how some researchers and scholars are figuring out what it can do, and how engineers could use the ideas. The adoption of smart materials will assist in resolving the problem to a greater extent. 4D printing relies on shape memory alloys/polymers (SMAs/SMPs) as so forth organic materials. Imminent enlargements of smart materials prospective to physique smart structures are still being experimented with by scientists and engineers.

Keywords Additive manufacturing · 3D printing · 4D printing · Smart materials · Smart structures

1 Introduction

Scientists and engineers have been developing new smart materials besides existing technologies. Smart materials and structures are promising for lifetime efficiency and reliability. Many materials have evolved in the past 20 years than in human history. The earliest actual manufacturing in human history took place in the Stone Age. Six main manufacturing methods have evolved over human history. Stone tools were made by cutting, changing the mechanical characteristics of the stone, joining, coating, molding, and forming. Technological progress improved manufacturing speed and efficiency. Material innovation continues at a "accelerated pace," [1] which he credits to 1980s military and NASA research. In 1932, gold-cadmium was the first smart material observed. And 1938 was the first transition phase in brass (copper-zinc). Beehler and associates discovered the alteration and shape memory mechanism in nickel-titanium in 1962 [2, 3]. Their lab inspired the term nitinol. After nitinol, more shape memory alloys were discovered. The research's importance lies in its research process on smart materials, their new enhancement prospects, and associated behavioral patterns as well as features and functions. As of 2022, additive manufacturing and 3D printing are interchangeable since the technology's accuracy, repeatability, and material diversity have improved enough to make some 3D printing processes an industrial production technology. As a result, 3D printing is regarded as one of the most revolutionary developments in contemporary industry. Manufacturers and researchers can now produce sophisticated shapes and structures that were previously

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unattainable with standard production methods. A 3D printer that operates in three dimensions can manufacture three-dimensional structures. To print a 4D object, you do most of the same things you would do to print a 3D object. The key distinction is that 4D printing technology makes use of programmable materials that change when exposed to water, light, or heat. Although 3D and 4D printings are promising technologies, there are a number of problems that prevent them from reaching their full potential.

To promote an integrated work that combines manufacturing designers and engineers. AM of smart materials and structures has gained popularity recently. The entire article of 4DP: SMs-SSs mainly concerns in the following distribution (part A and part B):

> Part A: the research aims to examine technicalities, characterizes, and categorizes smart materials to physique smart structure applications in different fields. (1) What capabilities are offered by smart materials? And formulated the shape-changing laws for 4D-printed structures. (2) Technology hierarchy for smart materials correspondence for recent devolvement and future prospective. (3) As a potential material for 4D printing, heat- and light-reactive smart materials are being researched.
> Part B: material-related key concept involves material-based design problems. The second issue uses material phenomena and principles. A third concern involves materials over structure. Finally, the problem arises when both the structure and its materials perform functions.

In a teleological approach, finding the perfect materials, stimulation, and amplitude is complicated, so it is not yet possible to create a 4D object with a certain functionality. Last but not least, this field of study is still prehistoric. 4D printing is technically feasible since of innovative materials, sophisticated printers, deformation processes, and basic arithmetic [4]. It possesses all the necessary abilities, including the capacity to be stimulated, and it can be folded, stretched, and twisted into various shapes.

1.1 Fundamental concepts

The ISO-ASTM 52,900:2017 [5, 6] standard describes seven AM methods that are implemented in AM technology. The goal is to have a deeper understanding of the fundamental concepts and technical terms used in 4D printing. This paper builds on aforementioned work on additive manufacturing ontologies, including ISO TC261 and ASTM International F42's efforts to standardize terminologies [6], NIST's work [7], and other publications [8, 9]. Essential preexisting ideas related to 4D printing are presented in this section4DP. Essential preexisting 4D printing concepts are discussed. The concept of "4D printing," which refers to the capability of additively manufactured objects to change shape over time, was initially put forth by an Massachusetts Institute of Technology (MIT) research team [10, 11]. Components can self-fold and restructure without human intervention [12, 13]. This self-folding phenomenon is related with shape change behavior, where 4DP structures can morph over time. The three main categories for the shape memory effect are as follows: a one way shape memory effect [14], a two way shape memory effect [15], in addition to multiple shape memory effect [16]. Several researchers have constructed "bistable" structures with two stable states that can be switched mechanically. The bistable structures do not need any extra energy to stay in their stable states. They can be used as mechanical switches or to enhance the ability to activate and control motion [17]. Figure 1 shows a diagram depicting the categorization, historical evolution, and technical characteristics of AM technology. According to the development history of AM components, it is divided into structural components, functional components, intelligent components, vital organs, smart objects, etc. It can be seen from Fig. 1 that with the further divergence of manufacturing thinking, the intelligentization, vitalization, and awareness of components in the manufacturing field are inevitable development trends. The concepts of "5D printing" and "6D printing" have also entered the AM family. Since then, AM is no longer synonymous with 3D printing but includes higher dimensions, more aspects, and deeper meanings. There have been laboratory research results in 5D printing. Although 6D printing is only a newly proposed concept and has not yet entered the substantive research stage, as the research of 4D printing technology gradually deepens, it indicates the possibility of higher-dimensional printing methods.

2 Imminent enlargements of smart materials and structures

Once a substance is turned into an item, it stays that way until unpredicted situations or aging. Nature has various sensitive and reactive materials, whether in the animal or plant realm. Essentially, these are non-static materials compared to what we are accustomed to. Solar cells, high-strength fibers, multi frequency radars, and camouflage coverings are all inspired by plant leaves. Let us identify several of them.

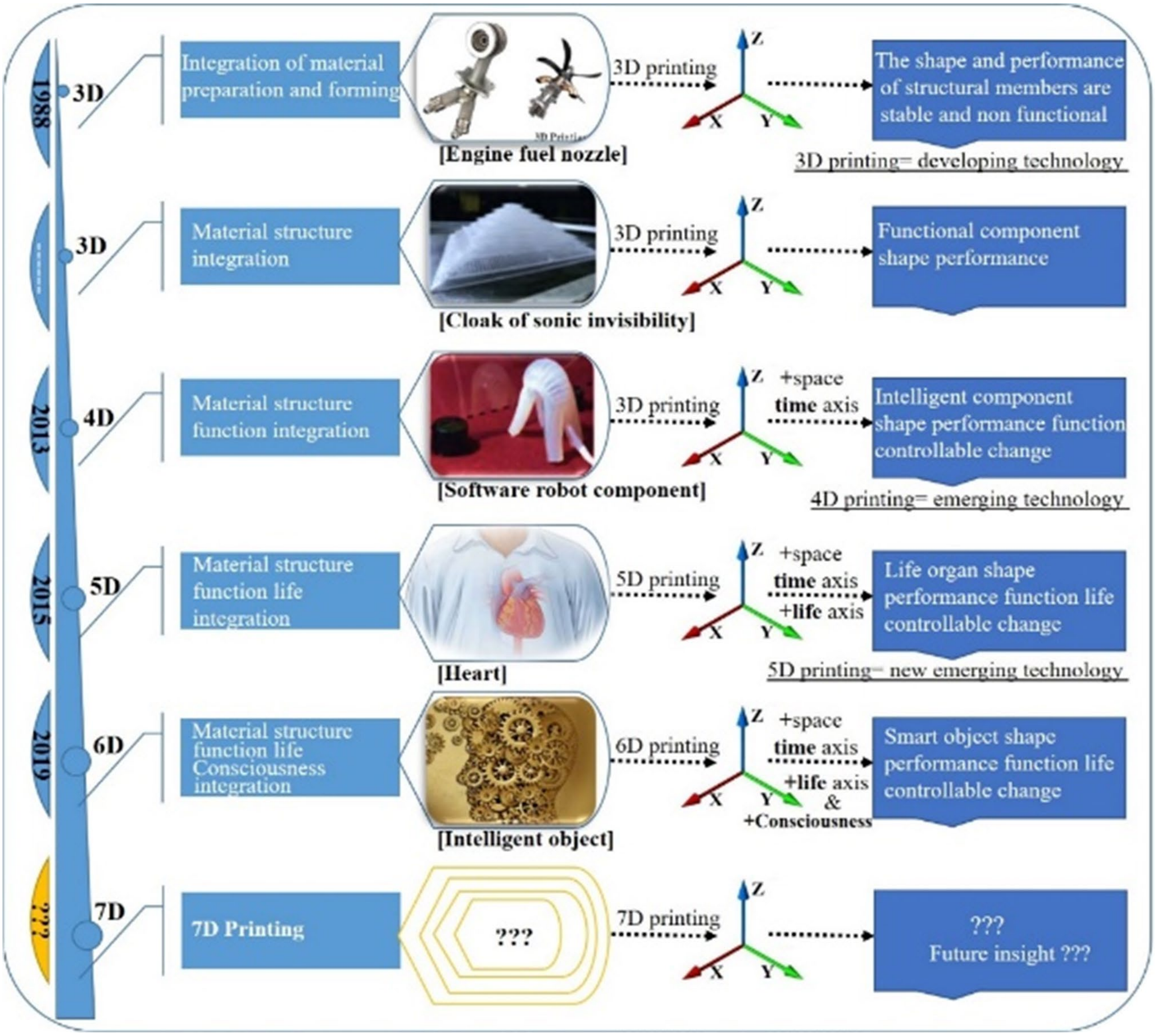

Fig. 1 Classification, development history, and technical characteristics of 4DP: SMs-SSs

2.1 Imbuing static object (man-made object) with the capability of evolving

There are numerous methods for endowing objects with such capabilities, and 4D printing is likely to be among them. Most man-made products are designed to have a single physical state (usually kinematic) to meet consumer needs and expectations. Static objects are insensitive to changes in their environment. Figure 2a, b, and c depict changeable items.

The sofa converts into bunk beds (Fig. 2a). The ottoman portion of the sofa bed that converts can be used in its non-bed state and does not require any assembly. To suit your diverse and flexible needs, it may be quickly and simply transformed into a sofa, lounger, or bed. Heat-sensing, color-changing spoons with temperature indication are shown in Fig. 2b. Tablespoon head elastomers contain materials that change color when the temperature of the food goes above 40 °C. When this happens, the flexible part of the spoon will turn white, indicating that the food is too hot to eat. This is very safe and easy to use. Shape-shifting wheel and tire is shown in Fig. 2c. Ackeem Ngwenya, a recent Royal College of Art graduate, designed a shape-shifting wheel and tire. Industrial designer created tire with two rubber skins. The base is flexible, and the outer is rigid.

2.2 Smart structures are found in nature

Smart structures can perceive, make decisions, and act; these skills should increase exploration success in harsh environments. A fractal's structure is invariant at different scales. Structure modeling can benefit from fractals. Figure 2d shows such natural structures. Remarks: manufacturing such structural features was currently not conceivable. Another pattern of Chinese lantern plants, Thigmonastery, and the like that is extremely intriguing [19]. The chameleon's skin is an example of a responsive material or organism. Its hue changes nearly instantly depending on its mood and the color of its environment as shown in Fig. 2e. Remarks: the chameleon as a creature is a sensitive, color-changing material.

Summary: concerning the practicality of such patterns of behavior, it is evident that they cannot serve as weight bearers like normal material does. In the meanwhile, they accomplish a goal.

Materials, such as the imbuing static object (man-made object) with the capability of evolving and smart structures, are found in nature aforementioned illustrations be situated called smart materials. Manufacturing is reaching a milestone. Let us explain step by step.

2.3 Additive manufacturing techniques

This section describes ASTM-standard 3D printing procedures. Figure 3 shows their significance, working mechanism, aspects, and limitations. Due to the great variety of 3D printing techniques and materials accessible, many of them are frequently useful.

In this portion, the article provided an extensive research from the state-of-the-art literature, clarifying key terms and concepts. Usually, there are three steps to 3D printing: designing the object model, making the model with a 3D printer, and finishing. The following are the main AM printing technology's basic stages. The basics begin with computer-aided design (CAD), STL (Standard Tessellation Language) file manipulation, and machine transfer; the next step is to set up the desired machine and begin the building process; then, the final step is a product post-processing. In Fig. 4, the 3D AM portion a layer-by-layer stacking process is divided into three phases. In the first phase to begin commercial software, SolidWorks, Pro/Engineer, and Materialise 3-Matic create the entity model. In the second step, a model is imported into slicing software for layering and slicing [22, 23]. Finally, a layered data file is loaded into a 3D printer, which builds the parts layer by layer from the ground up. The geometric design freedoms that can be obtained using 3D AM make it a very exciting technology for the future of manufacturing. To print structural components and outcomes often within a few hours from a CAD model. CAD generates a model's digital part design. The design is then sent to a 3D printing machine to be made real.

Existing mathematical models, enhanced categorization of stimuli-responsive materials, and refined stimuli will improve 4DP control. Figure 4 shows the main 4DP components, including the 3D AM process, interaction mechanism, mathematical modeling, stimuli-responsive material, and result-influencing stimulus [20, 21, 24]. The findings of Momeni and colleagues [14] suggest

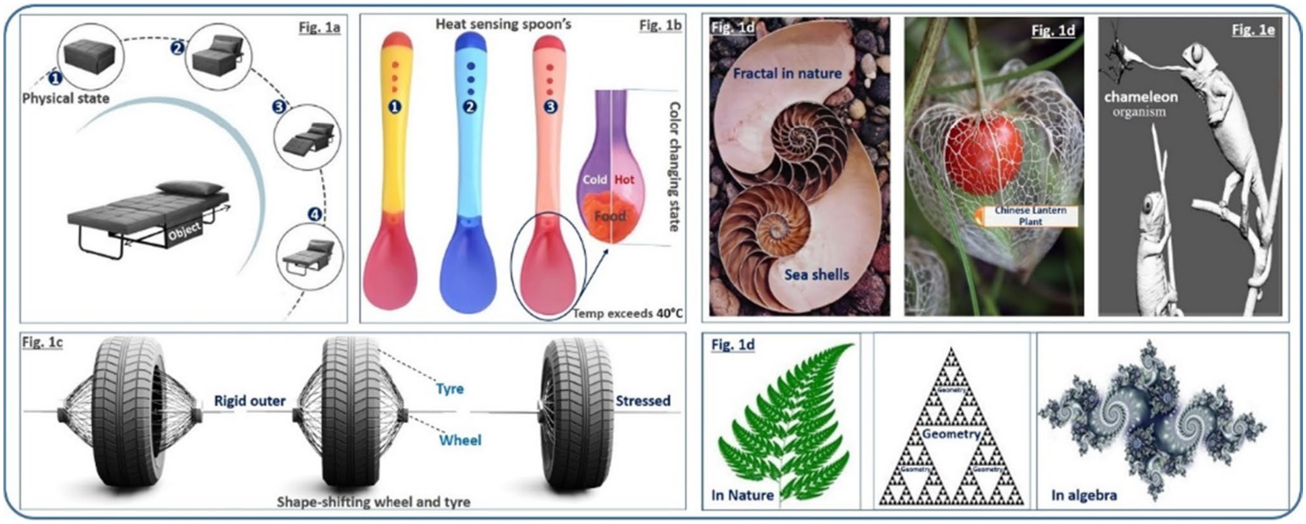

Fig. 2 **a**–**e** Several instances of creatures which are capable of transforming their appearance: **a** bunk beds that convert from sofa; **b** heat-sensing spoons; **c** shape shifting wheel and tire; **d** natural occurrences of fractals, sea shells, and Chinese lantern plant; **e** stimulus-responsive natural materials chameleon skin [18]

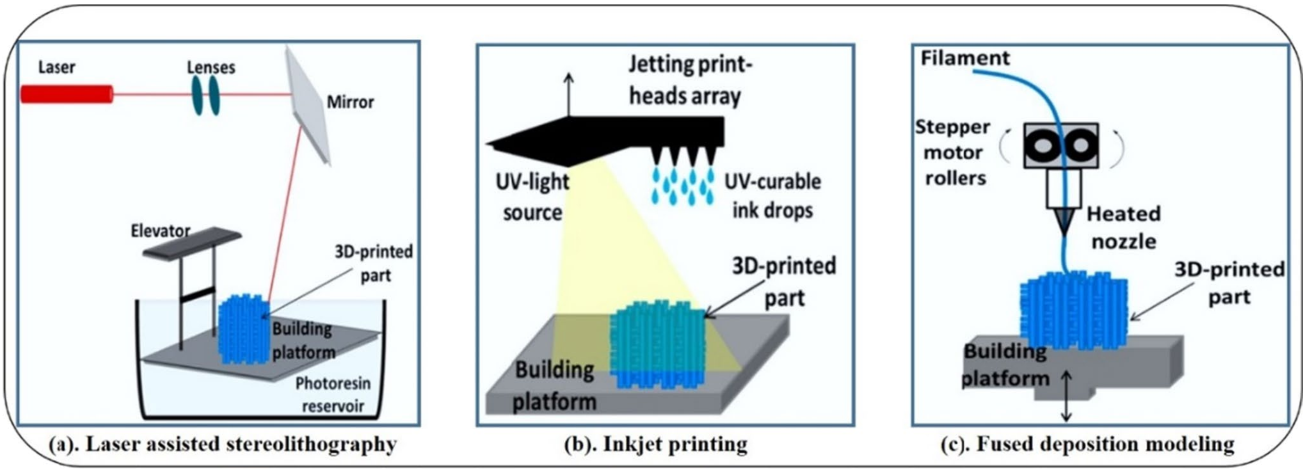

Fig. 3 Schematic representation of various AM techniques: **a** laser-assisted stereolithography (SLA); **b** inkjet printing; **c** fused deposition modeling (FDM)

that this represents a four-step cycle. An external force applied to the structure at a high temperature causes deformation in the first case; in the second approach, the deformation (strain and constraint) is then sustained. Third, due to the low temperature, the structure is unloaded, resulting in the achievement of the required shape. Fourth, the structure is capable of recovering its natural shape.

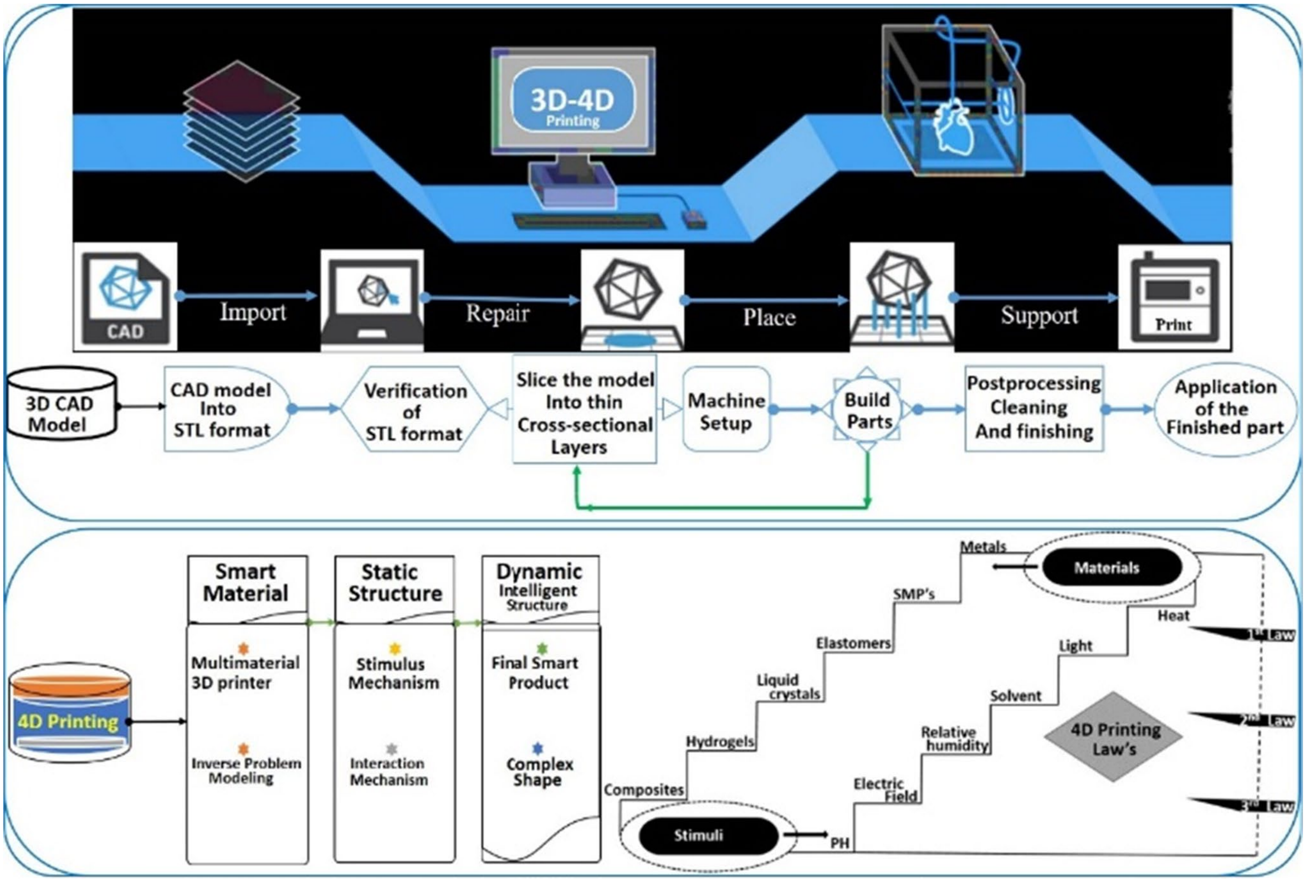

Fig. 4 Conceptual framework for 3D-4D printing process [14, 20], adapted from [21]

3 4D printing (stated smart materials and structure)

In 2013, the interpretivist approach concerning 4D printing was initiated (TED speech milestone). Using shape memory effect, printed active composites (PACs) turned a printable material towards a complex structure (SME) [25]. Among fundamental properties of 4D printing is that it is not static and may alter over time using a computer-programmed prompt. The term “4D printing” can be interpreted in a number of different ways. Initially, 4D printing could just be a more advanced form of 3D printing [26–28]. Elucidates in precise detail, the 4D printing is the breakthrough of a 3D-printed structure over time being subjected by heat [29, 30], light [31, 32], water [27, 33, 34], and pH [35], among others. Combining a 3D printer towards a smart material and perhaps a highly structured design results in 4D printing [36–38]. Such 4D-printed materials are ideal for manufacturing toys [39], robots [40], lifters[40], microtubes [41], and lockers [42] attributed to their capabilities. 4D printing involves applying a stimulus to a smart material utilizing while an AM process, an appropriate interaction mechanism and mathematical modeling, produces a 4D-printed structure. Three principles essentially control the ability among all 4D-printed structures to change shape were developed by Momeni and colleagues [43]. Insight into the physics that allows 4D-printed structures to change shape is provided by these principles. These laws are as follows:

> First law: in accordance with the first law, the relative intensification of both active and passive materials is responsible towards the shape-changing phenomena (except curling, curling, twisted, and bending, among others) of multi-material 4D structures.
> Second law: as stipulated by the second law, the ability of all multi-material 4D structures to change shape is based on four physical factors: mass propagation, thermal expansion, molecule transformations, and sustainable growth. All of the aforementioned capabilities have the potential to contribute positively in relation toward the relative growth that takes place concerning active and passive materials when a stimulus is applied, which eventually results in shape morphing.
> Third law: according to the third law of 4D printing, the time-varying shape-shifting in practically multi-material 4D-printed structures has two time constants. This law indicates that the shape-shifting can occur in either direction. This law describes the time-dependent shape morphing behavior of practically all multi-material 4D-printed structures. This rule was developed in an effort to characterize the behavior of almost all multi-material buildings that were constructed utilizing 4D technology throughout the course of time and how that behavior changed. Specifically, this law was designed to describe how the behavior changed. Depending on the stimuli and the material used for 4D printing, these constants can be equal, enormous, or even vanish with regard to each other. As a consequence of this work, fourth dimensional bi-exponential formula created, which can be included into software and hardware for application in the modeling of 4D structures in the future.

Structure key properties: Shape fixity, shape recovery, and repeatability are three of the key properties that are frequently used to characterize the characteristics of 4DP parts that are attributed to the competency of the components. For a “shape memory polymer” (SMP), the “shape fixity” refers to the degree to which a transient shape is fixed [44]. The shape fixity ratio (Rf) is the capacity of a 4DP continuation to carry out a mechanical deformation carried out since the programming method in equation (Rf).

$$Rf(\%) = \frac{\varepsilon_{unload}}{\varepsilon_{load}} \times 100 \tag{1}$$

The computation is based on the ratio of strain ε_{unload} obtained after cooling to strain ε_{load} recorded above T_g [45].

“Shape recovery” is a polymer’s capacity to retain its native structure after being deformed [45]. According to Eq. 2, the “shape recovery ratio” (R_r) is the capacity of a material to retain its stable shape. This represents the ratio of the deformation step’s beginning strain (ε_i) to the recovery step’s final strain (ε_f).

$$Rf(\%) = \frac{\varepsilon_i - \varepsilon_f}{\varepsilon_i} \times 100 \tag{2}$$

The amount of time required for a material to reach its recoverable strain, which is denoted by the variable (T_r) in Eq. 3, is referred to as the “shape recovery time” (t). The maximum shape recovery rate is indicated V_m, recovery deflection by S_i, and time interval by t [46–48].

$$V_m = max[\frac{S_i + 1 - S_i}{t}] \tag{3}$$

Calculating and forecasting the distribution of materials and the structure necessary to accelerate forth desired form change requires the use of mathematical modeling. Twelve types of deformation are included in the shape change behavior stated in the earlier section [20, 49].

4 Rapid advancement in 3D printing of smart structures

Propagating the availability and use of smart structures requires significant effort in the areas of material improvement, structural design, and production. Smart structures have come a long way in recent years, and these improvements are noteworthy. The contemporary needs and projected future direction for 3D printing technologies and smart structures are indeed acknowledged. Sensitive materials in smart structures adapt dynamically to environmental stimuli to perform specified functions [50]. In reaction to environmental factors (e.g., heat [34, 51], electromagnetism [52, 53], light [54, 55], pH [56], ion concentration [57], sound [58], and mechanical force [59, 60]), common intelligent structures enable programmable deformations. Soft robotics [61–64], aerospace engineering [65], electronics [66–68], and biomedicine [69–71] are among the fields to which techniques and technologies that take use of the possibilities offered by smart structures have been applied. Therefore, authors concentrate on the applications of functional polymers and composite materials, suitable 3D printing techniques for smart structures.

4.1 Temperature approachable smart structures

A temperature reactive smart structure is one that adjusts its behavior in response to shifts in temperature in order to carry out the functions that were previously specified. However, like traditional thermostats, sophisticated devices are typically constructed utilizing multilayer architectures with varying various ambient sensitivity levels for each layer [63, 72, 73]. Embedding shape memory (SM) elements into softer base materials can create temperature-responsive smart structures [74–78]. By using pre-stressing procedures before or after manufacturing, it has also been able to create temperature-responsive results [79, 80]. Those certain smart structures facilitate soft robotics, intelligent components [81, 82], and nonbinary actuators [75] while performing critical biomimetic tasks [83].

4.2 Electro responsive smart structures

Electroactive polymers, such as dielectric elastomer actuators (DEAs) and electroactive hydrogels (EAHs), drive electro responsive smart structures because of their strain capacity and energy density. Smart structures that respond to electromagnetic fields can perform specific tasks. Due to its greater capacity to respond quickly and at a high frequency, it finds widespread use in bionic structures [84–86], soft robotics [52, 61, 87, 88], and biomedical devices [69, 89].

4.3 Magneto responsive smart structures

Smart structures with magnetic responses are used frequently considering their quick response times and non-contact control capabilities. Doping ferromagnetic particles into a polymer matrix, such as polydimethyl siloxane (PDMS), UV resin, or hydrogel, is the typical method for achieving the magneto responsive function. Hard magnetic materials, in addition to soft magnetic materials, find widespread application in the construction of magneto responsive smart structures. It is therefore usual feature commercialize vat photopolymerization for the printing of magneto responsive smart structures.

4.4 Self-healing smart structures

Smart structures that self-heal can fix damage automatically or using light or heat. Consequently, they provide a straightforward and inexpensive method for extending the lifetime of structures [90]. Self-repairing structures are characterized by their healing efficiency and number of successful healing cycles. In addition, it contains intricate shapes of self-healing materials [60, 91, 92], and example includes the complex internal vascular networks [59, 93–95].

4.5 Smart sensing structures

A structure that is equipped with smart sensing capabilities is able to detect variations in external physical factors, displacement [96], pressure [97], and the humidity [66]. Wearable flexible sensing device research has grown to be one of these. Among these, research on wearable flexible sensing devices has become quite popular. A straightforward and inexpensive method for the 3D printing of smart-sensing structures was proposed in Leigh et al.'s [98] research work.

The ability to rapidly and precisely manufacture complex smart structures is a major benefit of 3D printing technology. In a reversal of roles, the growing need for the production of intelligent structures is driving forward the development of 3D printing technology. The foregoing are some areas that should be the primary focus of future research about the 3D printing of intelligent structures. Actuation and sensing capabilities can be added to a structure through the use of smart materials and structures in a way that is unobtrusive, integrated, and distributed. This is an important quality of smart materials and structures.

5 Smart materials

5.1 Comprehensive concept

Smart materials change their physical properties (color, stiffness, volume, shape) when exposed to varied stimulations (temperature, pH, magnetic field, wetness, light). A smart structure embeds or layers smart materials and performs sensing and actuating functions. Shape memory polymers (SMPs) are smart materials that can return to their original, permanent shape [99]. In order for polymers to have the ability to remember their original shapes, two types of domains are necessary: net-points and switches. Net-points have the highest *Ttrans* to prevent polymer flow and chain sliding during programming. The switching segment is a network that becomes flexible when its *Ttrans* temperature is above the net-point. When the switching region's Ttrans temperature exceeds the net point, the area becomes malleable and can be switched. Tm or *Tg*, the section's melting or collapsing point Tm. Amorphous with a *Tg*, semi-crystalline with a *Tg*, or liquid crystal with an isotropic temperature can all be used as switches. In contrast to SMPs with a Tm transiting, whose temperature transition is more rapid, those with a *Tg* switch undergo a gradual change in behavior across a large temperature range [100, 101]. Since these properties, SMPs have a wide range of adjustability.

5.2 Classes

There are two classes to smart materials as illustrated in Fig. 5: (a) shape change and (b) shape memory materials. Shape altering materials flip between two states when stimulated. In preliminary state-1, called the permanent/original shape, the material is not stimulated. The second state is the material's temporary form when subjected to an external stimulus. When the external stimulus is no longer present, the temporary form reverts to its original state-1, as seen in Fig. 5a. Materials with form memory have the capacity to be reshaped into a different configuration after being given the appropriate instructions. That means that the temporary shapes can be programmed into shape memory materials. Shape memory materials are distinguished by their ability to retain their original form. The materials can be deformed and repaired mechanically when subjected to an external stimuli. After the stimulus has been removed and the deformed shape has been restored, the temporary shape continues to be retained. The shape memory material will, as a concluding milestone, revert to re-exposed to the stimuli depicted in Fig. 5b.

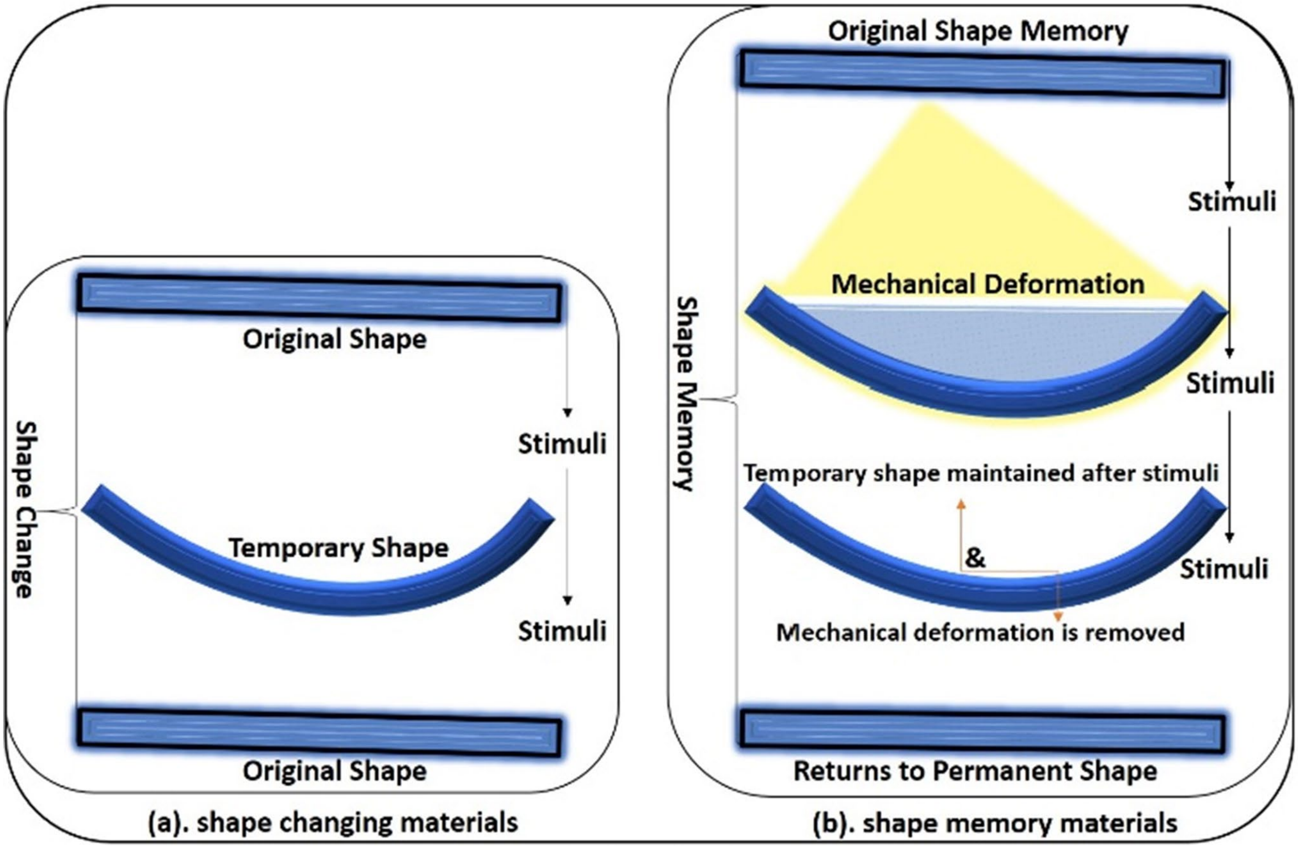

Fig. 5 A diagrammatic explanation of the processes involved in (**a**) shape-shifting materials and (**b**) shape memory materials

5.2.1 Shape memory alloys (SMAs)

As a potential action, smart materials merit extensive study and potential use. There are two stable phases of smart materials that occur at various temperatures: austenite, which is the phase that occurs at high temperatures, and martensite, which is the phase that occurs at low temperatures (austenite phase). Intelligent/smart materials have two distinct features that set them apart from conventional steels. The first one is known as super elasticity, and the second one is shape memory. It is the SME or transformation mechanism of smart materials that allows SMAs to be distorted into any shapes and then revert to their original form with thermal stimulation.

5.2.2 Memory effect (SME)

When the SMA's atomic crystal structure changes from one crystalline structure to another, the SME is produced. Thermomechanical programming has the potential to retrain SMAs to keep a specific permanent form. After the desired form is applied to the SMA, it is annealed at a temperature above its austenite phase transition temperature and subsequently cooled as illustrated in Fig. 6a. In the martensite phase upon annealing, the annealed SMA is malleable and can be deformed into various temporary shapes (Fig. 6b). Whenever the SMA is heated beyond its transformation temperature, the temporary shapes revert to their original permanent shape (Fig. 5c, d). Smart materials are utilized for coupling and form mechanism, actuators, combinations, shock fascination, vibration damping, automatic on–off switches, and biomedical applications [102–107].

5.2.3 Nitinol SMA wire

A nitinol SMA manufactured from a permanently compressed and momentarily stretched wire spring is depicted in Fig. 7. A robotic tentacle using SMA springs is bioinspired [108]. Nitinol, a SMA created by the Naval Ordinance Lab, is widely used in the automotive industry [109–111], aerospace [112, 113], healthcare [114, 115] advanced manufacturing automation, robotics [108, 116–121], and soft actuation industries [108]. Nickel and titanium were used to make it.

5.2.4 Shape memory polymers (SMPs) and shape-changing polymers (SCPs)

Shape memory polymers (SMPs) and shape-changing polymers (SCPs) are two further kinds of smart materials that are gaining interest. These "smart" materials are responsive to a variety of environmental stimuli, including but not limited to

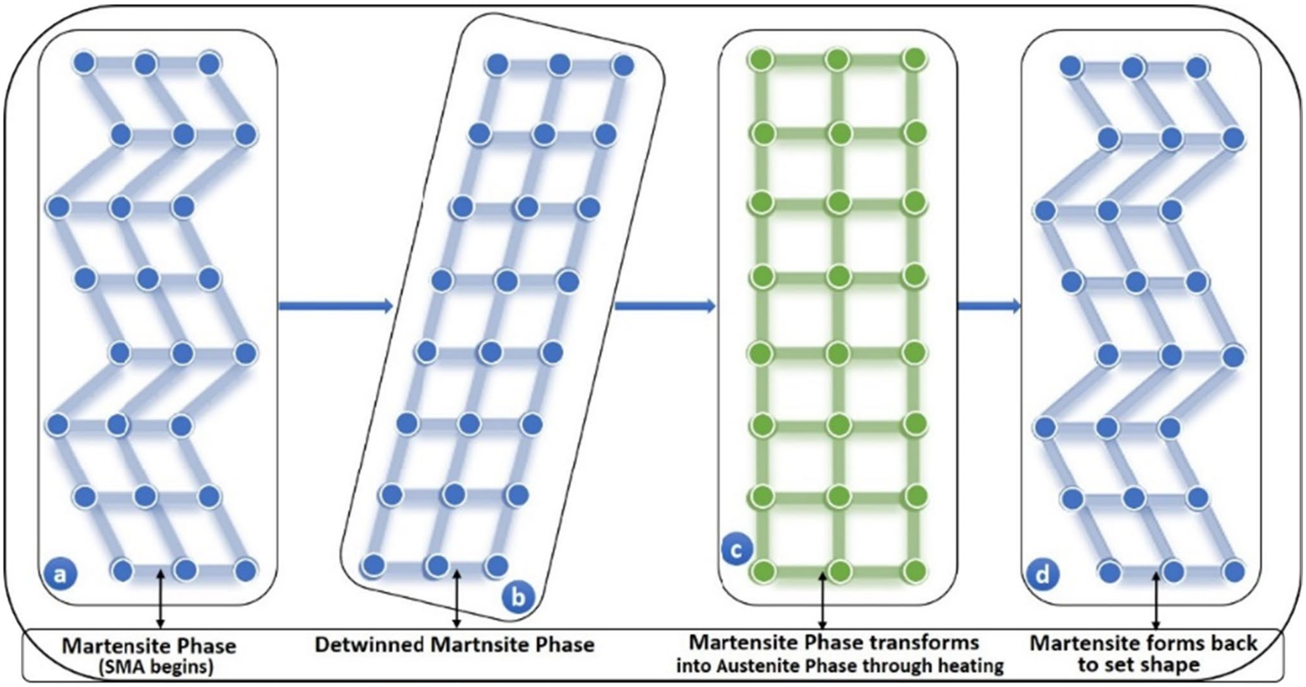

Fig. 6 A schematic of the shape memory effect (SME) in a shape memory alloy (SMA) where a material begins in the **a** twinned martensite phase and set shape, **b** the spring is deformed and aligns the crystalline structure into a detwinned martensite phase, and **c** the crystalline structure transforms into the austenite phase when heated and **d** returns to its martensite phase when cooled

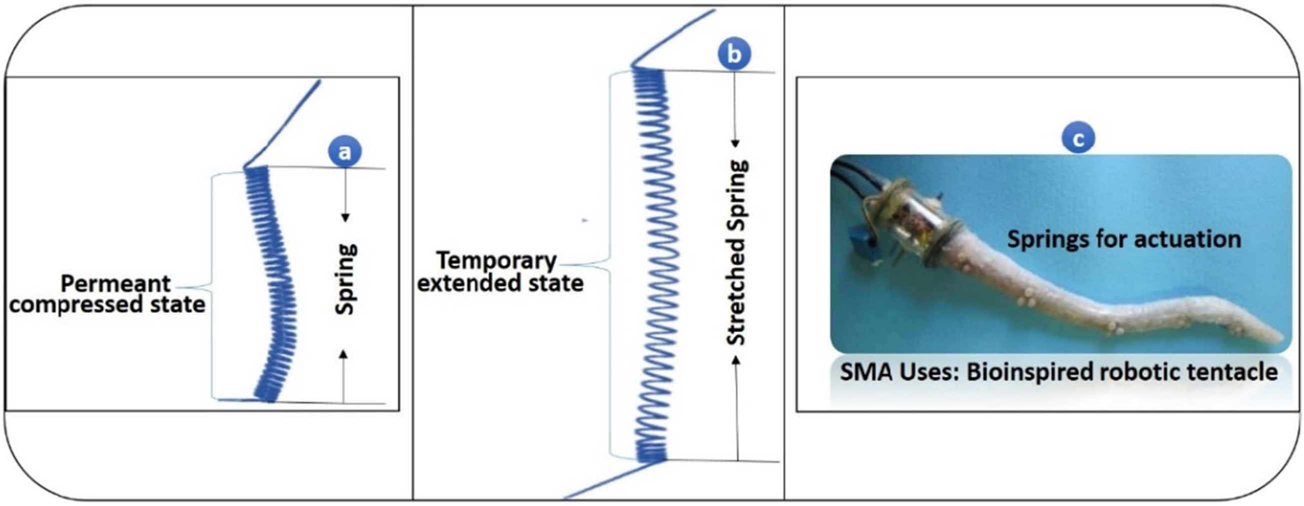

Fig. 7 An illustration of a spring made from a nitinol SMA wire that has been shaped into a coil

heat [122–124], pressure [125, 126], water, pH levels [127, 128], magnetism [129, 130], or light [131–133]. SCP may allow items to autonomously react to their environment without large, expensive, sophisticated electronic actuation systems [134]. By doing away with the requirement for onboard power supplies, sensors, computers, and motors, SCPs could simplify self-actuating structures. Shape memory polymers (SMPs) are materials enabling 4D printing that are gaining popularity. SMPs have lower processing temperatures and costs over SMAs and shape-changing functionality beyond composites. Smart memory polymers (SMPs) are a type of intelligent material that can restore their original shape in response to an external stimuli after having been bent and locked into a temporary shape. Changing the shape of a shape memory polymer (SMP) requires heating the polymer over its transition temperature (*Ttrans*), such as its glass transition temperature (*Tg*) or melting temperature (*Tm*). An external stimulation (such as heat [135–139]) remobilizes polymer chains and releases tension to restore SMP to its original structure. Fixing ratios measure how well a shape memory polymer (SMP) retains its temporary shape, while recovery ratios measure how well an SMP reverts to its original, unaltered shape. These measurements are absolutely necessary for gaining a knowledge of the functionality of SMP structures.

5.2.5 Self-healing materials (SHMs)

Self-healing materials, also known as SHMs, are a subcategory of smart materials that have the ability to respond to an external stimulus and then fix themselves. These materials have the potential to demonstrate their usefulness in the context of electronic devices that are subjected to harsh conditions such as high temperatures, low temperatures, pressure, and friction. There is also the possibility that these materials will demonstrate their usefulness in a different context [140, 141].

5.2.6 Smart polymers

In comparison to alloys, smart polymers are typically simpler to produce in large quantities. When compared to SMAs, smart polymers have a number of disadvantages, including low strength, low moduli, and low operating temperatures. On the other hand, smart polymers are more cost-effective and have high strain recovery, low density, biocompatibility, and biodegradability. Additionally, smart polymers are biocompatible and biodegradable [50]. This capability of SMPs to change shape is the one that has received the most attention in studies pertaining to 4D printing up to this point [25, 50, 142–144].

5.2.7 Azobenzene

The azobenzene family of smart materials stands apart from others in that it combines the properties of shape-changing and shape memory materials. Azobenzene is a photochromic molecule that can photoisomerize. Many photochromophores exist, including spiropyranes, stilbenes, and diarylethenes, but azobenzene is among the most explored attributed to certain reversible photoisomerization [145]. One wavelength of light can trigger and reverse material motion, providing different potential and uses for an azobenzene SCP [146–149]. The vast majority of azobenzene SMPs and SCPs are categorized as belonging to a class known as liquid crystal. In chemistry, materials comprising molecules in ordered arrangements are called liquid crystal polymers (LCPs) [150]. These molecules form nematic, smectic, chiral, and isotropic mesophases. The mesogens of nematic phases are aligned in the same direction along the long axis; however, these aspects do not often exhibit positional sequence.

In general, azobenzene is distinguished by a wide range of singular qualities that make it suitable for a variety of SMP and SCP applications. Respondents have used azobenzene and flexible films towards photoactivated actuators, artificial muscles, including surface relief gratings (SRG) [151], and sensors. Artificial photo-driven cilia has been developed by Van Oosten et al. for the purpose of micromixing [152]. In order to develop a light driven motor, the researchers utilized a similar process, which consisted of putting a photo responsive material on top of a PE film [153].

5.3 Programmable materials prospective to physique smart structures

5.3.1 Constitutive equation to predict SMP behavior

In order to construct intelligent buildings out of intelligent materials, a constitutive equation that can predict the behavior of these materials must be created firstly. SMPs are programmable materials that can change their shapes based on the temperature, magnetic fields, or electric fields that are applied to them. Both thermoviscoelastic modeling and phase transformation fall within this category, because of the speed with which SMPs have developed and the sophistication of their thermomechanical mechanism. There is no longer a requirement for additional electromechanical devices because smart materials are able to sense and act immediately. This results in a reduction in the total number of electronic and electromechanical components that are required for a construction.

5.3.2 Thermoviscoelastic approach with standard linear viscoelastic model (SLV)

Some researchers decided to use a standard linear viscoelastic model, which is more commonly referred to by its acronym, SLV, in order to simulate the SMP mechanism contained within the model [153]. A parallel arrangement of a Maxwell model and a spring element can be seen in this model. The behavior of SMP can be described and predicted with the help of thermoviscoelastic modeling, which is something that can be used. The constitutive equations, according to this point of view, are derived from rheological parameter temperature and time property dependent. Components that are seen frequently in thermoviscoelastic models include things like dashpots, springs, and frictional surfaces. In order to investigate the behavior of SMPs, one researcher came up with a straightforward viscoelastic model [154, 155]. The relationship between stress σ and strain ε is characterized in terms of the SLV model as follows:

$$\varepsilon^{\cdot} = \frac{\sigma^{\cdot}}{E} + \frac{\sigma^{\cdot}}{\mu} - \frac{\varepsilon}{\lambda}$$

This equation represents stress σ, strain ε, elastic module E, time retardation λ, and viscosity μ.

It is possible to express the relationship between stress and strain for the modified SLV model using the following equation:

$$\varepsilon^{\cdot} = \frac{\sigma^{\cdot}}{E} + \frac{\sigma}{\mu} - \frac{\varepsilon - \varepsilon_s}{\lambda}$$

The following is a form that can be used to describe the significant shift that occurs in the mechanical properties of SMPs when they pass through the glass transition region:

$$E = E_g exp(a_E(\frac{T_g}{T} - 1))\mu = \mu_g exp(a_\mu(\frac{T_g}{T} - 1))$$

where E_g and μ_g remain the philosophies of E and μ at T=T_g and a_E and a_μ demonstrate the gradient of straight line.

5.3.3 Phase transformation aspects

Researchers came up with the idea for a newfangled category of constitutive equalities through taking into account SMP's significance combinations involving two distinct stages [156]. Under thermal conditions, these phases are capable of transforming into one another, and while this transformation is taking place, the amount is continuously shifting. One of the techniques to modeling the phase transition of SMPs throughout the scalar variables can be used to describe the heating process called ξ_g and ξ_r, which can be defined as follows: where V_g signifies the glassy phase's volume and V_r indicates the volume of the rubbery phase. Subsequently, there are individual two phases in SMPs—rubbery and glass—the volume fractions of the two phases must add up to one ($\xi_g + \xi_r = 1$).

5.4 Magnetic dynamic polymer (MDP) composite

The MDP composite creates materials with complicated structure and magnetic properties variance for mechanisms that may assemble modules and change respective shapes. MDP concept diversity MSMs dynamic stimuli-responses and changeable magnetic materials mechanical, rheological, and magnetic properties. Envision the MDP and its derivative functions as promising shape-morphing approaches which represent an emerging multifunctional assemblies and gadgets. MDPs allow a novel manufacturing strategy for stress permitted 3D designs. As a result, a distinctive act can establish MDP's apart initiation other MSMs and current shape-morphing materials [51, 157–159].

6 Reimbursements of smart material in 4D printing

The development of 4D printing utilizing smart material structures is still trendy its infancy. There will be significant effects on the design and production of conventional mechanical structures as a result of its use in research and development [160]. The following aspects are examples of how this tendency might be seen:

1. The degree of freedom for mechanical structure will no longer be a constraint for 4D-printed materials, which will result in a significant reduction in weight.
2. Stimuli-responsive materials improve environmental monitoring. Changes in environmental circumstances can cause deformation.
3. Using the technology of 4D printing, smart materials integrate actuators and sensors [160].
4. Shape-shifting 4D-printed materials could streamline intricate designs by responding to external stimuli.
5. The correct application of smart material in 3D printing makes it feasible to create objects that can self-assemble.

7 Futuristic materials towards novel 4D printing

Future-forward materials include self-repairing concrete and bone-like glass. One of the "smart" materials in this set is self-healing concrete. Several aspects of the diagrammatic presentation are shown in Fig. 8.

7.1 Aerogel: a cosmic sponge

The consistency of aerogel is similar to that of smoke as shown in Fig. 8a. The way it refracts light makes its edges fuzzy and indistinct. It has the same texture as polystyrene when held in the hand; however, it is very friable, meaning it crumbles or shatter easily. In the 1990s, a sample of aerogel was generated that was 99.8% air, making it the lightest material in the world [161, 162]. As fantastical wherever it looks, a certain item has magical properties among others.

7.2 Bioglass: healing the human body

The animate and the inanimate coexist in bioglass, which straddles the boundary between the two themes. It was the first material invented by humans as shown in Fig. 8b that was able to form an interaction with living tissue, and the majority of its applications today involve the regeneration of bone. A patient's stem cells are "seeded" into bioglass before it is implanted into the area of the body that requires new bone [163]. As bone cells proliferate, they eat bioglass, leaving only genuine bone. This large white tablet was developed in the labs under Hench's leadership at Imperial College.

7.3 Self-healing concrete: a life-saver

Smart materials can respond to environmental changes, heal, and grow as depicted in Fig. 8d. This category of materials is in its infant stages right now. Self-healing concrete repairs itself when pressured. Since half of the world's structures are

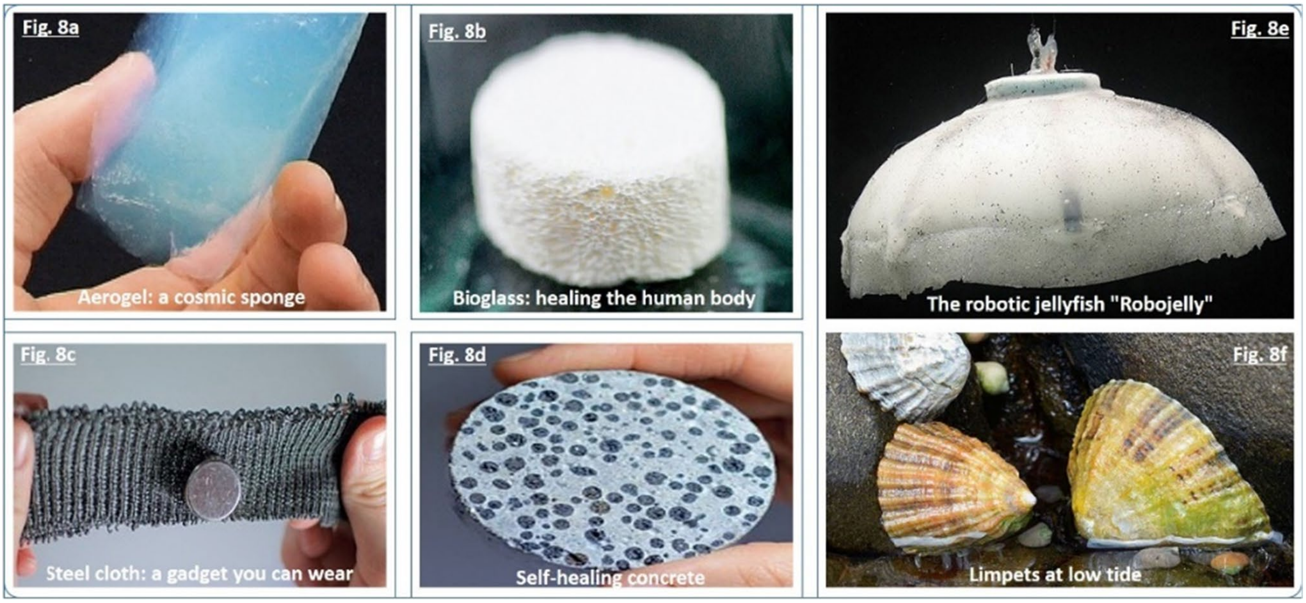

Fig. 8 Futuristic materials towards novel 4D printing (**a**, **b**, **c**, **d**, **e**, and **f**)

constructed of concrete, maintaining it is significant. In Haiti (2010) and Japan (2011), severe earthquakes destroyed concrete buildings [164, 165]. In the future, unloved concrete buildings will be able to take care of themselves because of this development.

7.4 Steel cloth

Wearable tech: while this conducts electricity, it may have a future in wearable electronics. This steel fabric resembles and feels like an elastic cuff. However, due to the fact that it is made entirely of steel, it possesses magnetic properties, as can be seen in the accompanying Fig. 8c. The company makes car tires came up with the steel thread; they embed it in the rubber to make the tires stronger. Textile designers became interested in weaving and knitting the material after it was widely distributed. Despite its impressive properties, this fabric has certain utilization [166, 167].

7.5 A limpet's tooth

Researchers say limpet teeth are the strongest man-made material, which could impact engineering and design [168, 169]. Researchers believe limpet teeth could be used to make the cars, boats, and planes of the future. For constructions with outstanding mechanical qualities, nature is an excellent source of inspiration as shown in Fig. 8f. Engineers are continually looking to make structures stronger or lighter preserve material.

7.6 Robojelly

The artificial jellyfish propels itself through the water by harnessing the boundless potential energy of the ocean. "Robojelly" mimics a jellyfish's movement of opening and closing a bell-like body to empty water and move forward. They have a platinum black powder coating that generates heat when in contact with the oxygen and hydrogen in seawater. First underwater robot powered by external hydrogen, Robojelly only moves in one direction because all eight segments are engaged at once. As shown in Fig. 8e, the research was published in the journal smart materials and structures, which is put out by the Institute of Physics in the UK [170].

8 Potential applications

Future smart device and structure development will place a significant emphasis on smart materials as depicted in Fig. 9, particularly in the biomedical sector. Smart materials and structures are transitioning from high-end, one-of-a-kind medical, military, and aerospace [171–174] items to mainstream, high volume/low cost automobile solutions [175–178]. High energy/power density, reduced vehicle mass, functionality and design flexibility, and smaller/cheaper components are all benefits. The majority of the novel uses, such microfluidic medication delivery, are being used on a slightly smaller scale. Particularly, the vehicle industry uses smart materials to produce safety, comfort, and fuel-efficiency gadgets and parts. Recently, shape memory alloys have been proposed for passive and/or active vibration and earthquake control in civil engineering.

Real-world implementation is crucial for the success of smart structures. After conceptualization, significantly improve the smart structure's driving force, displacement capacity, and response time. Secondly, additional research is needed into the long-term reliability of smart structures.

8.1 Smart burs

Those certain polymer burs exclusively remove diseased dentin. The remineralization-capable damaged dentin is left unharmed. Smart preparation burs avoid overcutting tooth structure caused by conventional burs. These intelligent preparation burs help dentists minimize the overcutting of tooth structure that often occurs when using standard burs [179].

8.1.1 Smart glass ionomer cement (RMGIC)

Davidson was the one who initially proposed the intelligent behavior of GIC. Gels absorb or release solvents quickly in response to stimuli like temperature, pH, etc. Mixing

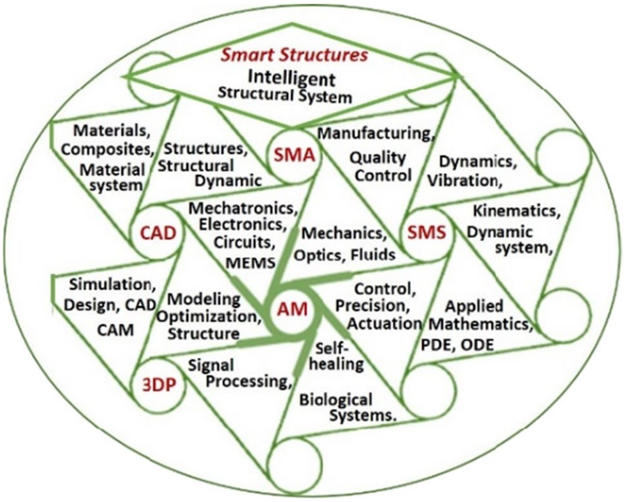

Fig. 9 Significant emphasis on smart structures, intelligent structural system

conveniently utilizing micro CT scanning can regulate cement porosity. These smart ionomers behave in a manner analogous to that of human dentin. Resin-modified adhesive resin cement, compomer, or giomer can however manifest smart capabilities [180].

8.1.2 Smart impression material

These materials are hydrophilic for void-free impressions, have shape memory for accurate impressions, and resist ripping. Snap set reduces working and setting times by 33% and produces distortion-free restorations that fit perfectly. These materials, such as Imprint™ 3 VPS, Impregum™, and Aquasil Ultra, have a low viscosity while yet maintaining a high flow [181, 182].

8.1.3 Miniature functional trocar for eye surgery

The use of additive manufacturing allows for a significant deal of creative leeway in the design and production of intricate components and mechanisms. AM is recognized in the medical field for its customization, additional functions, and complicated structure production [180]. AM is used to make eyeglasses, ocular prosthesis, implants, and ophthalmic devices in ophthalmology. Ophthalmic surgery uses trocar cannulas to access the eye's interior. Using an inserter knife, a tiny incision is made in the sclera (eye's outer layer) to allow the trocar to be inserted. The trocar is a cannula with a moveable valve. After the trocar has been positioned, the flexible closure valve will ensure that the channel remains closed.

8.2 Prosthetic arms

The initial stage of the design is a high-resolution scan of both patient arms. The artificial hand or arm will be 3D manufactured backwards. The external shell, socket, fingers, and joints are made of lightweight, adaptable PA12 Nylon using 3D printing. The control and oversight of it while given the appropriate case, a TrueLimb hand can be initiated to acknowledge one of six major grips: resting, hooked, prepaid card, closed hand (fist), pincer, or closed tripod. The adaptability of the grips is illustrated in Fig. 10, and it enables them to assume a number of configurations. When grabbing an object, each finger closes until it hits a particular resistance. In order to grasp a ball, for instance, the thumb, forefinger, and middle finger must first experience resistance from the ball's upper section before they can continue to close. Contrarily, the ring finger which is underneath the ball continues closing until it is continuing to support the ball.

8.3 Smart product design with a 4D structure

4D printing increases 3D printing's reliability and performance. Flexible 4D structures can be modified either water, heat, gravitational forces, or light. It is being investigated whether 4D printing can be used in manufacturing to create smart products with a 4D structure.

8.3.1 Smart product manufacturing

Manufacturing smart objects can be aided by 4D printing. Intelligent materials that react to environmental stimuli can be produced by aerospace manufacturers. Automating operations with 4D printing includes cooling engines and air conditioning. The benefits of 3D printing for the defense sector are numerous. There seem to be novel uses for 4D printing. Military uniforms that are camouflaged or gas-proof could be produced via 4D printing [183, 184].

8.3.2 Airbag and comfortable seat

Adaptable car safety seats and airbags are possible with 4D constructions. Four-dimensional printing has the potential to revolutionize the manufacturing of common household items. Flat-pack furniture like chairs and tables could be assembled by this technology on their own. Less stuff would need to be stored, and moving about would be simpler [185, 186].

8.3.3 4D-printed smart plumbing appliances

One potential application for 4D printing in plumbing is to create pipes with variable diameters that adapt to changing water flows and demands. If pipes are adaptive enough, they may be able to fix themselves when the environment changes. Only by adding water or light to a flat board within the printer's height can 3D-printed furniture be manufactured in a 4th dimension.

8.3.4 Nature transformation

In the long run, massive-scale projects will benefit greatly from the usage of 4D printing. Potential future uses include use in vacuum environments like outer space. There are currently problems with the building's 3D printing in space operation's energy consumption, performance, and cost. Consequently, 4D-printed materials should be used to make the most of their malleable nature, rather than 3D printed ones. Because it can grow and repair itself, it could be the answer to the problem of building bridges, shelters, and installations that do not get damaged when there is a weather disruption [78, 187].

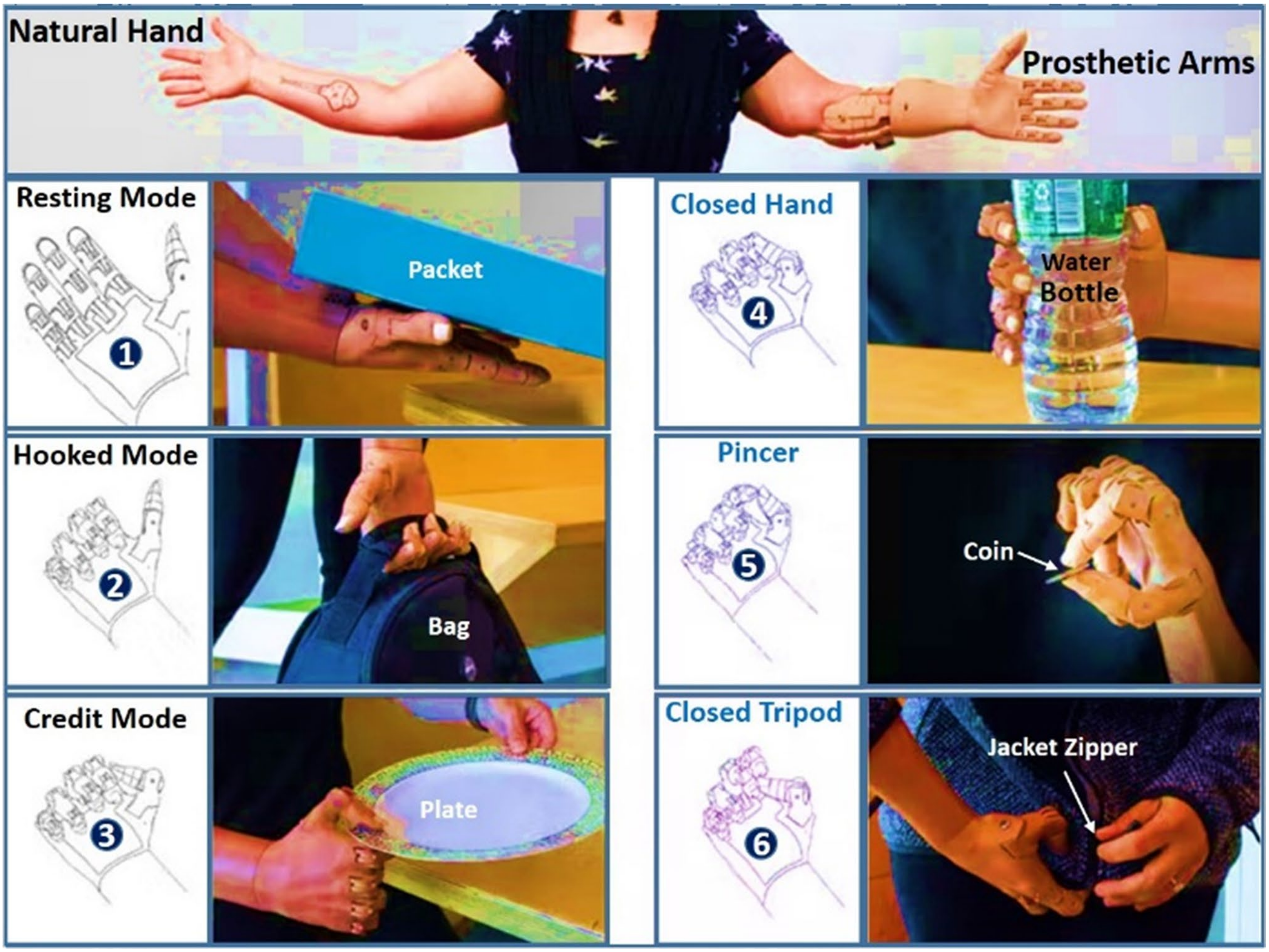

Fig. 10 Grips and control of prosthetic arms with six different grips

8.3.5 Smart water valve

The smart water valves that can be made using 4D printing are impressive. Hydrogel ink has a fast reaction to heat and closes a valve when it comes into contact with hot water, then opens again when the temperature drops. The aerospace industry is making use of 4D printing technology to create self-deploying devices, air conditioning, engine cooling, and other similar products. Similarly hoped-for are biocompatible, 4D-imprinted devices capable of enlarging or shrinking a living organism. These items might be used in place of a traditional stent to reduce the likelihood of complications in coronary artery procedures [188–191].

8.3.6 Combinatorial structures

The current technology makes the creation of complex assemblies far too labor-intensive and expensive to be practical. Consumers are exposed to game-changing capabilities such as 4D printing and are able to develop incredible applications by utilizing additive manufacturing. Both 3D and 4D offer a substantial improvement over the norms that are now in place, but only one of them is more forward-looking than the other, with a primary focus on the former [192–194].

In the future, it will not be difficult to face these obstacles. The high cost of technology and materials, as well as limitations in mechanical properties of materials and regulating of deformation, remains obstacles and problems for 4D printing.

9 Conclusion

The domain of AM remains in its infancy. Future manufacture of composite structures has much to gain from AM-ACM. Smart materials of 4D printing potential to construct smart structures (4DP: SMs-SSs) show that these materials have a bright future. Since there is a wealth of information to be gleaned from studying smart materials, it is necessary to derive the behaviors that will be most useful to those working in product or industrial design. The emergence of novel materials and the improvement of existing ones provide fresh inspiration for designers. Time-dependent materials include shape-shifting and self-repair and form memory materials. 4D printing has gained popularity because printed structures are capable of developing and altering throughout time in response various stimulations. New and better machinery, printing techniques, software, and materials are always being invented. The application of 4D printing technology ranges from basic shape modifications to bio printing of living organisms, using smart materials, designs that anticipate change processes, and smart printing.

The technology of smart materials by its nature, is a highly interdisciplinary field, as are the many research areas of smart material facts bases and design approaches that educate the future. This new feature makes tiny deployable structures, and the entire structure must be split and treated independently.

1. The initiative's intention was to assess the technology's potential.
2. The forecasting of stimulus-sensitive compounds' behavior and its emphasis on material characteristics.
3. 4D printing will enable new applications, act in extreme environments, and build transformable structures.
4. The investigation of multifunctional structures is anticipated to be an unstoppable trend in perspective of the functionality of the smart structure.
5. Smart structures that shrink should receive a lot of attention, and more large-scale structural research is required.
6. The final factor is future impact. It will benefit not only the scientific community, but all of humanity.

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Declarations

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Consent for publication N/A.

Conflict of interest The authors declared that there are no conflicts of interest.

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