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Challenges and Status on Design and Computation for Emerging Additive Manufacturing Technologies

The revolution of additive manufacturing (AM) has led to many opportunities in fabricating complex and novel products. The increase of printable materials and the emergence of novel fabrication processes continuously expand the possibility of engineering systems in which product components are no longer limited to be single material, single scale, or single function. In fact, a paradigm shift is taking place in industry from geometry-centered usage to supporting functional demands. Consequently, engineers are expected to resolve a wide range of complex and difficult problems related to functional design. Although a higher degree of design freedom beyond geometry has been enabled by AM, there are only very few computational design approaches in this new AM-enabled domain to design objects with tailored properties and functions. The objectives of this review paper are to provide an overview of recent additive manufacturing developments and current computer-aided design methodologies that can be applied to multimaterial, multiscale, multiform, and multifunctional AM technologies. The difficulties encountered in the computational design approaches are summarized and the future development needs are emphasized. In the paper, some present applications and future trends related to additive manufacturing technologies are also discussed. [DOI: 10.1115/1.4041913]

1 Introduction

Additive manufacturing (AM), also known as three-dimensional (3D) printing, has been around for decades. The technology has come on leaps and bounds in the past 10 years, provided an alternative approach to traditional manufacturing processes to producing parts. The capabilities of creating complex internal geometries give engineers more options to innovate without being limited by fabrication approaches. Recently, the technology has evolved from geometry-focused fabrication into producing functional components with varying material compositions and geometric scales. Nowadays, fabrication of a multifunctional structure is made practical by the next generation of AM technologies, enabling advances in products across a wide range of applications. However, the increased interdisciplinary interactions and the urgent need for practical applications have put forward new demands on the design and fabrication of such multifunctional structures.

Developing appropriate tools to design a part with functional consequences is urgently needed. The existing computer-aided design (CAD) software is mainly developed for traditional manufacturing processes, where geometric shapes are the major concern. Although some of the CAD systems allow users to assign material properties on models, the operations cannot guarantee the functional capability, especially when the functions can hardly be realized or optimized by manual design activities. Therefore, most current research still uses CAD software coupled with finite element analysis (FEA) and trial-and-error approach to design functional properties. Meanwhile, a growing number of researchers began developing dedicated computational methods to automate the design for functionality enabled by AM.

Researchers have extensively studied the topics of changing geometric shapes to alter an object's mechanical property. Commercial software systems such as OPTISTRUCT [1] have been developed to help designers to create conceptual designs with target structural properties. In addition to geometric shapes, researchers have tried to alter material compositions to create even more complicated properties. Varying material compositions within layers of 3D printing can now be achieved through controlling process parameters. This additional design freedom offers new and significant solutions to many industry sectors, such as aerospace [2,3], defense [4], biomedical [5,6], wearable devices [7], and tissue engineering [8].

In additive manufacturing, the internal structure can be optimized in multiple scales to satisfy functional requirements. Through optimizing structural parameters, the multiscale structures can offer multifunctional properties. For example, the wettability of an object is changed from hydrophilic to superhydrophobic when the surfaces are embedded with micropillars [9]. In addition, a new type of material with microstructures based on varying unit cells has emerged as an alternative to fulfill complex functional demand by using properties that can be dynamically programed. Coupling with recent multiscale additive manufacturing techniques, designing engineering materials upon requirements is becoming possible.

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Structural property has been the focus of AM since beginning. As the multimaterial and multiscale AM capabilities continue to grow, people began to consider other material properties such as thermal, optical, acoustic, and electrical, as well as how to combine them with structural property to create multifunctional objects. The additional functionalities add even more challenges to the system designers who are now facing not only interdisciplinary problems, but also the unique criteria and characteristics of different multimaterial and multiscale AM processes. At this moment, systematic design methodology is required with a better integration of design for additive manufacturing methods and tools.

This paper reviews recent research of AM technologies on the fabrication of functional objects and the related design methodologies for AM processes. According to the main design requirements and constraints, we classify the new capability of AM technologies into four categories including

(1) *Multimaterial*: Design for enhancing mechanical properties or material properties (e.g., color) by depositing multiple dissimilar materials within one single object (Secs. 2.1 and 3.1).
(2) *Multiscale*: Design for achieving functional requirements by printing geometric features in multiple geometric scales (Secs. 2.2. and 3.2).
(3) *Multiform*: Design for programed shape changing property after fabrication (Secs. 2.3 and 3.3).
(4) *Multifunctional*: Design for objects with non-structural requirements. The objects can still have structural properties; however, the main focuses of the studies are on the nonstructural properties (Secs. 2.4 and 3.4).

The purpose of this paper is to give an overview of the current status on functional design for additive manufacturing. We first summarize the opportunities enabled by recent AM technology developments in Sec. 2. We then highlight the existing challenges faced by designers and suggest the best practices and future directions for the research community in Sec. 3. Finally, conclusions and outlook are drawn in Sec. 4.

2 Recent Development on Additive Manufacturing Technologies

Additive manufacturing (AM) technologies have been extensively developed in the past few decades, with specific techniques invented in depositing materials layer upon layer [10]. Compared with traditional manufacturing processes, e.g., machining, casting, injection molding, and joining, additive manufacturing is more flexible in building complex 3D objects in a short period of time [11,12]. Due to its unique advantages, AM technology has been widely applied in the fields of aerospace, medical, dental, and sociocultural sectors [13]. This section provides an overview of recent developments and current status on AM technologies. We will discuss four promising directions for the future development of AM technologies, i.e., multimaterial printing, multiscale printing, four-dimensional (4D) printing (i.e., 3D printing with time-variant structures), and multifunctional printing. The discussions are mainly based on the process development, the fabrication requirements, and the promising applications of such additive manufacturing technologies.

2.1 Multimaterial Additive Manufacturing Processes. A vast variety of multimaterials structures and systems with innovative functions have been developed for applications in various fields. Some examples include multimaterial composite structures with shape-changing function, bioinspired multimaterial composites with promising mechanical performance, multimaterial scaffold for tissue regeneration, and multimaterial fiber with attractive optical applications [14]. Fabrication of novel multimaterials has become increasingly significant for functional integration of two or more biological materials. However, traditional manufacturing methods can only provide limited possibility on fabricating 3D structures with complex spatial distributions of multiple materials. In addition, the functional performance of the fabricated structures is limited by the fabrication resolution of the traditional manufacturing processes. Due to its fabrication capability, additive manufacturing provides a promising solution to fabricate multimaterial structures with high resolution and complex geometric shape. Meanwhile, the design of complex structures with multimaterial may also drive the demand for developing even more advanced multimaterial AM processes.

2.1.1 Jetting and Stereolithography Based Multimaterial Three-Dimensional Printing. In most of extrusion-based 3D printing processes, thermoplastic is utilized and the state of material alters from liquid to solid during the extrusion process as a result of changing thermal conditions [15–17]. Different from thermoplastic, photo-curable polymer can be solidified with sufficient light exposure. For instance, based on material jetting technologies, 3D multimaterial inkjet printing is developed to fabricate complicated structures using photopolymer and wax. Microscale droplets of photo curable ink are deposited layer by layer in the inkjet printing process, and droplets can be turned to solid after receiving enough energy from light exposure [4,18,19]. Due to the high resolution of mature jetting technology, the surface quality of objects printed by polyjet/inkjet printing is much better than the one built by the fused deposition modeling (FDM) process. In addition, high-resolution multimaterial 3D printing opens up a new future to the optical application. Bio-mimic imaging optical eye and display window, which is not easy to be fabricated using traditional methods, were fabricated by the inkjet-based 3D printing using transparent acrylic polymer [20]. The jetting-based multimaterial 3D printing can also achieve superior mechanical performance that cannot be provided by single material printing. Biological structures found in nature give one inspirations that soft and hard materials can be allocated in a distributed pattern to achieve certain mechanical performance. Multimaterial 3D printing processes enable the improvement of structural properties with special design of material distribution. Gu et al. [4] used an Objet 500 3D printer to replicate the innate toughness of the nacre and a conch shell. In the nacre-like designs, two base materials, which are vastly different in properties, were assembled in a ply with an architecture similar to nacre. These plies were then stacked with orientation angles of 0 and 90 deg to generate a laminate structure by multimaterial 3D printing (Fig. 1(*c*)). Similarly, prototypes of mixing stiff plate and soft matrix of bone-like plate, mollusk shells shaped structures, and ganoid fish scales were fabricated by the inkjet printing process, and the printed part demonstrates promising mechanical performance [19].

Stereolithography (SL) is another 3D printing process by using photo-curable polymer to build 3D objects. Instead of curing droplets, one layer of photo curable polymer can be solidified by the exposure of the two-dimensional (2D) patterned light beam in the mask-image-projection-based stereolithography (MIP-SL) [21]. Compared with other AM methods, the building speed of MIP-SL process is relatively fast by taking advantages of high-resolution 2D patterned light beam. Therefore, numerous studies are conducted to develop MIP-SL based multimaterial processes [22–25]. With the special design of the layouts of different materials, the structure can be controlled to bend or twist under different environmental situations. Using multimaterial 3D printing techniques, such as inkjet or SL processes, shape-changing anisotropy can be achieved by combining a responsive shape-changing material with a passive matrix material [23]. Similarly, the thermal performance of 3D printed parts can be manipulated by material allocation. As shown in Fig. 1(*d*), negative thermal explosion micro lightweight multimaterial lattice structures were printed by mask-image projection-based SL printing process, with different mixture ratios of photo-curable polymer and copper nanoparticles solutions [22]. According to the fabrication requirements, new

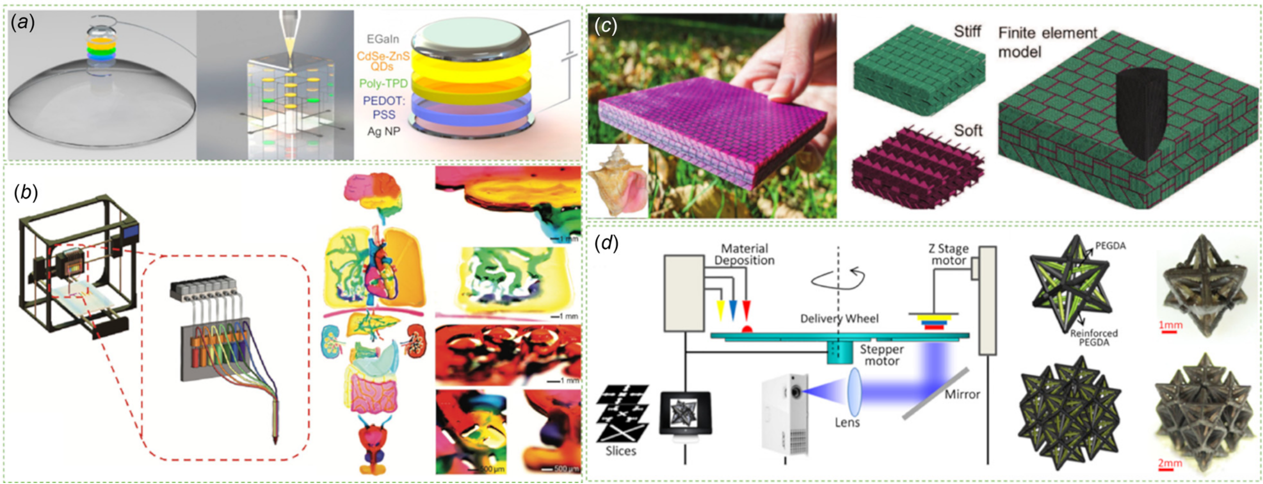

Fig. 1 (*a*) Direct 3D printing of QD-LEDs on a substrate [15] (Reprinted with permission from American Chemical Society © 2014). (*b*) Design of a digitally tunable continuous multimaterial extrusion bio-printer and the side view of selected organ-like constructs [21] (Reprinted with permission of John Wiley and Sons © 2016). (*c*) 3D-printed nacre-inspired sample and quarter geometry of the Nacre-like design in simulation [4] (Reprinted with permission of John Wiley and Sons © 2017). (*d*) Three-dimensional fabricated negative thermal expansion lattice structures using multimaterial projection microstereolithography system [22] (Reprinted with permission from American Physical Society © 2018).

material is easy to be added in the SL-based system by increasing the number of material reservoirs. Current multimaterial MIP-SL process is rather slow, since the residual material removal is mandatory prior to the placement of new material. Due to insufficient removal force as well as adhesive forces between resin molecules and a cured part, incoming new material tends to mix with the residual and generate blur mixtures attached to the cured part. Such blur mixtures existing in the interface area of different materials usually affect the performance of fabricated objects and is still a challenge for researchers to overcome in the future.

2.1.2 Extrusion Based and Other Multimaterial Three-Dimensional Printing Methods. Unlike subtractive manufacturing processes, raw material is gradually deposited in AM processes to build an object from scratch. Based on the deposition principle, multimaterial 3D objects can be constructed by using multiple material supplies. For example, multimaterial FDM process has been developed in which different materials are extruded from different extruders [16]. Based on the material extrusion method, a broad variety of material such as thermoplastics, ceramic slurries, and metal pastes can be printed using the FDM process. Moreover, structures with a lot of overhangs can be easily printed using a multimaterial FDM machine with dissolvable supporting material. However, this inexpensive multimaterial AM solution is limited by poor fabrication resolution due to the dimension of extruders [26–28]. To get better fabrication resolution, another kind of 3D printing method using specially designed printheads has been developed to fabricate multimaterial structures [15,17,29]. One kind of such printheads that consist of a bundle of capillaries in connection with multiple printing-ink reservoirs was designed to continuously actuate digital material under controllable pneumatic pressure, as shown in Fig. 1(*b*). Cells, culture matrix, and growth factor were continuously extruded together into specially designed organ structures, and the biomaterials kept bioactivities during the extrusion process. Multimaterial 3D structures show multiple functional performances because each type of material can have unique physical properties. Multimaterial 3D printing process enables the fabrication of active functional structures with multiple materials to achieve interesting applications. Traditionally, single material, such as plastic polymer, conductors, and biological material, can be easily printed using the extrusion-based process. Five different types of materials, including semiconducting nanoparticles, elastomer, organic polymer, solid and liquid metal, and ultraviolet curable polymer, are integrated together by the extrusion-based process to build a functional quantum dot light-emitting diode (Fig. 1(*a*)) [15]. The extrusion-based multimaterials 3D printing process offers the capability of highly flexible fabrication, and the capability of directly depositing multiple functional materials enables one to build a semiconducting electronic device with complex geometric shapes. In addition to the aforementioned processes, which are mainly developed to fabricate liquid-based materials, researchers have developed various powder-based multimaterial printing processes. For example, the binder jetting 3D printing method was developed to fabricate multi-material structures using various powders including polymer powders, ceramic powders, and metal powders [30].

2.2 Multiscale Additive Manufacturing Processes. With increasing biomimetic research on the design of multiscale structures for different functions, the fabrication of novel multiscale structures has become increasingly important. The development of multiscale additive manufacturing processes is desired and critical to achieve such biomimetic designs for certain functionality. However, most of the existing AM technologies can only fabricate 3D structures with a uniform resolution throughout the entire fabrication process. However, a large amount of functional structures contains both micro- and/or nanoscale features on macroscale subtract, such as shark skin, peristome surface of Nepenthes alata, gecko feet, fly eyes, and butterfly wing [31]. It is difficult for the existing manufacturing processes to fabricate such complex geometric shape, and the functional performance of the built artificial biomimetic objects cannot be comparable with respect to their genuine counterparts in nature. Therefore, the development of multiscale AM processes attracts much attention in recent years. There are two main representative ideas that have been investigated. One solution is to fabricate multi-scale structures by the integration of multiple AM processes, each of which best suits a certain scale. This method can make multiple sections of a structure by applying optimized processes [32–34], and a designed hybrid process can provide capability and flexibility superior than operating each of the individual printing processes separately. However, the integrated hybrid solution can only adapt to building multiscale objects with a special design; how to integrate different 3D printing processes to fabricate 3D objects with any universal design still remains a significant challenge. Another solution that has been investigated is the development of standalone 3D printing process that is capable to achieve multiscale fabrication on its own.

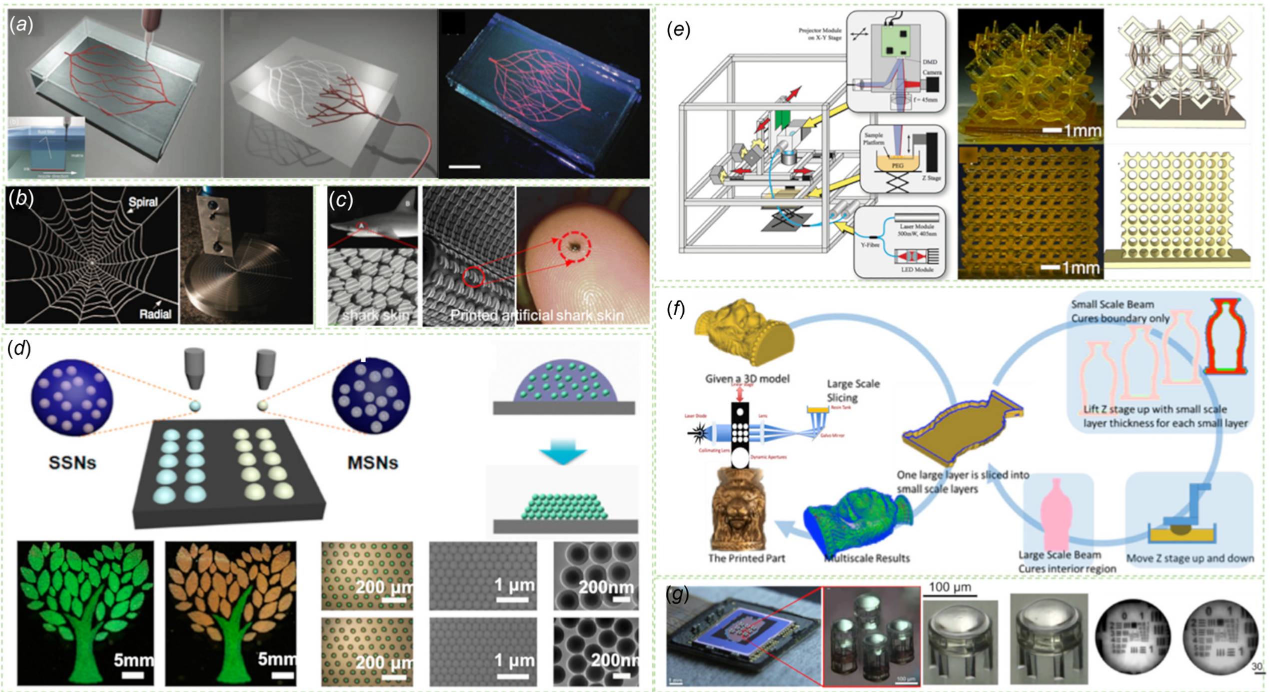

Fig. 2 (*a*) Omnidirectional printing of 3D microvascular networks within a hydrogel reservoir [43] (Reprinted with permission of John Wiley and Sons © 2011). (*b*) 3D-printed multiscale spider web displaying interacting radial and spiral elastomeric filaments [44] (Attribution 4.0 International CC BY 4.0). (*c*) 3D-printed multiscale biomimetic artificial skin [45] (Reprinted with permission of Company of Biologists Ltd., © 2014). (*d*) Bio-inspired vapor-responsive colloidal photonic crystal patterns by multiscale inkjet printing [46] (Reprinted with permission from American Chemical Society © 2014). (*e*) The multiscale printing based on scanning projection stereolithography and the 3D-printed lattice structures [39]. (*f*) A schematic diagram of multiscale fabrication process. The multiscales in the *XY*-plane are achieved by using laser beams in different sizes, and the multiscales along the *Z*-axis are realized by using different layer thicknesses [42]. (*g*) 3D-printed eagle eye: compound micro-lens system for foveated imaging [47].

2.2.1 Stereolithography-Based Multiscale Three-Dimensional Printing. To generate smooth and uniform microscale structures, liquid-based material deposition needs to be highly accurate thus requires high-precision motion control of printing nozzles with extremely small openings. In contrast, SL process can fabricate high-resolution microfeatures using controlled light exposure [35,36]. However, the size of macroscale focus image, which in turn determines the fabrication range, is restricted to the physical dimension of the digital micromirror device (DMD) chip, and such an issue is open to be resolved for the purpose of multiscale fabrication using the SL process [33]. One straightforward solution is to jointly use multiple DMD chips to shape a larger array; however, the uniformity of projection light with multiple DMD chips working at the same time becomes difficult to control. Other than the simple combining approach, a hybrid process could also be a potential solution to address the multiscale fabrication problem. For example, a swirling flow coaxial phacoemulsifier sleeve with internal microvanes were fabricated by combining multijet modeling (3DP) and mask image projection based microstereolithography (PμSL) [32]. Besides, some multi-scale structures, whose dimension ranges from macro-scale to nano-scale, were fabricated by the integration of SL process and the two photo polymerization process [33]. Alternatively, for the mask image projection based SL process, researchers also achieved multiscale fabrication by adding movement of the projection light beam. For example, Emami et al. [37] extended the fabrication area of the MIP-based SL process by moving the optical system only one-pixel length each step, illuminating one portion with several time exposure. The known issue for this method is that overlaps exist between two adjoining printed sections [37,38]. To eliminate the overlap, Lee et al. [39] developed a low-cost scanning projection printing system, which can project microscale features at 10 μm onto a 50 mm large area by precisely controlling the exposure time.

Meanwhile, laser spot with dynamic changing focus can also be used to print multiscale structures [40]. For a given multiscale structures, the appropriate laser spot can be selected to cure corresponding sizes of features, respectively. Similarly, the laser can be adjusted by an optical filter with high-contrast gratings to accommodate features at different scales, similar to the principle of nanolithography technology [41]. However, it is time-consuming to fabricate objects with large area using the nano-scale laser beam. To solve the fabrication efficiency problem, Mao et al. [42] developed an optimized multiscale fabrication process with shaped beams, and the 3D printing speed and resolution were significantly improved. The developed process planning associated with the shaped beam method is shown in Fig. 2(*f*). The SL-based multiscale process is also applied to fabricate cases that are either hard to be implemented or even impossible before. For example, multicomponent objective lenses mimicking the eagle eye were designed and printed onto a *complementary metal-oxide semiconductor* image sensor using a revised SL process [45]. This artificial optical system shown in Fig. 2(*g*) can achieve a full field of view of 70 deg, with the angular resolution up to 2 cycles/deg in the center of the image [45,46]. Besides, micro- and nano-optics with complex artificial eye lens was fabricated by a novel microscale 3D print method called femtosecond two-photon direct laser writing. The printed microlens at 100 μm forms a high-performance multilens with the field of view at 80 deg.

2.2.2 Other Multi-Scale Three-Dimensional Printing Methods. Multi-scale fabrication can be implemented by using 3D printing with nozzles in different sizes. As shown in Figs. 1(*a*) and 1(*b*) and Figs. 2(*a*) and 2(*b*), large scale structures with micro-scale features were successfully fabricated by the method of direct ink writing, where the fabrication resolution can be controlled by multiple process parameters, such as the moving speed of the

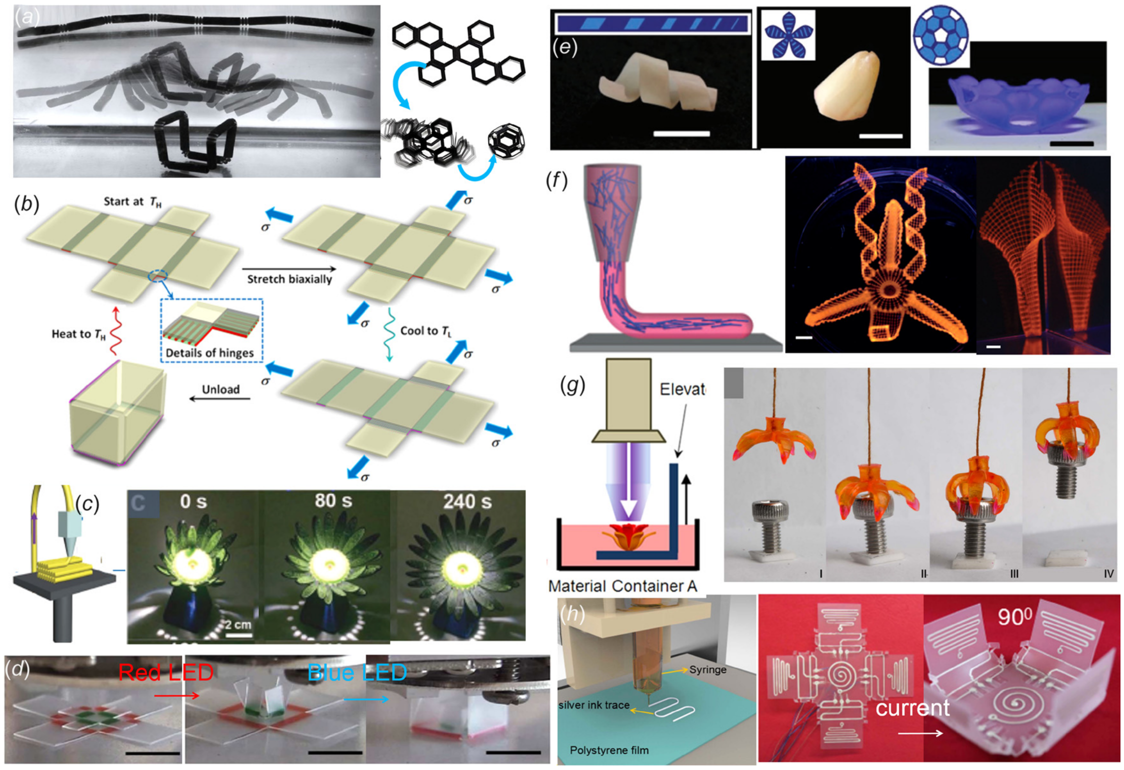

Fig. 3 **(*a*) Photographs show the transformation from a flat 3D-printed structure to a precisely folded structure [56,57] (Reprinted with permission from John Wiley and Sons © 2014). (*b*) A self-folding and opening box fabricated by 4D printing [58] (Reprinted with permission of AIP Publishing © 2013). (*c*) A 4D-printed photoresponsive flower [69] (Reprinted with permission from John Wiley and Sons © 2017). (*d*) Sequential self-folding nested boxes—a small box with green hinges on top of a large one with orange hinges [70]. (*e*) Self-folding structures with cross-link density gradient achieved by controlling light exposure [76] (Reprinted with permission from John Wiley and Sons © 2016). (*f*) Biomimetic 4D printing structures fabricated by the direct ink writing with shear-induced fiber alignment [77] (Reprinted with permission of Springer Nature © 2016). (*g*) The snapshots of the process of grabbing an object by multi-material 4D printing [24]. (*h*) A self-sequential folding antenna structure utilizes 4D printing [68] (Reprinted with permission from IOP Publishing, Ltd. © 2017).**

nozzle, the material feeding speed, and the dimension of nozzle [43,47–52]. Similarly, a new direct ink writing method was developed to fabricate multiscale biologic structures, e.g., microvascular network. In the process shown in Fig. 2(*a*), hydrogel was injected into the gel tank according to the 3D geometry of vascular structures, followed by the forming of vessel cavity as injected hydrogel turned to be liquid when temperature changes [43]. In addition, multi-scale complex fluidic networks were printed in granular gel slurry using the nozzle-based 3D printing [48]. After removing granular gel from the printed structures, multiscale hierarchical branching networks were easily generated with the dimension range from 100 μm to 10 mm. Recently, a nozzle-based 3D printing process was applied to fabricate a multiscale biomimetic, spiders spin that possesses high strength, elasticity, and tensile failure stress at the same time. As shown in Fig. 2(*b*), the mechanical response of elastomeric webs was investigated under multiple loading conditions, and the study results show promising characteristics of the webs' performance [44].

Recent progresses on multiscale AM technologies have facilitated the performance study of multi-scale structures such as superhydrophobicity, self-cleaning, drag reduction, energy conversion, biological self-assembly, and focusing imaging [53]. As an example, special placoid scales associated with the surface of shark skin have intriguing properties to dramatically reduce frictional fluid drag. While it is difficult to use traditional manufacturing processes to fabricate such placoid scales, they have been successfully built onto the artificial shark skin by the nozzle-based 3D printing methods (refer to Fig. 2(*c*)), and such multiscale shark skin presented excellent flow ability compared with the surface without any microfeatures [54]. Also, the multiscale nozzle-based 3D printing process provides a great promise to developing advanced optical elements, such as dynamic display or multifunctional sensor array. For example, the multicolor shifting van was printed with multiscale colloidal photonic crystals patterns using mesoporous colloidal nanoparticle ink, as shown in Fig. 2(*d*). Through adjustment on the size and mesoporous proportion of nanoparticles, original color and vapor-responsive color shift were precisely and easily controlled [55]. While 3D printing is being introduced to more applications of biology, tissue engineering, autonomous vision, and optical systems, the development of multiscale 3D printing continues to attract increasing interest from researchers and industry professionals.

2.3 Shape Changing Additive Manufacturing Processes. Tibbits [56,57] used a term *four-dimensional* (4D) printing to describe a class of 3D printing technologies applied to building shape-changing structures (see Fig. 3(*a*)). 4D printing overcomes the traditional fabrication limitations by designing heterogeneous materials to enable the 3D-printed structures evolving over time (the fourth dimension) [58–63]. There are many different ways to generate the time-variant structural change using 3D printing processes. Some common 4D printing approaches are listed in the section.

2.3.1 Thermal Stimuli. One way to build shape changing structures is to use multimaterial 3D printing processes with the integration of additional thermal stimuli [24,64,65]. Basic shape-changing materials available for these multimaterial 3D printing techniques include *shape-memory polymer* (SMP) [66] and hydrogel [67]. Additionally, elastomers are typically used as the passive matrix in these structures. Ge et al. [58] printed active composite materials that were realized by directly printing glassy SMP fibers in an elastomeric matrix (see Fig. 3(*b*)). The initial configuration is created by 3D printing, and then the programmed action of these shape memory fibers creates the time dependence of shape changing configurations (i.e., the 4D aspect). The 3D-printed structure can be thermomechanically programmed to assume complex four-dimensional configurations, including bent, coiled, and twisted strips, folded shapes, and complex contoured shapes with nonuniform, spatially varying curvature. More interestingly, incorporating more than one shape-changing material with different responsive properties enables sequential shape changes via the same multimaterial 3D printing techniques. For example, when multiple SMPs with different thermomechanical properties were incorporated, sequential shape changes that are time-dependent can be accomplished by changing the triggering temperatures, as shown in Fig. 3(*g*) [24]. A 3D-printed gripper was opened (or closed) after applying appropriate thermal stimuli and the functionality of grabbing (or releasing) objects was triggered. Deng et al. [68] further present the 4D printing of self-folding structures that can be sequentially and accurately folded using heating provided by electric circuit (Fig. 3(*h*)). When being heated above their glass transition temperature, prestrained polystyrene films shrink along the *XY* plane. Accordingly, silver ink traces printed on the film were used to provide heat stimuli by conducting current to trigger the sequential self-folding behaviors. Some programmable structures such as a lock and a three-dimensional antenna were demonstrated to illustrate the feasibility and potential applications of this method.

2.3.2 Light Stimuli. Light stimuli have also been used to build shape changing structures. Yang et al. [69] demonstrated the 3D printing of photoresponsive shape memory devices through combining the FDM process and photoresponsive shape memory polymers/carbon black composites (see Fig. 3(*c*)). A biomimetic sunflower is built to demonstrate its shape changing function under sunlight. Furthermore, Liu et al. [70] created a sequential folding structure by different colors of light sources (see Fig. 3(*d*)). Controlled ink printed on the surface of polymer sheets can discriminately absorb light on the basis of the wavelength and the color of the ink defines the hinge about which the sheet would fold. The absorbed light gradually heats the underlying polymer across the thickness of the sheet, which causes relief of strain to induce folding. These color patterns can be designed to absorb only specific wavelengths of light, thereby providing control of sheet folding with respect to time and space. This type of programed shape variation can have numerous applications, including reconfigurable electronics, actuators, sensors, implantable devices, smart packaging, and deployable structures.

2.3.3 Moisture Stimuli. The anisotropy in a 3D-printed structure is the key that is used to trigger shape changing. Another popular stimulus for 4D printing is provided by moisture. The mechanical anisotropy that comes from bio-inspiration can be realized by various methods including magnetic alignment and shear force alignment of fillers [71–75]. The cross-linking density gradient in polymers can be achieved by tuning the process parameters during the selected fabrication process, such as the light dose exposure in stereolithography, or the heating temperature and the moving speed of the nozzle used in FDM [76]. The shrinkage is constrained by the building platform during the fabrication process, yielding a strain gradient within the 3D-printed structures (as shown in Fig. 3(*e*)). Heating the final structures releases the built-in strain and accordingly results in desired shape-changing behaviors. Shear-induced alignment has been successfully used in a direct ink writing process to attain localized swelling anisotropy in swellable shape-changing structures, as depicted in Fig. 3(*f*) [77]. The alignment of stiff cellulose fibrils in hydrogels was controlled by the prescribed printing paths, and the extent of the alignment can be adjusted by the nozzle diameter and the printing speed. After being cured by ultraviolet light, a 3D-printed structure was immersed in de-ionized water to initiate the swelling-related shape changes. Compared with the traditional subtractive manufacturing processes to fabricate fiber-based hydrogel composites [78], the 3D printing technique offers increased flexibility in controlling the local alignment of fibers during the fabrication process, which enables the shape-changing structures to have more complex behaviors.

Overall, various shape-changing structures can be achieved via 3D printing responsive and deformable materials in an architecture with anisotropic material properties. The responsive and deformable materials can exhibit simple shape changes, such as shrinkage or expansion, upon exposure to external stimuli including moisture, heat or light, and a structure with both responsive and passive materials can achieve more complex shape changing configurations.

2.4 Multifunctional Additive Manufacturing Processes. Additive manufacturing processes have been used to build multifunctional structures, e.g., multifunctional flexible sensors [79–83], electronics [84,85], and hydrodynamic structures [86]. Due to the advantage of being able to fabricate objects complex geometric shapes, AM technologies have already been used to fabricate devices with enhanced functionality or performance. Among a wide range of research on various functions beyond structural property, we selected one or two representative work for some common functions and discussed them in the section.

2.4.1 Sensing Property. A multimaterial and multiscale 3D printing approach has been employed under ambient conditions to fabricate 3D tactile sensors that conform to freeform surfaces [87]. The customized sensor is demonstrated with the capabilities of detecting and differentiating human movements, including pulse monitoring and finger motions. The 3D-printed tactile sensor consisting of a base layer (silicon), top and bottom electrodes (with 75% Ag/silicon), an isolating layer, a sensor layer (with 68% Ag/silicon), and a supporting layer (see Fig. 4(*a*)). The 3D-printed flexible, stretchable, and sensitive sensors were found to be capable of detecting and differentiating human movements, including radial pulse, finger pressing, and bending [88]. Development of a custom-built multifunctional 3D printing process, combined with functional inks, is at the core of this approach and determines the functional features of final devices. A real-time monitoring system of body motion was designed by using smart phones and 3D-printed calcium-silicate-hydrate hydrogel. The autonomous intrinsic self-healing of hydrogel is attained through dynamic ionic interactions between carboxylic groups of poly(acrylic acid) and ferric ions (Fig. 4(*b*)). Establishing a fair balance between the chemical and physical cross-linking networks together with the conductive nanostructure of polypyrrole networks leads to a double network hydrogel with bulk conductivity, mechanical and electrical self-healing properties (100% mechanical recovery in 2 min), ultrastretchability (1500%), and pressure sensitivity.

2.4.2 Thermal Property. Yao et al. [89] developed 3D-printed reduced graphene oxide (RGO)-based heaters to function as high-performance thermal supply with high electrical conductivity, high temperature, and ultrafast heating rate. Joule heating was used to effectively reduce RGO at high temperature (Fig. 4(*c*)). The 3D-printed heater with RGO flakes can reach a high heating temperature, up to 3000 K. The heater temperature can be ramped up and down with extremely fast rates (i.e., up to about 20,000 K/s). The 3D printable RGO heaters with different shapes can be applied to a wide range of nanomanufacturing when precise temperature control in time, position, and the ramping rate is important.

2.4.3 Hydrodynamic Property. Superhydrophobic microstructure inspired by *Salvinia molesta* [9] was fabricated by the immersed surface accumulation 3D printing process. The multiscale artificial hairs with eggbeater heads were reproduced according to the eggbeater structure design in nature. The head is fabricated by intersecting different numbers of circumferences with a diameter of 35 μm and a height of 250 μm (Fig. 4(*d*)). The

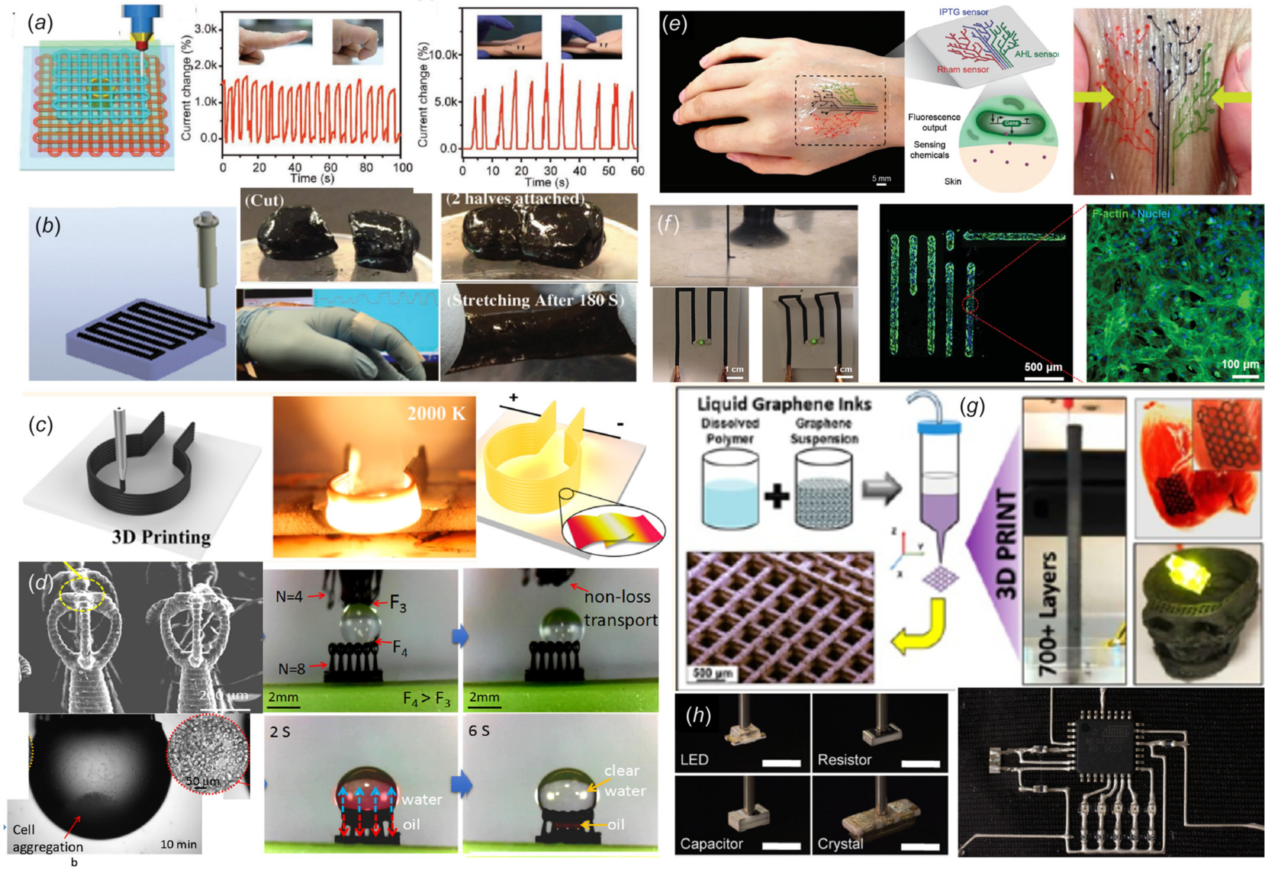

Fig. 4 **(*a*) Three-dimensional printing of multifunctional sensor with helicoidal structures for bending and tactile sensor [87] (Reprinted with permission from John Wiley and Sons © 2017). (*b*) 3D printing of flexible sensors with self-healing hydrogels [88] (Reprinted with permission from John Wiley and Sons © 2017). (*c*) 3D-printed high temperature and high ramping rate heater [89] (Reprinted with permission of American Chemical Society © 2016). (*d*) 3D-printed biomimetic multifunctional superhydrophobic microstructures for nonloss microdroplet transportation and oil/water separation [9] (Reprinted with permission from John Wiley and Sons © 2017). (*e*) 3D-printed living tattoo for chemical detection on human skin [90] (Reprinted with permission from John Wiley and Sons © 2017). (*f*) 3D printing of bioactive carbon nanotube-based ink for flexible electronics [91] (Reprinted with permission from John Wiley and Sons © 2016). (*g*) 3D-printed multifunctional user-defined architectures from graphene inks for electronic and biomedical applications [92] (Reprinted with permission of American Chemical Society © 2015). (*h*) Hybrid 3D printing of soft electronics, image of pick and place of surface mount electrical components, including LED, resistor, capacitor, crystal oscillator, and microprocessor chip [93] (Reprinted with permission from John Wiley and Sons © 2017).**

controllable adhesive force (from 23 μN to 55 μN) can be easily tuned with different numbers of eggbeater arms. The results show that the 3D-printed eggbeater structure could have numerous applications, including 3D cell culture, water droplet manipulation, microreactor, oil spill clean-up, and the separation of oil/water mixtures.

2.4.4 Biology Property. Three-dimensional printing was used to fabricate programmed bacterial cells into large-scale (30 mm) and high-resolution (30 μm) living networks that accurately respond to signaling chemicals in a programable manner (Fig. 4(*e*)). Novel applications enabled by 3D printing of programed living cells were demonstrated in Ref. [90], including logic gates, spatiotemporally responsive patterning, and wearable devices. The integrative technology of 3D living printing has the potential to be used as a general platform where a range of genetically programed cells, matrices, and structures can be applied to designing more customized living materials and devices with predictable dynamic functionalities. Shin et al. [91] successfully developed electrically conductive carbon nanotube (CNT)-based inks that were cytocompatible by using bio-surfactants including DNA, HA, and chemically modified gelatin to successfully improve CNT dispersion in water and its stability (Fig. 4(*f*)). The developed electronic circuits possess good maintenance of the resistance as well as good cellular behavior. The 3D-printed circuits were built with bio-ink and embedded within hydrogel constructs. The developed CNT hybrid materials are beneficial for the fabrication of flexible and foldable biosensors and advanced functionalized tissue-engineered scaffolds.

2.4.5 Electrical Property. A 3D printable graphene (3DG) composite consisting of majority graphene and minority polylactide-co-glycolide, as a biocompatible elastomer, is 3D-printed from a liquid ink (Fig. 4(*g*)) [92]. In vivo experiments indicate that 3DG has promising biocompatibility over the course of at least 30 days. Surgical tests using a human cadaver nerve model also illustrate that 3DG has exceptional handling characteristics and can be intraoperatively manipulated and applied to fine surgical procedures. This 3D printable composite could be applied to the design and fabrication of a wide range of functional electronic, biological, and bioelectronic medical and nonmedical devices. Hybrid 3D printing is a new fabrication method for producing soft electronics. Within an integrated additive manufacturing platform, the direct ink writing of conductive and dielectric elastomeric materials can be combined with the automated pick-and-place of surface mount electronic components (Fig. 4(*h*)) [93]. Using this approach, insulating matrix and conductive electrode inks were directly printed in specific layouts. Passive and

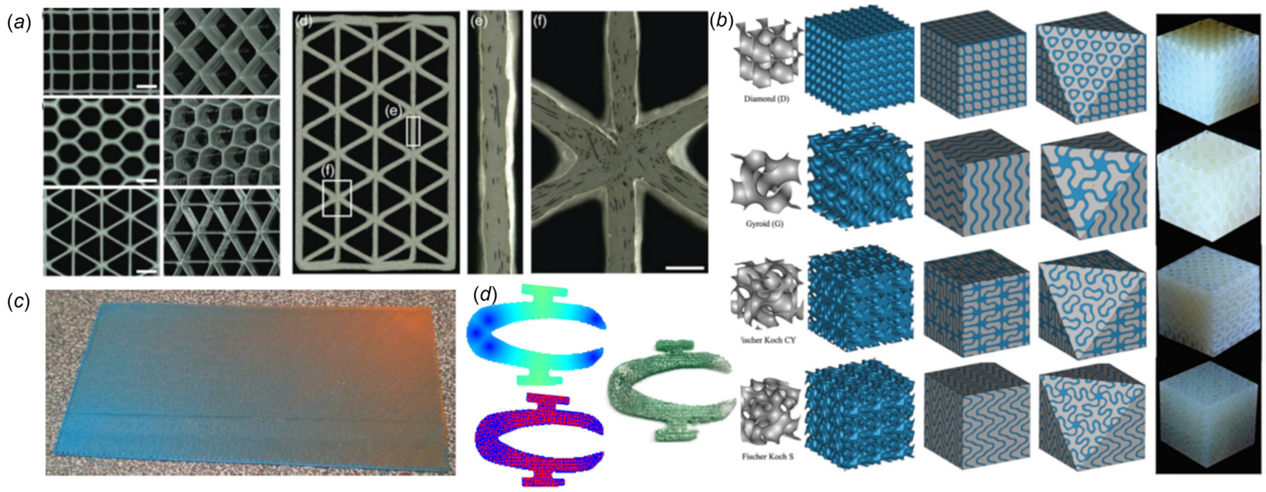

Fig. 5 (*a*) Discrete cellular composite in square, hexagonal, and triangular honeycomb structures. The triangular honeycomb structure is printed with highly aligned carbon fibers oriented along the print direction [3] (Reprinted with permission from John Wiley and Sons © 2014). (*b*) Different TPMS topologies used as composite solid [95] (Reprinted with permission from John Wiley and Sons © 2016). (*c*) An example of gradient structure [96]. (*d*) An example of using two materials to approximate the deformation of continuous material distribution. The blue-to-red colors represent Young's modulus. The simulation and the fabrication results demonstrated the effectiveness of their approach [97].

active electrical components were then integrated to produce the desired electronic circuitry by using an empty nozzle (in vacuum-on mode) to pick up individual components, place them onto the substrate, and then deposit them (in vacuum-off mode) in the desired location. The components are then interconnected via 3D-printed conductive traces to yield soft electronic devices that may find potential application in wearable electronics, soft robotics, and biomedical devices.

The growing maturity of multimaterial and multiscale 3D printing capabilities enabled different industries to develop new products that are tailor-made, high performance, and multifunctional. We will see a much more radical change in the way that products are designed and manufactured. At the same time, the needs for standardized and automated design process are becoming critical, and the related design computation methods are one of the most essential components of design for additive manufacturing.

3 Recent Development on Design for Additive Manufacturing Technologies

Additive manufacturing processes always start from a three-dimensional solid model that specifies the necessary information in order for AM to fabricate the exact shape. Usually, only geometry is provided in a digital CAD file, which is converted into 2D layers by a slicing software system. The 2D layers hereby depict the contour of the digital model and can facilitate the layer-by-layer printing processes. For decades, researchers have conducted studies on how to do process planning to enhance the quality of fabricating results [13].

Recently, with the emergence of new 3D printing processes, a paradigm shift has occurred in the additive manufacturing field from geometry-centered fabrication to supporting more functional requirements. This shift is changing the design methodology from single requirements to catering solutions for more demanding requirements such as fabricating heterogeneous objects with enhanced mechanical properties. In addition to geometric shapes, additional information like material compositions is required to be computed in the design stage. In this section, the current design methodologies are reviewed with the challenges for each type of AM processes discussed.

3.1 Design for Multimaterial Additive Manufacturing Processes. Multi-material object often refers to the class of objects that have different material compositions with a single object. Although the state-of-the-art CAD software systems are capable of defining discrete multimaterial regions, the variety of functional requirements, engineering materials, and AM processes still makes the formulation of a standard pipeline challenging. Most of the CAD software systems only focus on how to assign materials, such as through geometric operations [94], yet lack the ability to design where to place materials to achieve demanded functional properties. Sections 3.1.1–3.1.3 will explore a variety of design methodologies developed for heterogeneous objects, specifically about enhancing structural and other material properties by fabricating the heterogeneous objects through multimaterial AM processes.

3.1.1 Periodic Heterogeneous Objects. Periodic cellular composite is one of the material classes that benefit from the new AM technology in controlled material composition, geometric shape, and complex layout. A composite structure may consist of many identical base cells or representative volume elements, and each cell incorporates structural material (matrix) and reinforcements (e.g., fibers). There are many different multiphase composite materials that exist in nature or are synthetically fabricated. They can be classified in discrete and continuous manners. The composite material in discrete manner (see Fig. 5(*a*)) is reinforced with dispersed particles or fibers (e.g., continuous or discontinuous carbon fibers, carbon nanotubes, and graphene) that characterize the performance and properties through manipulating fiber volume fraction, fiber aspect ratio, and fiber orientation [3]. The composite material in continuous manner (see Fig. 5(*b*)) has phases that are interconnected and co-continuous in the cell [95]. This class of shapes is represented by *triply periodic minimal surfaces* (TPMS), in which the surface is described by a mathematical function, allowing designers to easily architect the topology and arrangement of the constituents toward desirable isotropic or anisotropic mechanical/physical properties.

Design methodologies for discrete cellular composites can be classified into two main groups: intuition-driven design [2] and topology optimization (TO) [98]. Compton and Lewis [3] created lightweight cellular composites with the controlled alignment of fiber reinforcement inspired by balsa wood. Yang et al. [5] and Gu et al. [4] designed different architectures that are inspired by lobster claw and nacre to enhance the impact resistance of the composite, respectively. Computational models (e.g., finite element analysis) are often used to characterize the performance and properties of the designed composites, taking into account the materials' properties [99]. Hu et al. [2] proposed to randomly distribute the reinforcement to extract the composites' properties. Quan et al. [100] reviewed other design models of reinforcement for cellular composite, such as woven fabric and braided preforms. With computational modeling and simulation, high-performance design would be possible after optimization. However, when the fabrication of composites involves several groups of intertwining yarns such as textile assemblies, the computational cost on the existing CAD design tools could be extremely high. To obtain the optimized design of cellular materials, some recent works have focused on topology optimization. For instance, Long et al. [101] proposed a concurrent optimization for composites composed of phases with distinct Poisson's ratios. Their approach optimized the composite unit cells and their distribution in macrostructures simultaneously. Nevertheless, new frontier AM technologies keep increasing the printing dimension of the objects, and concurrently, the available printing resolution becomes increasingly finer. As a result, the computational effort rapidly becomes prohibitive.

Another composite material, periodic interpenetrating phase composites, has recently caught attention due to its smooth-curved nature of the TPMS surfaces, which possesses a higher surface area to volume ratio. As a result, it provides exceptional mechanical, thermal, acoustic, and electrical properties [95]. There are two variants of TPMS solid of composites. One is sheet solid created by thickening the surface, where the volume fraction is controlled by the desired thickness. Another one is network solid created by solidifying one phase of the surface, where the volume fraction is controlled by the approximated level-set constant. Several studies showed that sheet solid possesses better mechanical properties than the network solids at the same volume fraction [95,102]. Design methodologies for modeling TPMS solids have been proposed in the literatures (e.g., [103–105]), which mainly adopt volume representations such as voxels or volumetric distance field to describe the model. Last but not the least, with the help of multimaterial AM technology, the field of metamaterials [6] has been extended from homogeneous to heterogeneous. Additional materials in metamaterials offer a different way to increase one specific property without compromising other properties. For example, a stiffer beam means designing a thicker beam, which lowers the flexibility of the joints. Because of the underlying contradictions in single material design, using additional materials can tune the properties and overcome the geometry barriers [7,106]. Unfortunately, current CAD software systems are limited in their capability on providing fully interactive design function for heterogeneous periodic structures. The difficulties come from the inability to assemble unit cells as to form a complex scaffold and efficiently represent internal architecture in terms of varying materials. To relieve the burden, researchers have developed geometric representations and utilized graphics processing unit to offload some computationally intensive tasks [107].

3.1.2 Graded Heterogeneous Objects. Functionally graded material (FGM) can be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the composition material. FGM as an interface layer that combines two or more materials in the same component (Fig. 5(*c*)), such as metal and ceramic, can enhance the bond strength [108] and effectively overcome the shortcomings of traditional composite material [109].

Designing FGM objects is difficult because the distribution of internal material cannot be simply bounded by a geometrical shape. Additionally, functional outcomes are very important and should be considered during the design of FGM objects. Important aspects of FGM design include model representations, process planning, and evaluation of material properties [110]. Different representations have been proposed in literatures [111], which can be classified into two main groups: discretized representations and function-based representations. (1) The discretized model (e.g., distance field) can specify the composition of every volumetric element within the parts; however, it requires an enormous amount of data and the related design methods are not intuitive. (2) The function-based models use a global function or piecewise blending functions in different regions to mathematically represent the volume fraction composition of the designed part at each point. Yet, for complex geometries, this representation often does not work well, especially when retrieving material at specific locations. In order to generate a fully optimized FGM part, optimizing both topology [112] and material composition [113] using suitable representation is necessary. On the other hand, research showed that a particular AM process chosen to fabricate the part can significantly affect a design's outcome [96,110]. Hence, manufacturing constraints should be associated with the representation, allowing the optimal parts to be adjusted based on process planning strategies including slicing, orientation, and path planning.

The concept of FGM can be further integrated with microstructure and porous structure. Bahraminasab et al. [114] designed a new metal-ceramic porous functionally graded biomaterial to replace the existing metal alloy material that is normally used. The use of metal-ceramic FGM reduced the stress-shielding effect of the femoral component, which is the primary cause of aseptic loosening. And the porous structure can cause more uniform stresses in the femur. This type of new material is particularly useful in bio-engineering applications, as the pore structure facilitates the cellular activities. To fully make use of the integration concept, the optimization-based design methods for the constituents' material gradation, interface geometry, and structural porosity need to be further studied [115].

3.1.3 Nonperiodic Heterogeneous Objects. Most nonperiodic heterogeneous designs are goal-driven with respect to a different functionality. Brunton et al. [116] produced 3D color prints that are highly accurate and detailed with four translucent materials. They developed an error-diffusion algorithm for voxel representation of surfaces to approximate the color gradients. Gu et al. [117] proposed an algorithm to yield designs that are composed of soft and stiff materials to create composites with more than 20 times tougher than the stiffest single material used in the composite. The authors optimized the design using a modified greedy algorithm. The algorithm works by picking an initial random geometry and then switching all elements one by one and checking if the stiffness can be improved. The authors later proposed a machine learning method to improve the accuracy and efficiency [118]. Bader et al. [119] presented a data-driven approach for the creation of high-resolution, geometrically complex, and materially heterogeneous 3D-printed objects. This approach utilized external data source as the primary design element and can generate material distributions during slicing. The models derived from these examples rely heavily on a discrete representation to describe the whole solid point by point. But discrete representations often have problems to be scaled up for the production of high-resolution and/or large-volume models. On the other hand, standard techniques like topology optimization do not scale well and they cannot be run on objects with billions of elements (or voxels) due to the large number of design variables. Therefore, Yu et al. [120] proposed to design and perform optimization on the model in mesoscale. The basic idea is to optimize the design in coarser level and then further optimize with finer scale via finite element analysis. Leung et al. [97] proposed a data-driven approach to design composite structure (soft and stiff materials) such that it can achieve prescribed deformation. They discretized the design domain and approximated a solution by finding composite patterns that possess closely matched behaviors (Fig. 5(*d*)). Kennedy [121] also presented a work to address the difficulty of large scale. He proposed to use a multigrid-preconditioned Krylov method for solving large structural finite element problems and a parallel interior-point optimization technique for solving large-scale constrained optimization problems.

To represent a multimaterial object, most geometric-based representations are insufficient to specify material composition, especially when the material distribution needs to be associated with the

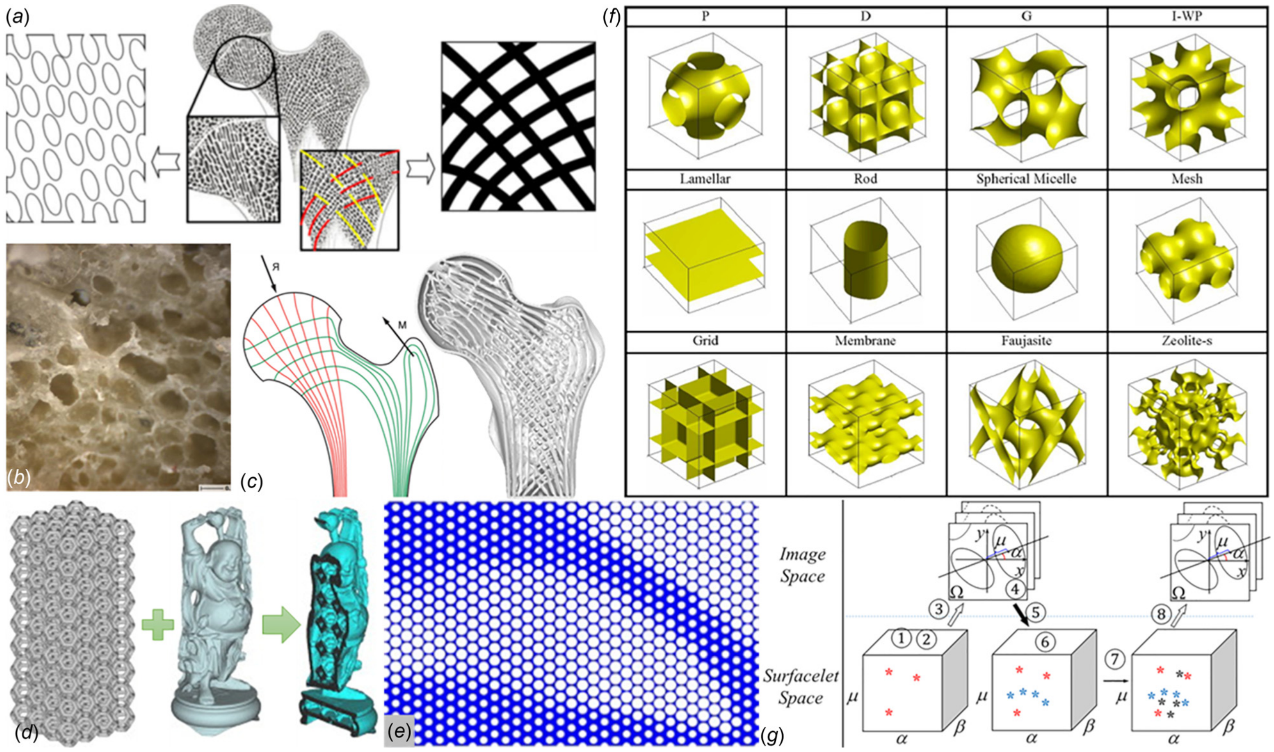

Fig. 6 **(*a*) Natural bone architecture is mimicked by integrating network of channels and pores [129] (Reprinted with permission of Springer Nature © 2013). (*b*) A printed structure with sugar particles dissolved mimicking natural foam structure [130]. (*c*) Topological optimized porous infill in a bone model [152] (Reprinted with permission of IEEE © 2018). (*d*) Surface and internal structures can be modeled by Boolean operation [107] (Reprinted with permission of Elsevier © 2010). (*e*) A pseudoperiodic cellular structure designed by cells with same topology but different sizes and shapes [166]. (*f*) Cells defined by geometry function [131]. (*g*) The specification of material function can be designed by transforming between image and surfacelet spaces [176].**

functional specification. Simply integrating both geometric and material information in one representation (e.g., voxels) may not be a good option due to the redundancy and cannot be designed intuitively, although it is favorable for the functional analysis. Developing a representation that can work in both design and analysis stages could be critical for multimaterial 3D printing [122].

3.2 Design for Multiscale Additive Manufacturing Processes. As emerging AM technology can fabricate details of materials at multiple scales to achieve behaviors that are significantly different from 3D-printed monolithic solid, the next generation CAD systems need to support specification at multiple size scales. However, the design methodology and representation could be significantly different among various scales. For example, the reverse engineering in macroscale is normally based on 3D surfaces, while it is mainly based on digital material images obtained from microscope scanning in nanoscale. The challenge is how to link the various scale transitions and how to model both geometry and material structure concurrently. As mentioned by Panchal et al. in a review paper [123], a transition method may only be applied to some scales. Their paper focuses on the micro- to macroscales for AM applications. We will review the design strategies and different representations for multiscale modeling and design.

3.2.1 Biomimicry and Topology Optimization. The main factors of a structure that affect its properties are the topology, shape, and density of the structure besides its composition material itself [124]. Therefore, much progress has been made in developing and identifying microstructures with desired behaviors [125–127]. For example, structures at the scale of microns influence the physical properties such as weight and ductility. Microstructured material can be considered as a new material with totally different properties compared to its primitive as a solid [128]. To design the microstructures, an intuitive approach is to mimic the forms that can be found in nature such as bone (Fig. 6(*a*)) and foam (Fig. 6(*b*)). By taking X-ray tomography or scanning electron microscope images, Vlasea et al. [129] took the natural bone porous macro architecture as an input, and draw the microchannels to mimic its biological and mechanical properties. Quinsat et al. [132] extracted surface information from images and represented the information by skin voxels corresponding to the internal and external surfaces in subvoxel to super-voxel scales, which are used to determine the filling strategy. Martinez et al. [133] applied the Voronoi diagram to generate an implicit representation to create foam geometry. The procedural Voronoi foams are the microstructures that exhibit different elastic behaviors. The implicitly modeled foams adapt locally to follow the elasticity field but connect the frame and microstructures seamlessly. Martinez et al. [134] synthesized the foam structures by controlling the elasticity independently along three orthogonal axes, called orthotropic foams. The fine-scale structures were generated procedurally that resemble foams and can be scaled up to arbitrarily volumes.

The common mathematical way to optimize the microstructure and material layout for given loads and boundary conditions in a design domain is TO (Fig. 6(*c*)). TO is one of the early approaches developed for microstructure design, such as homogenization method [135], solid isotropic material with penalization [136], differential growth [137,138], and level-set method [139,140]. Several CAD software systems, such as *DreamSketch*, *Solidworks*, and *SolidThinking Inspird*, have been developed to generate design using topology optimization [141–143]. However, these are iterative approaches which perform FEA repeatedly until the best solution is found, resulting in high computational efforts, especially in fine resolution of design domain. Another widely used approach, called ground structure [144–148], starts with the union of all potential members and eliminates the "vanishing" ones, i.e., zero cross section area, throughout the optimization process. Gilbert and Tyas [149] introduced a growth method called "adaptive ground structure," which starts with an initial ground structure with minimal connectivity, and increases the number of members at each step. This approach is further modified by Sokół [150,151] in a level-set manner by first considering the shortest members in the ground structure, and then longer members are considered as candidates in each of next iterations. Wu et al. [152] speeded up the voxel-based TO by aggregating local per-voxel constraints to global constraint, and the method can work on high-resolution design domain. Kwok et al. [153] made use of principal stress lines to convert the structural optimization to a geometry design problem, and their method is less dependent on the resolution of finite elements and can achieve interactive speed. To solve the problem of support removal for infills, TO is computed on a carefully designed rhombic structure so that the self-supporting can be guaranteed on the result of optimization [154].

3.2.2 Cellular Structure. Although the aforementioned concurrent methods can design geometry and material at the same time, it can only explore a very small region of the design space because of its computing cost. When the structure needs to fill a large volume, the current computational power and memory are not sufficient to manage a large design space. Rosen [155] proposed using manufacturable elements as an intermediate representation to support additive manufacturing. The manufacturable element is a predefined and parameterized decomposition of a volumetric region of a part such as a cell. The periodicity simplifies modeling and simulation, reduces memory costs, and can be assembled by Boolean operation [107] (Fig. 6(*d*)). The cellular structure is promising in a variety of engineering applications. Sá et al. [156] generated a parameterized infill cellular structure adaptively by a recursive subdivision approach. Given a volume boundary, this approach makes use of primal or dual cellular structure to fill up the volume, which can be 3D-printed. Qi and Wang [157] presented a feature-based approach to create crystal structures with such building blocks, where periodic surfaces of basic features are used to construct complex crystal structure rapidly and parametrically. Xiao and Yin [158] modeled the random structure of porous media using Voronoi tessellations.

Lattice structure is a type of cellular structures, which has inherent advantages over foams in terms of mechanical property by the volumetric density of the material. There are randomized, periodic, and pseudoperiodic lattice structures, and the cells of a lattice structure can be homogeneous or heterogeneous [159]. Dong et al. [160] reduced the simulation cost for solid-lattice hybrid structures by using beam elements for the lattice and tetrahedral elements for the solid. To connect the two elements that have different degrees-of-freedom, they calibrated the parameter of rigid body element for the connection. Tang et al. [161] took the manufacturing constraints into account during the design and optimization of lattice structure to ensure its manufacturability. By applying size optimization to update the sizes of struts, it can improve the printing quality and the stiffness of the model without increasing the weight of the part. Sigmund [162] introduced a method to design the periodic microstructure of a material to obtain prescribed constitutive properties. They formulated the problem of finding the simplest possible microstructure to achieve desired elastic properties as an optimization problem named *inverse homogenization* problem. Bickel et al. [163] presented a method to measure deformations of base material's structure and stack them to reach a target behavior through combinatorial optimization. Schumacher et al. [164] extended this idea by designing microstructure to match given homogeneous material properties. These microstructures are tiled to create objects with spatially varying elastic properties. On the other hand, Panetta et al. [165] introduced a library of tileable parameterized 3D microstructures to control the elastic material properties of an object. By choosing a space of structures with limited but sufficiently large set of parameters, a small family of structures can be optimized to achieve specific material properties.

There are some hybrid approaches combining several celluar structure design methods to improve accuracy and reduce computational cost. For example, Zhang et al. [166] related the cellular microstructure to the topology optimization results at macroscopic scale (Fig. 6(*e*)). The hexagonal structure is reconstructed by mapping the optimized density to the strut diameter. Zhu et al. [167] proposed a two-scale topology optimization that computes an optimal topology in the low-level building blocks using a level set field and maps the results onto the microstructures to generate a high-resolution printable structure. They have demonstrated that the hybrid method can optimize the material property spaces on the level of a trillion voxels.

3.2.3 Shape Descriptors. The decomposition methods discussed earlier can simplify the design problem, but the simplification with fixed topology also sacrifices certain degree-of-freedom. Some researchers modeled the material properties by using implicit representations or functions (see Fig. 6(*f*)). Under this scheme, the shapes of various regions are not limited by the predefined topology, and very detailed structures can be generated in a large object without having a full explicit representation. The absence of global organization and periodicity allows the free gradation of density, orientation, and stretch, leading to the controllable orthotropic behaviors. The challenge here is how to define functions using what types of shape descriptors. One popular approach is to use surfaces that are similar to the biological membranes studied in natural science. Wang [168] proposed the analytical models of TPMS for the nano design. Yoo [169,170] combined volumetric distance field and TPMS pore morphology to generate porous scaffold design systematically, which is also used to generate projection images for image-based AM processes directly without the need of slicing the complicated 3D scaffold models [171,172]. Schroder-Turk et al. [173] used Minkowski tensors to extract physically relevant spatial structure information to quantitatively characterize and analyze the cellular structures. Wang and Rosen [174] presented a new dual representation to model heterogeneous materials based on a new basis function—surfacelet, which can capture material distributions at multiple scales. Huang et al. [175] extended the method to a new multiscale specification environment based on material images and microstructural feature modeling (see Fig. 6(*g*)). With both the forward and inverse surfacelet transformation [176], their method has the capability to zoom-in and zoom-out seamlessly to exchange material information at multiple scales.

Localization (as opposed to homogenization) describes the spatial distribution of the response field of interest (stress or strain fields) at the microscale for an imposed loading condition at the macroscale. Fast and Kalidindi [177] applied the materials knowledge systems, which facilitates bidirectional exchange of information between different scales and calibrates the higher-order terms in the localization relationship to improve the accuracy of multiscale modeling and simulation. Baniassadi et al. [178] applied Monte Carlo sampling method to reconstruct microstructure using two-point correlation functions. They have also used in the colony and kinetic algorithms to simulate the virtual microstructures. The lower-order functions can be used to approximate solution for the higher-order ones (n-point correlations) for heterogeneous materials [179]. Xu et al. [180] derived 3D descriptors from 2D images based on the characterization of 2D microstructural morphology. Their method can reconstruct large size 3D structures, even when the direct 3D microstructure analysis is not available. Gupta et al. [181] established surrogate models with low computational cost for measuring the microstructures using n-point spatial correlations and *principal component analysis*. Huang et al. [182] generalized the periodic surface model to model the shapes of the fibers in porous media, and the developed model can construct the 3D volume element of randomly distributed fibers.

In the multiscale modeling, the transitions among scales are usually modeled by concurrent and/or hierarchical schemes. However, certain information is lost in either way, and there is no single multiscale modeling technique that is sufficient for various applications in different length-scales. Hansmeyer [183] presented

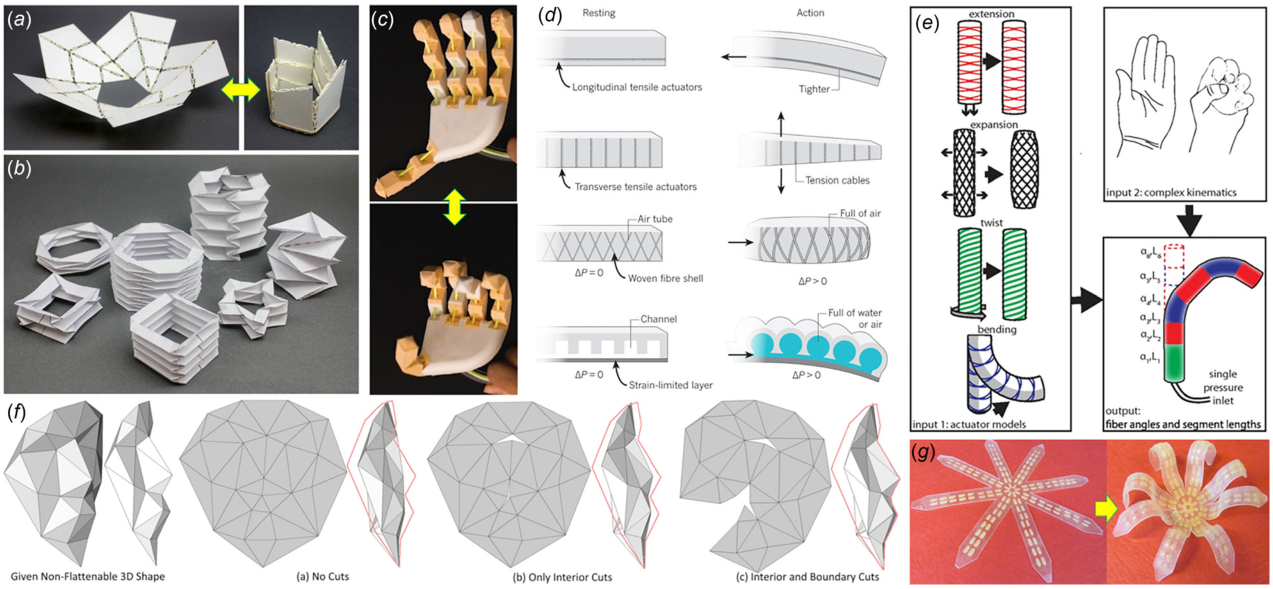

Fig. 7 (*a*) An origami antenna in both stowed and deployed states. (*b*) The database of origami models can be applied to a bellows [192]. (*c*) A hand design using elastomer and joints to achieve different curvatures [196]. (*d*) Various actuation designs for soft-robots [198] (Reprinted with permission of Springer Nature © 2015). (*e*) The database of fiber-reinforced soft actuators are used to design for matching the input trajectory [199]. (*f*) Shape optimization and cutting are done for 4D-printing nonflattenable object [66]. (*g*) A self-transformed flower with designed pattern to constrain the shrinkage of a prestrained film [65].

a procedural subdivision process to articulate the model at multiple scales, yet the approach is rather limited only for certain applications. With the growth of computational power and cloud computing, the concurrent methods will play a very important role—particularly when the response within a microstructure cannot be localized. At the same time, a promising trend of generative design [184] can be applied. Nevertheless, the data-driven methods and the dual-representation approaches are still the most practical strategy at this moment. At present, the material and manufacturing information of the microstructures can be extracted on-the-fly, so that the demand of memory and commutation is minimized. However, the major challenge is still the high-dimensional optimization during the iterative computation. One possible direction is to convert the iterative optimization problem into a geometric design problem, such that the accuracy does not rely on the resolution of the solution space. But this requires a complete understanding of the problem and the development of design principles for the problem in different scales.

3.3 Design for Multiform Additive Manufacturing Processes. With the newly tailor-made materials and the multi-material 3D printing capability enabled by AM technology, multi-form products using intelligently designed layout of various materials such as plastic, elastomer, composites, and shape memory polymer can now be fabricated. Designers can focus more on the intended forms of a designed product during its usage over time. In this section, we will review different design methodologies for multiform fabrication and the related form-changing mechanisms.

3.3.1 Folding and Origami. In classical mechanics, motions between rigid bodies are realized by their connections such as kinematic pairs or joints. The connection could be located at a point or along a line, such as mechanical linkage or folding. With the help of additive manufacturing, the kinematic pairs can now be directly fabricated using different choices of materials, which could result in a more complex system that cannot be designed and produced before. Wang et al. [185] studied mobility and foldability of foldable mechanisms. Their method is based on the formula of the revolute-joint design related to the joints' degrees-of-freedom and the order of wrench system. They described that a shape-shifting structure can be folded into the same pattern through different methods and can also be folded to different patterns.

Recently, one of the active topics in folding mechanism is the origami (or kirigami) designs. Having the ability of transforming back-and-forth between its stowed state and the deployed state (see Fig. 7(*a*)), the origami-based mechanisms have many attractive applications, e.g., the origami wheel presented in Ref. [186]. Belcastro and Hull [187] used affine transformations to compute the valid origami structures and the mappings between unfolded and folded configurations. Schenk and Guest [188] proposed a model for origami structures with elastic creased folds via truss representations. Their model is based on introducing the behavior of torsional springs at the creases. Tachi [189] used a similar approach to model the elastic behavior of sheets with creased folds and also idealized the folds as torsional springs. He also solved the equations of mechanical equilibrium under constraints assuring that no fold line or boundary edge is elongated. This model provides the theoretical basis for his origami simulation tools (i.e., the freeform rigid origami simulator [190]) to compute the unfolded patterns for a given folded target shape. Zhu et al. [191] developed a method for analyzing surfaces under creased and bent folds. Their tool allowed for the superposition of folds with arbitrary sharpness and angle that collectively dictated the ultimate shape of the analyzed surface. Recently, Morgan et al. [192] presented a design process for generating origami-adapted products based on an exemplar-based methodology (see Fig. 7(*b*)). The design process includes (1) evaluating the criteria to verify if the problem is suitable for origami-adapted design, (2) picking seed origami from standard patterns that function close to the need, (3) modifying fold patterns to meet the design requirements, and (4) integrating the pattern with material and prototyping. On the other aspect, modeling a freeform surface using foldable mechanisms is also relevant to the geometric modeling of developable surfaces [193–195]. In these approaches, an inverse design problem—finding the planar structure for a given 3D target—was studied.

3.3.2 Elasticity and Soft Robotics. With the capability of printing elastomeric and/or rigid materials, certain mechanical deformation to mimic physical objects like gripper [196] (see Fig. 7(*c*)) and heart [197] can be designed. Most current practices are to compute in a trial-and-error manner by using different actuations such as tensile cables, constraint fibers, and pneumatic bellows [198] (see Fig. 7(*d*)) and then testing the responses and the deformations. Connolly et al. [199] created a database of fiber-reinforced soft actuators and developed an automatic selection of mechanical properties to match the kinematic trajectory of a gripper using the exemplars in the database (see Fig. 7(*e*)). In other methods, material parameters of constitutive model were estimated by considering Young's modulus [200,201] and acquiring complex heterogeneous deformation through optimized material distribution of Young's modulus [202]. However, the results generated by these approaches may not be fabricable due to the limited materials that can be 3D printed by current AM processes. A halfway approach is to design microstructures with single material to approximate elasticity for 3D printing [164,165,203], which has been discussed in Sec. 3.2.1.

Until today, it is still difficult to directly generate design for performance and manufacturability. A more common way to generate optimal design is to integrate simulation into the design phase that allows an iterative process to update the design and estimate the physical effects of the changes. Skouras et al. [204] presented a design method for deformable character with a set of target-poses as input. The method combines FEA, sparse regularization, and constrained optimization in the design phase to compute a set of actuators along with their locations and material distribution so that the resulting character exhibits the desired deformation behavior. As FEA is often the bottleneck in computation, some approaches make use of numerical coarsening [205,206] to speed up the FEA without a huge penalty in accuracy. Another speedup technique is data-driven methods, which are effective in the applications that require interactive response demand [203].

In fact, the data-driven method is common in the design of soft robot, where 3D printing is getting more and more adopted. While commercial software like ABAQUS and COMSOL can be used in soft robot design [207], Hiller and Lipson [208] developed a platform called Voxelyze that is able to generate results of dynamic simulation for multimaterial soft objects with a fast simulation. Voxel representation is used for simulating large deformation, and evolutionary computation is employed to obtain optimized material distributions [209]. Nevertheless, many voxels are needed to represent models with complex shape, which will tremendously slow down the computation. SOFA [210] is a widely used framework in the field of surgical and biomedical simulation. Based on SOFA, Duriez et al. [211–213] developed an asynchronous simulation framework by considering the trade-off between deformation accuracy and computational speed such that a real-time simulation of soft robots was realized to support interactive deformation. Their algorithm uses the iterative method to solve ordinary differential equations and transfers boundary conditions using Lagrangian multipliers. This method is fast but suffers from the problem of numerical accuracy, particularly if there is large rotational deformation. Wang and Hirai [214] presented an optimization-based method to find an accurate mathematical simulation model for pneumatic driven grippers. With the help of mass–spring system, Stanley and Okamura [215] presented a close-loop control for haptic jamming deformable surface. However, they are application-specific and may not be generalized to other domains. Recently, Fang et al. [196] presented a geometry-based approach that can simulate multimaterial actuators in large rotational deformation in a quite accurate way.

3.3.3 Self-Transformation. Sections 3.3.1 and 3.3.2 discussed the mechanisms of transferring external forces and movement into deformation either by designed connections or elastic materials. Other research for fabricating smart structures and products focuses on the development of self-folding, self-assembly, and programmable materials to mimic the biological process such as DNA [216]. Many prototypes have been developed based on different materials, fabrication technologies, and external energy sources [217]. However, most of these prototypes require an additional production step to embed the "programmability" and the potential energy for transformation, e.g., adding magnets and elastic strands, which is difficult. This leads to the development of *four-dimensional (4D) printing*, which streamlines the process of production for programmable and adaptive materials. There are survey papers [62,64,218] reviewing the current 4D printing processes, concepts, and related tools. They have described different shape-transformation behaviors such as bending and folding, the commonly used materials and structures, and the shape-shifting mechanisms. The papers also mentioned that the design for shape-transformation behavior is needed to predict and model the structures, such that the number of trial-and-error experiments can be reduced.

Gladman et al. [77] studied a bilayer structure that is fabricated by depositing the ink of hydrogel composite in different print paths for the two layers. They defined the elastic and swelling anisotropies by controlling the orientation of cellulose fibrils within the hydrogel, and the orientation is computed by the mathematical relationships of desired curvatures and the parameters including elastic moduli, swelling ratios, and layer thicknesses. Kwok et al. [66] pointed out that only developable surfaces can be shaped-transformed from 2D to 3D. Based on differential geometry, they developed a geometry optimization method for freeform surfaces to modify a nonflattenable surface into a flattenable one. The shape optimization framework also supports topological operators by adding cuts to improve the flattenability (see Fig. 7(*f*)). Deng et al. [65] used an exemplar-based approach to approximate a smooth surface. They created a library of constraint patterns with controllable variables and studied the relationship between the patterns and the deformation (see Fig. 7(*g*)). As a smoothly curved surface can be subdivided into patches and approximated by the patterns in the library, their method can approximate different folding types, folding orientation, folding axis, and folding curvatures. Kwok and Chen [219] developed a geometry-driven finite element method to efficiently simulate shape-transformation behavior, which can be integrated in the design phase for an iterative design algorithm. They also demonstrated that, by using the geometry-driven finite element framework to understand the material distribution and the resulting curvature, a mathematical model can be formulated to design for general freeform shapes.

Since many causes of motion are based on geometric variations such as displacement, a more direct way of simulating motion for input geometric variations rather than using well-defined structural loads is needed to achieve better convergence and accuracy. One of the most recent efforts can be found in Ref. [187]. Furthermore, the simulation only solves a forward problem that determines the final shape with given material structures and deformation principles. A more challenging problem is how to design the optimal material structure that can be transformed into a desired shape. This is an inverse design problem, which is the determination of the material distribution in a structure based on the final desired shape and the given deformation principle. The inverse problem is far more complex in determining a discrete small-scale material distribution that yields the desired self-transformation behavior. One direction in solving this problem is to apply pattern learning and synthesis techniques with the data-driven approaches. The 1D–2D, 2D–3D, and 3D–3D shape-transformation behaviors should be studied, and various deformation principles need to be fully understood in order to design the evolution of 3D structures.

3.4 Design for Multifunctional Additive Manufacturing Processes. Earlier additive manufacturing techniques were mainly used to fabricate structural components with mechanical properties. With the recent developments of more advanced techniques [220], AM technology has been used to achieve more functionality. Complex multifunctional components can now be fabricated through multimaterial and multiscale AM processes,

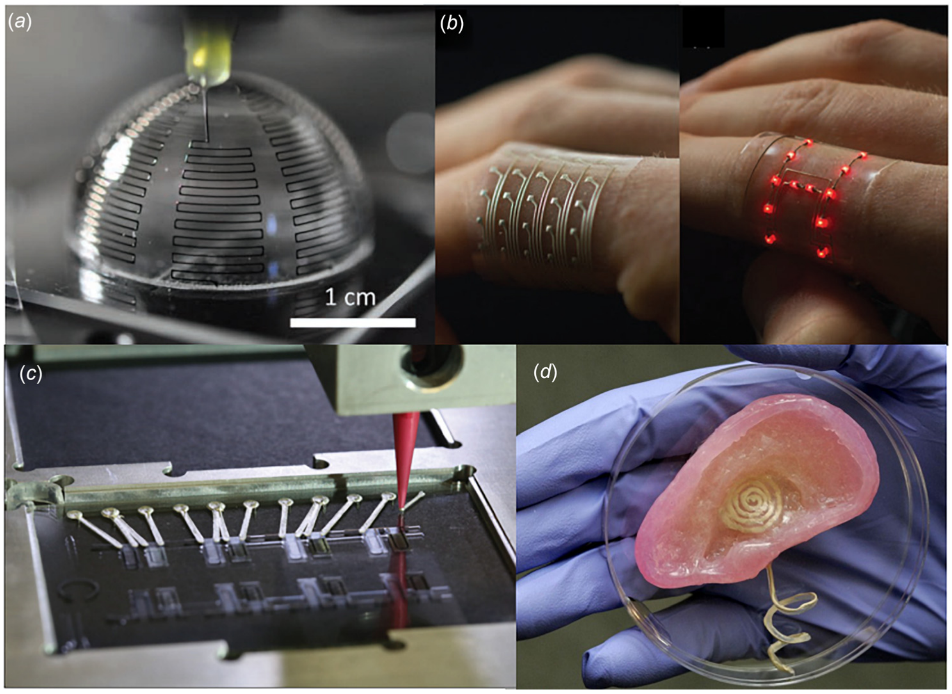

Fig. 8 (*a*) A conformal electrical antenna [230] (Reprinted with permission from John Wiley and Sons © 2011). (*b*) A stretchable device with embedded LED arrays [93] (Reprinted with permission from John Wiley and Sons © 2017). (*c*) Heart-on-the-chips with integrated sensing [231] (Reprinted with permission of Springer Nature © 2016). (*d*) A bionic ear can hear radio-frequencies that are a million times higher than human ears [232] (Reprinted with permission of American Chemical Society © 2013).

which cannot be realized by conventional fabrication methods. Next, we will provide an overview of research on design for some popular functional properties including optical, thermal, and electrical properties.

3.4.1 Design for Optical Properties. Advancements in 3D printing technology have led to the capability of fabricating complex optical components, such as microlenses, freeform optics, and multicomponent optical systems. The unrestricted design freedom and the flexibility to write on arbitrary substrates may lead to revolutionary optical designs. Gissibl et al. [48] presented a study of using 3D direct laser writing to fabricate an optical system with multilens that shows high optical performances and tremendous compactness. The optical system can be directly fabricated on the optical fiber for endoscopic applications. Thiele et al. [47] demonstrated 3D printing of four-lens systems onto a chip to form a multi-aperture camera. Based on the 3D-printed aspherical freeform surfaces, a future device based on the related lens design can become smaller but transfer images with higher resolution. In order to design such compound lenses, an optical design software is used first. Then, the optical properties are optimized through simulation, and the performance and functionality are finally validated with the fabricated lens.

Freeform surface allows higher degrees-of-freedom in optical design to achieve unique optical properties and provides substantially improved imaging performance. In particular, the representation technique of a freeform surface has been a key research topic in recent years since it has a close relationship with design, manufacturing, testing, and final application [221]. A good representation of freeform surface has the advantages of improving the imaging performance, reducing the lens number and weight, and further increasing the compactness of optical components. From the manufacturing point of view, it is also important to consider surface quality during the design stage [222]. The surface profile can strongly affect the optical properties. Although postprocessing offers significant surface finish improvements, designing an optional lens with complex geometry must take into account for stair-case effect and supporting structure, which are still the bottlenecks for 3D printing of optical components.

3.4.2 Design for Thermal Properties. Maintaining an acceptable temperature range for a thermal-related application can require complicated techniques and related component designs. Additive manufacturing offers a unique solution for thermal management by providing more design freedom. NASA [223] recently developed a space folding fabric that has four essential functions: reflectivity, passive heat management, foldability, and tensile strength. By depositing material in layers, they can add multiple functions to the design. Dry-cooling channel is another heat management example that takes advantage of AM technologies. Felber et al. [224] designed a heat exchanger with a tunable microstructure to enhance heat transfer. They also suggested embedding conductive fillers such as graphite, carbon black, or carbon fibers to further improve the conductivity. Other examples of novel thermal designs enabled by AM include injection molds with designed conformal cooling channels to reduce the cooling time as well as the printing cost [225]. More complicated design for conformal cooling in injection molding can be found in Ref. [226], which is further improved with faster coolant velocity in a spiral cooling channel [227]. Zhang et al. [228] introduced a method for designing personalized orthopedic casts, which are aware of thermal-comfort while satisfying mechanical requirements. They created a hollowed Voronoi tessellation pattern with optimized density based on thermal image to maximize both thermal comfort and mechanical stiffness. Similarly, some researchers used lattice structure with defined density distribution for thermal problems. Cheng et al. [229] presented a method to concurrently optimize the density distribution of the lattice infill and the layout of functional features. Asymptotic homogenization is employed to obtain the effective thermal conductivity of lattice structure in terms of the relative density.

3.4.3 Design for Electrical Properties. Several 3D printing techniques have been developed to build parts with embedded

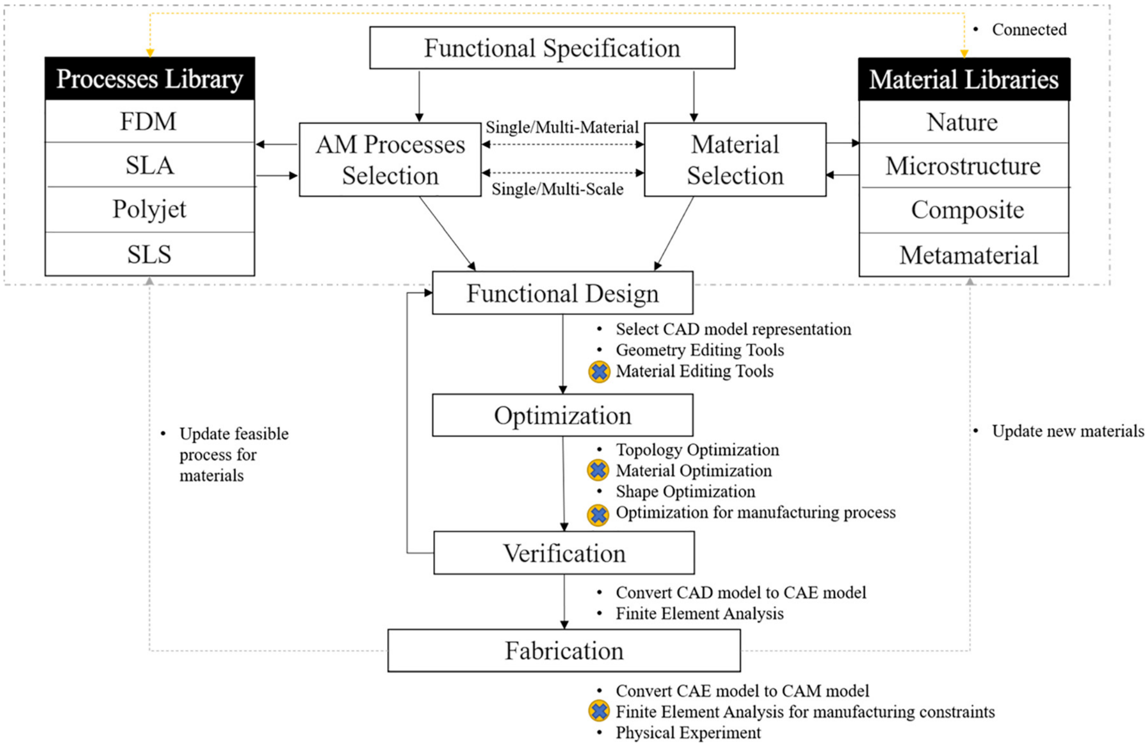

Fig. 9 A design framework for functional additive manufacturing. Crossed bullet points suggest the directions that are getting insufficient attention.

electronic (e.g., *Voxel8* printers). Such processes can integrate conductive inks and electronic components within the 3D-printed objects, allowing a degree of design complexity that is not possible through the standard soldering method by manual labors. For example, Adams et al. [230] demonstrated how to fabricate a conformal 3D antenna by printing conductive inks onto convex and concave hemispherical surface (Fig. 8(*a*)). The 3D design enabled the specification of both operating frequency and size, achieving near-optimal bandwidth at several frequencies of interest to wireless communications. The ability to print conformal antennas that are compact and encapsulated within their support substrate further enhanced the mechanical robustness. Not only on special type of surface, Valentine et al. [93] printed soft stretchable electronics by combining direct ink writing with automated pick-and-place of surface mount electrical components (Fig. 8(*b*)). Their hybrid fabrication method enables surface mount electrical components of arbitrary shapes and sizes onto 3D-printed soft wearable circuits, offering a unique opportunity to expand the functionality of fabricated structures. With the capability of printing on arbitrary surface, it is necessary to consider how to perform 3D placement and routing in an effective and efficient way. Panesar et al. [233] introduced a design framework to optimize a multifunctional 3D part by coupling both aspects of functional and structural designs. They proposed methods to select locations of components based on performance and/or geometry criterion, and identify component orientation using the skeletal information. They also suggested using approximate yet accurate shortest path computation approaches to generate electrical connection to form a circuit (i.e., routing). Optimizing routing can improve the circuit efficiency by lowering resistance that is proportional to the conductive track length. Later, they used coupling strategies to solve (1) the placement and routing problems using a heuristic approach, and (2) the structural optimization with the placement and routing via topology optimization algorithms [234].

Printing electronic components seamlessly with biological tissue and organs is even more complicated. Lind et al. [231] utilized multimaterial 3D printing technology to fabricate soft strain gauge sensors in cardiac microphysiological devices by the integration of six types of materials at microscale (Fig. 8(*c*)). In Ref. [232], a bionic ear was printed to demonstrate the feasibility of enhancing human's capability (Fig. 8(*d*)). For biological applications, the 3D-printed devices are required to match geometries, mechanical and biochemical properties to every cell source/material, making the design process even more complicated. Ultimately, like Festo [235,] who has taken the delicate anatomy of the natural ant as a role model and control bionic ants to complete complex tasks together, they brought the integration of AM technologies into another level of complexity.

Multifunctional AM technology has become an intensive research field. Researchers are trying to combine the multimaterial and multiscale fabrication capabilities enabled by recent AM technology to create different multifunctional devices for a wide variety of applications. Meanwhile, there is no automatic way to categorize the information with respect to the functionalities and accordingly to provide effective designs for different functions. Currently, researchers usually need to equip with domain knowledge in various fields in order to interpret the problem to be addressed. Insufficient understanding could lead to long design cycles with difficulty in obtaining an optimal design. How to integrate information from each individual function and make tradeoff from different aspects would be a key factor for research development in future.

4 Conclusion and Outlook

Additive manufacturing is a promising manufacturing technology in terms of geometry complexity and integrated functionality. Considering the developments of AM processes and the availability of programmed materials enabled by them, we presented a framework as shown in Fig. 9 to summarize the design of functional parts with AM processes and related materials. The areas that have gotten insufficient attention and some possible directions for future research on design for additive manufacturing are also discussed in the section:

(1) Based on given functional requirements, the design framework begins with the selection of AM processes and the related material options. AM technology has shown great

advantages in fabricating multifunctional structures. However, there are still several problems that need to be addressed. For example, multifunctionality of a designed component usually requires using multimaterial 3D printing processes. However, the kinds of materials that are available for such multimaterial 3D printing processes are usually limited. The study to broaden the materials that can be 3D printed as well as to enable novel composites is a critical task in the future. In addition, it is very challenging for current 3D printing technology to process materials in different categories due to the incompatible forming conditions. New material deposition mechanisms may also enable multimaterial 3D printing with higher resolution and faster speed. In the hydrodynamic level, some multifunctional bioinspired structures possess multiscale features, which are difficult for current 3D printing processes to replicate. The further development of multifunctional AM processes will lie in the combination of multimaterial and multiscale AM technology.

A database linking AM processes, material and functional specification will also become urgently needed. As shown in Fig. 9, two libraries are established that need to allow the interoperability (yellow dotted line) between them. A comprehensive collection of materials (includes programed materials) with experimental data from the related fabrication processes can support designers to determine how functions are related to the manufacture constraints and material properties. Every profile of materials should be linked with at least one AM process, and each AM process should provide a list of manufacturable materials along with the necessary values of process parameters. The connection guarantees that any profiles created in the libraries are feasible and practicable. In the AM process/material selection stage, there exists a two-way coupling relationship (as shown in black dotted arrows). The relationship indicates that not only the process could be affected by the available materials, the material selection is also affected by the manufacturability. Therefore, in the early stage of functional design, it is very important to be guided by the established libraries.

(2) One important challenge is to set an appropriate representation model that is reliable, reasonably accurate, computationally efficient, user-friendly, and easy to modify, share and store [236]. For example, the overall characterization of microstructures needs to be improved. A standard protocol for assessing the dimensions/microstructure/mechanical performance needs to be developed. Multifunctional additive manufacturing is a new emerging technology and still being under development. As this area of manufacturing is nascent, most ongoing research goes into materials and process configuration. Little work has been carried out on developing the design methodologies specifically for multifunctional AM processes. Designing a multifunctional device with prefabricated components (e.g., circuits and sensors) requires a more complex design representation when compared to a simple mechanical structure, due to the existence of nonmechanical features, e.g., optical, thermal, and electronic features. These simultaneously designed features require more than one design methodologies, and their combination/coupling issues are manually handled in current research. A thorough design consideration for the currently existing procedures and applications is needed. In the future, it is expected to have proper design operations and representation to allow multifunctional design on arbitrary geometry, arbitrary material composition, and arbitrary size scales.

(3) From our review, it was found that most of current design methodologies are through an iterative process to optimize the simulation-based design results. The most common tool in computer-aided engineering for estimating the behavior of an object is finite element modeling (FEM). However, the FEM framework is known to be computationally expensive, and relies on accurate input of structural loads and material properties. As a consequence, simplifying the FEM computation is an active and emerging topic, especially when the capability of AM is extending to multiple materials with complex shape and topology. When the functional specifications are getting more complicated, efficient and effective optimization methods on geometry and materials are particularly essential that need to be developed.

(4) Eliminating the information gap between the design phase and the manufacturing process is also very important. The final fabricated product needs to reflect the design as best as possible. One major factor that leads to the discrepancy is the human involvement during the design-to-fabrication process. Automating some critical steps, such as process parameter controls (e.g., extrusion temperature and overlap percentage) and design constraints (e.g., building orientation and material selection), could significantly reduce mistakes the may be made during the design-to-fabrication process. In other words, managing and interpreting data has come to be regarded as a key concern across the design and manufacturing processes. In particular, when it comes to multiple materials, data are certainly needed for reproduction and control. To establish the foundation for future AM industry, one way is to associate the data with the mentioned material library, which consists of a comprehensive description of each digital material. The library is then opened for the assessment in different applications. Therefore, whenever a new digital material is successfully printed, the database will be updated for verification. In the long-term, using AM machines to "read" the library and assist in design stage could better handle more complex problems.

(5) From the process perspective, despite the recent advances in 3D printing, there are still plenty challenges that need to be addressed in future. For example, the material selection for the 3D printing of shape-changing structures is still limited. Only a few categories of polymers are currently available, which significantly restrict the potential applications of shape-changing structures. Moreover, the stimuli used to trigger shape-changing behaviors are still based on laboratory environments and might not be broadly applicable to the real world. Meanwhile, the shape-changing behaviors triggered by these stimuli have big variations and cannot be reliably and accurately controlled, which makes 4D printing difficult to be applied in an actual human-centered system. In the future, more new materials need to be explored and incorporated into printed structures to achieve multifunctional properties, e.g., ceramics with mechanical rigidity, scaffolds with bio-degradability, and nanocomposites for chemical or thermal resistance.

In addition, multimaterial AM processes are difficult to achieve micro- and nanoscale features due to some crucial problems of multimaterial printing technology such as material blur. The problem exists in the adjacent regions of different 3D-printed materials, which restrict the resolution of multimaterial printing. As discussed before, an effective material changing system is critical for multimaterial AM process to achieve desired functional performance on the 3D-printed structures. Researchers have made strides to expand the dimensional span of AM technologies, achieving fabricable feature sizes ranging from dozens of centimeters to several microns. Recent progress in the development of multiscale 3D printing technologies also shows applications of 3D printing as a tool to validate designs with advanced materials and multiscale structures. To address the known limitations of AM processes such as fabrication efficiency and limited materials, recent research also reveals a feasible solution by integrating AM with traditional manufacturing processes. Such hybrid processes based on the integration of multiple AM processes and other traditional fabrication processes provide the capability of building multiscale and multimaterial objects. The hybrid process development is becoming a trending topic for additive manufacturing research.

In summary, many research groups are currently exploiting the fabrication capabilities of AM to meet the ever-changing needs for high-performance engineering systems. It has led to the ongoing development of new design methodologies for integrating the state-of-the-art AM technologies and programmable materials to enable new functional performance or novel products. In the future, we envision a more collaborative and connective design-to-fabrication process codeveloped by the design and manufacturing communities. Together with interdisciplinary teams, multifunctional design challenges can be addressed by developing the next generation of computational design system for additive manufacturing.

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