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The status, challenges, and future of additive manufacturing in engineering

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HIGHLIGHTS

- The fundamental attributes and challenges/barriers of Additive Manufacturing (AM).
- The evolution of research on AM with a focus on engineering capabilities.
- The affordances enabled by AM such as geometry, material and tools design.
- The developments in industry, intellectual property, and education-related aspects.
- The important future trends of AM technologies.

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ABSTRACT

Additive manufacturing (AM) is poised to bring about a revolution in the way products are designed, manufactured, and distributed to end users. This technology has gained significant academic as well as industry interest due to its ability to create complex geometries with customizable material properties. AM has also inspired the development of the maker movement by democratizing design and manufacturing. Due to the rapid proliferation of a wide variety of technologies associated with AM, there is a lack of a comprehensive set of design principles, manufacturing guidelines, and standardization of best practices. These challenges are compounded by the fact that advancements in multiple technologies (for example materials processing, topology optimization) generate a "positive feedback loop" effect in advancing AM. In order to advance research interest and investment in AM technologies, some fundamental questions and trends about the dependencies existing in these avenues need highlighting. The goal of our review paper is to organize this body of knowledge surrounding AM, and present current barriers, findings, and future trends significantly to the researchers. We also discuss fundamental attributes of AM processes, evolution of the AM industry, and the affordances enabled by the emergence of AM in a variety of areas such as geometry processing, material design, and education. We conclude our paper by pointing out future directions such as the "print-it-all" paradigm, that have the potential to re-imagine current research and spawn completely new avenues for exploration.

1. Introduction

Additive manufacturing (AM), also referred to as 3D printing, has gained popularity in media and captured the imagination of the public as well as researchers in many fields. With recent interests, this technology is continuously being redefined, reimagined and

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customized to a wide application spectrum such as automotive, aerospace, engineering, medicine, biological systems, and food supply chains. A historical analysis of AM reveals its roots lie in photo sculpture (in the 1860s) and topography (in the 1890s). These early technologies led to the "Photo-glyph recording" technique (patented in 1951) that selectively exposes layers of a transparent photo emulsion while scanning cross-sections of the object to be replicated [1]. The modern day process of Stereolithography (SLA) shares a remarkable likeness to the now obsolete "Photo-glyph recording" process, and has been enabled by the advancements in computing, lasers, and photopolymers. Therefore, it is of no surprise that techniques and patents for photo sculpture are heavily referenced in current day AM literature. Modern AM techniques have their foundations in four key patents: vat photopolymerization, powder bed fusion, material extrusion, and binder jetting [2–5]. A more detailed analysis of the major milestones in AM technologies and related NSF funded awards (over $240 million) are discussed in the report by Weber et al. [6].

The significant amount of recent interest and investment towards AM technologies does not come as a surprise, as this layer-wise additive method is an elegant concept that can build complex shapes using a wide variety of materials. The reducing cost of programmable controllers, lasers, ink jet printing and computer-aided design (CAD) software has democratized the design process, allowing individuals to utilize, tinker with, and improvise these technologies. The main market driver for such systems has been consumers and industries that rely on low–medium fidelity prototyping in the early stages of product design. Several startup companies are creating innovative and low-cost 3D printers for thermoplastics. As a result, plastics-based 3D printing has captured the imagination of the general public through platforms such as Do-It-Yourself (DIY) and the Maker Movement [7]. Although this technology cannot guarantee the part quality and scalability of current production methods, we expect this gap will reduce significantly in the near future. Supply chain and retail businesses such as Staples,[1] Shapeways[2] and Sculpteo[3] are taking advantage of the popularity of such platforms and bringing commercial printing and shipping services directly to customers. These companies are also supporting hobbyist communities by providing them with simple online 3D modelers allowing them to create or tailor designs and turn them into customized products.

From the industry perspective, AM technologies have the potential for significantly impacting traditional production models in terms of industrial machinery, assembly processes, and supply chains. For example, multi-nationals such as General Electric (GE)[4] are investing in research for commercializing metal-based AM technologies for remanufacturing. If successful, such technologies can simplify their manufacturing value chain by giving them independence from third-party suppliers, improve performance, and extend useful life of their engines. AM can also positively impact smaller corporations and end-customers by changing their roles into self-sufficient "designers and manufacturers" that can develop innovative products and production systems. The rapid proliferation of AM technologies is driven by the increase in the variety of materials, low-cost machines, and potential for new application areas. This has resulted in a lack of fundamental design guidelines or standardization of best practices. For example, the same digital input (3D model) may give rise to parts that can be different in surface finish and geometric torlerance. These effects are due to differences in manufacturing techniques (material extrusion, jetting, deposition, curing, lamination, etc.), materials (thermoplastics, photopolymers, epoxy resin, metal powder, conductive composition, etc.), and the geometric positioning/orientation of the geometries. As a result, designers' often waste building and support material due to the multiple trial-and-error iterations required for fixing unqualified feature requirements, surface resolution and clearances of mechanical parts and assemblies. The use of electronics and circuits at macro- and micro-levels, both by embedding and integrating materials and sensors, is another trend that adds functionality, but threatens to complicate the design process for AM technologies.

The dependencies of AM techniques on related technologies such as material modeling, design tools, computing, and process design represent a challenge for both applied and basic research, shown in Fig. 1. In order to advance research interests and investment in AM technologies, some fundamental questions and trends in these avenues need highlighting. The goal of this review paper is to organize this body of knowledge and present challenges in the gamut of AM technologies. We believe that these technologies are at a critical stage as advancements in science and engineering are generating a "positive feedback loop" effect with regards to AM. For example, advancements in related technologies (such as a new material, or a novel topology optimization technique) can significantly affect or sometimes give rise to novel AM techniques. Similarly, advancements in AM techniques can directly affect applied and basic research providing new affordances that cannot be delivered by any other manufacturing technique. Therefore, we feel it is necessary to explore these dependencies and present significant findings to researchers who are driving these areas of interrelated research. Many roadmaps and reports have been carried out recently, including NIST roadmap [8], America Makes roadmap [9–12], CSC report [13], Wohlers reports [14–16], etc., to provide industry and business perspectives on AM technologies. In comparison to these efforts, our review paper focuses on presenting the current barriers, findings and future trends for the research community, and integrating techniques in AM-related domains towards the goal of enabling future research. These research areas span design, materials, machines, and associated technologies that all influence computer-aided design methodologies that support as well as create affordances for changing the future capabilities and expectations. This paper starts by describing fundamental attributes of AM processes in Section 2. We also present a comparative overview of AM technologies, illustrative cases, and challenges/barriers to be overcome. In Section 3, we discuss the evolution of processes and building capabilities of AM technologies with a focus on engineering capabilities for polymers, metal and ceramic powders. Next, in Section 4, we review the affordances enabled by the emergence of AM in a variety of areas such as geometry exploration and optimization, material and mechanics exploration during design, and the development of computational and fabrication tools. Section 5 summarizes developments in the industry, relevant intellectual property, and education-related perspectives of AM technologies. We conclude our discussions by outlining important future trends in Section 6.

2. The fundamentals of additive manufacturing

The fundamental attributes of Additive Manufacturing technologies are presented in this section. Additional information on AM processes can be found in prior overviews [17–20]. AM processes fabricate parts by creating successive cross-sectional layers of an object. The process begins with a three-dimensional solid model, which is initially modeled or scanned as a digital CAD file,

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[1] http://www.staples.com/.

[2] http://www.shapeways.com/.

[3] http://www.sculpteo.com/.

[4] http://www.ge.com/.

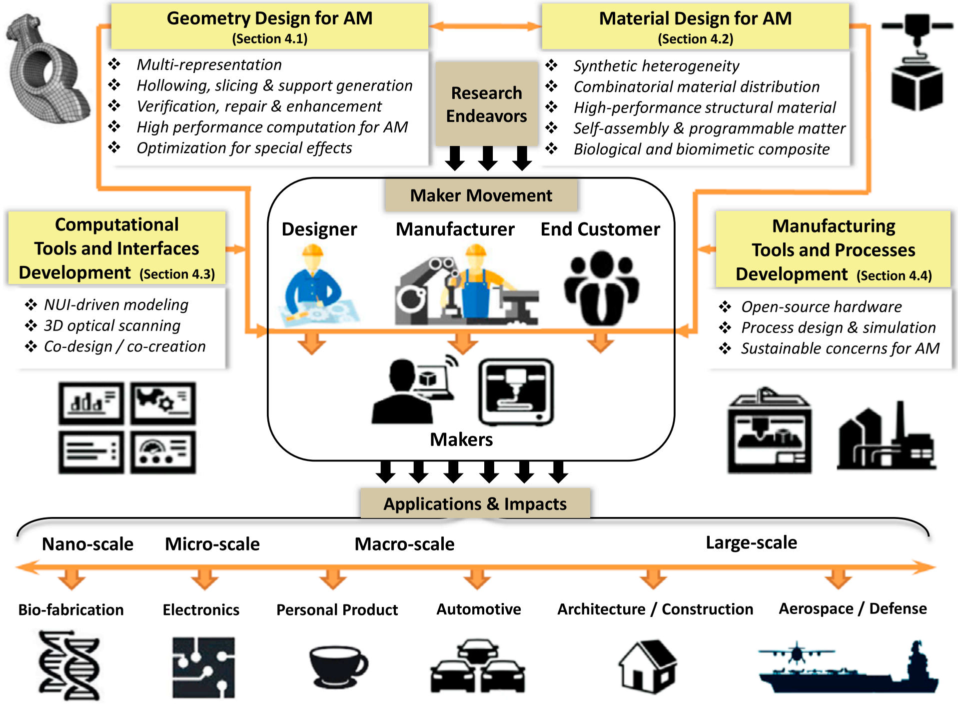

Fig. 1. A geometry-material-machine-process roadmap for AM and Maker Movement.

and then sliced into thousands of layers (depending on the resolution) by preparation software. Each layer is created via the selective deposition of material (and/or energy to fuse the raw material) to form a printed primitive. Research on non-layer based AM processes and its tool path planning may further extend the capabilities of AM technology in the future [21,22].

2.1. A comparative overview of AM

Distinguishing features of AM technologies are often presented in the context of a comparison with conventional manufacturing processes. The term "additive manufacturing" was ultimately chosen by the ASTM F42 committee as it clearly distinguishes the processes from subtractive manufacturing techniques wherein material is removed from a workpiece (e.g., cutting, milling, grinding) [23]. The unique capabilities of AM technologies are noted below:

Design flexibility. The distinguishing feature of AM processes is their layer-wise fabrication approach, which enables the creation of almost any complex geometric shape. This is in contrast to subtractive processes, which constrain design freedom due to the need for fixtures, diverse tooling, and the possibility of collisions and difficulty of the cutter in reaching deeper and invisible zones when fabricating complex geometries [24]. Other traditional manufacturing processes, including formative techniques (e.g., pressing, casting, forming), impose additional design constraints to those inherited by the subtractive techniques used to fabricate the required tools and patterns. Fundamentally, AM technologies impose only a few constraints and thus provide a designer the ability to selectively place (multi-)material precisely where it is needed to achieve the designed functionality. This capability, coupled with the digital thread of production, enables the realization of structures that have been topologically optimized (or feature cellular mesostructured) to reduce material use and decrease mass.

Cost of geometric complexity. Current AM technologies provide the most freedom to a designer in the realization of complex geometric shapes. When employing AM, this complexity comes at no additional cost, as there is no need for additional tooling, re-fixturing, increased operator expertise, or even fabrication time. While complexity can be achieved in traditional manufacturing processes such as injection molding (especially if it is justified via the profits found in a large production quantity), there is a direct relation between geometric complexity and the mold cost.

Dimensional accuracy. The dimensional accuracy (print tolerance) determines the derivation of the finished model when compared to the original digital model. In the traditional manufacturing system, general and specific dimensional tolerances and machining allowances based on the ISO and US standards are necessitated for quality assurance. Most AM machines are used to build parts that measure several centimeters or more across and have tolerance capabilities that are tighter than several hundredths of a millimeter. The distinction between accuracy and resolution did not matter much in the early AM development mainly for prototype making. However with current expectations of AM technologies growing into delivering finished parts, there is an increased need for establishing industrial dimensional accuracy standards for AM, such as the tentative tolerance benchmark [25] proposed by Todd.

Need for assemblage. AM processes enable the production of geometric shapes that would otherwise require assembly of multiple parts if produced conventionally. In addition, it is possible to use AM to produce "single-part assemblies" products that feature integrated mechanisms. The parts and joints are printed in place and are suspended by support material (or unbound/sintered powder) that must be removed in post-processing (and can result in some geometric inaccuracies).

Time and cost efficiency in production run. Some conventional processes such as injection molding are very time and cost efficient for mass production, regardless of high start-up cost [26]. While AM processes are significantly slower than injection molding for fabricating components, they are better suited for low part quantities as there is no startup tooling required for production [27]. Furthermore, on-demand and on-location AM production can lower inventory costs and potentially reduce costs associated with supply chain and delivery. In general, there is very little wasted material when fabricating components via AM. While some material scrap is incurred due to support structures and powder recycling in powder bed fusion technologies, the "buy-to-fly" ratio (the ratio of the amount of material purchased to the amount of material found in the final component) is very low for AM processes [28]. The combination of improved designs and reduction of supply chain and delivery overheads can prove to be an economic "tour de force" for application of AM technologies in a wide variety of applications.

2.2. Concurrent barriers and challenges of AM

Personal fabrication vs. mass manufacturing. Current embodiments of AM technologies are suitable for fabrication of products that feature customized features, low-volume production, and/or increased geometric complexity. Typical markets that currently employ AM to fabricate end-use products include aerospace, high-end automotive, and bio-medical. AM technologies are also used to satisfy individual needs, such as collectables, jewelry, and home accessories. Typically, the cost for achieving economies of scale via batch fabrication of standardized part geometry using AM is significantly larger than via injection molding techniques due to the discrepancy in cycle time. However, there are scenarios wherein the slower cycle time is outweighed by the opportunity to consolidate parts, reduce material waste, and/or there is market demand for customized geometry. Align Technology's Invisalign custom orthodontics,[5] Ownphones custom earphones,[6] and GEs fuel nozzle[7] are emerging examples of using AM to achieve cost-effective large-volume production of products.

Building scalability vs. layer resolution. There exists an inherent tradeoff within AM between the layer resolution and the overall scale of printed parts. While a higher layer resolution (i.e., smaller layer thickness) provides a better surface finish, it greatly increases the total build time as more layers are needed to create the desired geometry. For this reason (and for reasons related to fundamental physical process) layer resolution and part scale for commercially-available AM systems is typically ∼0.1 mm and ∼25 mm, respectively. Researchers have explored AM systems capable of working along the entire spectrum of build sizes, from nanofabrication [29] and micro-sculpting [30], to large-scale contour crafting [31], architectural construction [32] and electron-beam welding [33]. While the large-scale systems use large layer thicknesses (and thus have high build speeds), surface quality can be assured by process planning [34], hybrid AM processes [35], and/or post-processing by subtractive machining or sanding.

Material heterogeneity and structural reliability. While consumer goods are comprised of a wide variety of materials that render different behaviors and functionalities, the material selection of AM systems is quite limited. Products resulting from state-of-the-art AM systems suffer from anisotropic mechanical properties due to interlayer bonding deficiencies [36]. Additionally, a large majority of AM systems process only a single material at a time. While multi-material AM systems that enable functionally-graded materials are emerging in both polymer [37] and metal [38] contexts, the adoption of these systems is limited due to uncertain behavior at the material interfaces [39] and a lack of design software support. More specifically, existing commercially-available software packages do not enable a designer to easily model or analyze multiple material geometries and their accompanying anisotropy.

AM standardization and intellectual property. To ensure part quality, repeatability, and consistency across builds and machines, it is imperative that AM industries develop material, process, calibration, testing and file format standards. The recent F2924-12 Standard Specification for Additive Manufacturing Ti-6Al-4V initiated the first AM material standards approved by the ASTM International. The sheer variety in machines, materials and processes makes the development of a uniform standard for AM a challenging task. Another aspect that competes against the need for standardization is the financial interest of machine manufacturers (similar to the document printing industry) in providing custom consumables and spares. Both the industry and research institutions have a long road ahead before a consensual set of standards are realized in this domain. From an intellectual property standpoint, the emergence of 3D printing marketplaces and downloadable open-source projects, have challenged the current legal landscape and social regulations that safeguard inventors against infringement. We can expect that the emergence of AM is likely to cause a fundamental shift in the way design patents are filed and protected. To protect intellectual property of the CAD models, researchers have put their efforts in generating encryption via embedding certain 3D information into spectrum domain [40] and internal structures being only visible under terahertz waves [41].

2.3. Printing attributes of AM processes

In this section, we review attributes of printing a 3D object that are significant considerations for selecting an appropriate AM technology and a corresponding build layout. The attributes that we list along with factors such as machine selection, processes and materials, orientation and position of the geometry, and finishing can alter the resulting quality of the printed part.

Build time. Generally speaking, the build time for an individual model or an assembly depends on printer's printing speed, part size, layer thickness and build orientation. Regardless of the printing processes, in general, the larger the object's height in the lay-up direction, the longer it takes to print. Therefore, given the print speed and object size, in order to reduce the build time, it is necessary to make the overall built height low.

Feature resolution. Feature resolution on AM systems is primarily dependent on the energy/material patterning principle. Extrusion AM requires a relatively large deposition head (∼0.4 mm) in order to effectively process the viscous melt polymer. This, coupled with the inability to effectively start/stop thermoplastic extrusion, limits the possible feature size. Alternatively, vat photopolymerization and powder bed fusion AM processes are able to process much finer features due to the ability to precisely focus an energy beam. The resolution of both material jetting and binder jetting AM processes is dictated by the inkjet print heads' dots-per-inch (DPI). For example, current material jetting machines offer a 600 dpi XY resolution. While binder jetting AM systems have high-resolution jetting heads, their resolution is limited by the coarse powder particles in the process. The achievable feature resolution is inherently constrained by the fact that these (and other powder-based) systems require particles that are larger than 20 μm so that the powder can be successfully spread during the recoating step [42].

Surface quality. In general, the quality of a printed part's surface is mainly determined by the thickness of each printed layer. Similar to conducting an integral, a larger layer thickness results in a poorly approximated curvature of the part. This build error, also called as the "stair-stepping" effect, is dependent on the underlying deposition technology. Extrusion AM systems typically have the largest layer thickness (∼0.2 mm) due to the large diameter of the deposition nozzle. Alternatively, powder bed fusion and vat photopolymerization AM technologies systems have much smaller layer thicknesses (∼0.1 mm), and thus smoother

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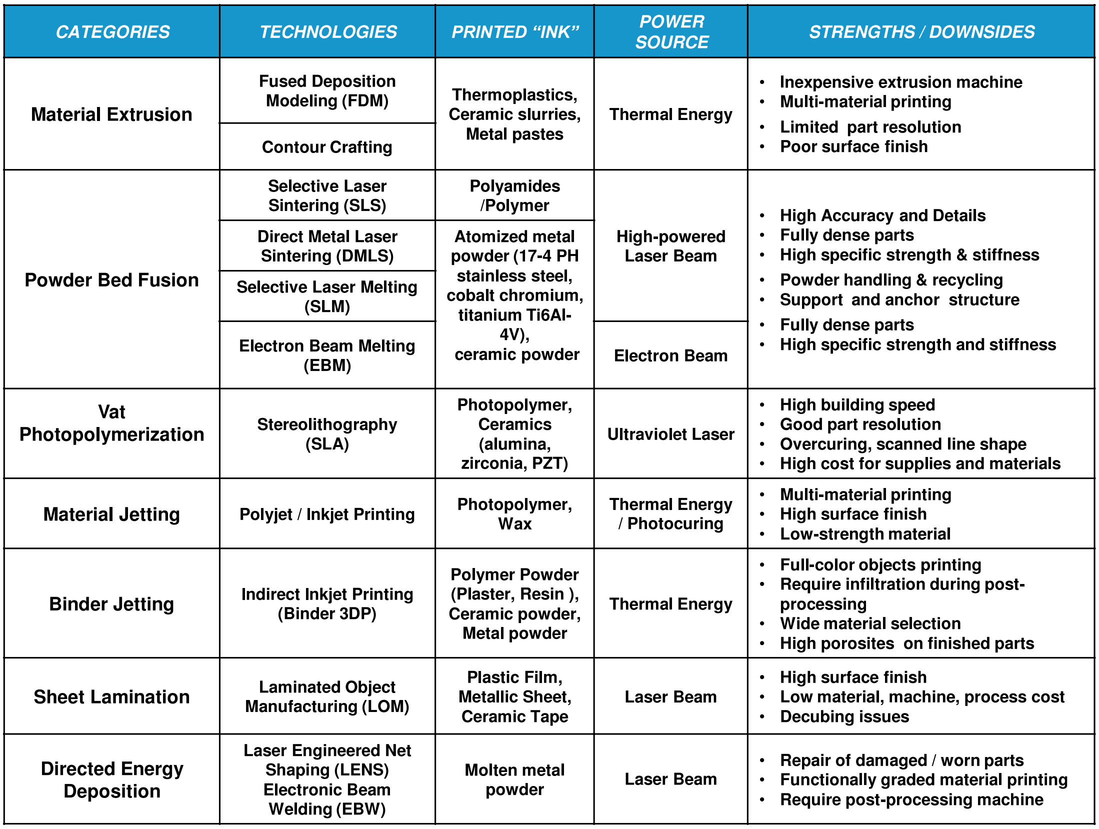
[5] http://www.aligntech.com/.

[6] http://ownphones.com/.

[7] http://www.ge.com/stories/advanced-manufacturing/.



CATEGORIES	TECHNOLOGIES	PRINTED "INK"	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	• High Accuracy and Details • Fully dense parts • High specific strength & stiffness • Powder handling & recycling • Support and anchor structure • Fully dense parts • High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)			
	Electron Beam Melting (EBM)		Electron Beam	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	• High building speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	• Multi-material printing • High surface finish • Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosites on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	• High surface finish • Low material, machine, process cost • Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	• Repair of damaged / worn parts • Functionally graded material printing • Require post-processing machine

Fig. 2. Classification of additive manufacturing processes by ASTM International [23].

surfaces, due to the ability to precisely focus the energy beam radius. Material jetting systems also offer a fine layer thickness (as low as ∼0.02 mm) due to the small jetted droplets. Surface quality is also dependent on the form of the raw material; powder bed AM processes have poorer surface quality than others due to large and partially melted powder particles that reside on the printed part's surface.

Anchor and support material. In order to create complex geometries such as overhangs, undercuts, and printed part assemblies with moving components, all AM systems must provide some means of supporting the printed features of subsequent layers. This is typically done by printing fine scaffold structures from the build material (e.g., vat photopolymerization and single-nozzle extrusion AM systems), or via the selective deposition of a secondary, sacrificial (i.e., soluble or pyrolizable) support material (e.g., multi-nozzle extrusion and material jetting AM systems). In all binder jetting and polymer powder bed fusion AM systems, the unsintered/printed powder material itself provides support for overhanging features; no support is needed. This excess powder is removed during post-processing using a combination of compressed air and vacuum. However, in metal-based powder-bed fusion AM processes, note that secondary structures are still needed to anchor the printed part to the build tray and/or to dissipate heat into building platform and unsintered powder. Without these anchors, the printed metal parts would warp and curl during printing due to the residual stresses created from the rapid cooling of the small melt pool [43].

Post-processing. Printed objects with built-in support material require post-processing operations that separate them. The methods and ease of removal vary by printing methods and build materials. If the support material is water-soluble, it can be washed away by a lye bath with gentle scrubbing. Non-soluble support materials require breaking and peeling away from the model using pliers or conventional cutting tools. In order to further ensure a smooth surface finish, printed parts often need to be polished using sanding or vapor smoothing.

3. A review of additive manufacturing processes

In the early 1990s, Kruth [44] categorized various additive manufacturing processes from three perspectives: liquid-based, powder-based and solid-based systems according to different material creation; and direct-3D and 2D-layers techniques according to different shape building. A whole family tree and AM process classification, including research and commercial methods, were presented by Helsinki University of Technology [45] and in the German production process standard (DIN8580) and (DIN8581). A functional classification schema of AM systems has also been presented by Williams [46]. Most recently, ASTM International has classified AM technologies into seven categories: (1) material extrusion, (2) powder bed fusion, (3) vat photopolymerization, (4) material jetting, (5) binder jetting, (6) sheet lamination, and (7) directed energy deposition [23]. In this section, these technologies are presented via an overview of technology evolutions and research reviews over the last two decades for commercially available AM systems (see Fig. 2). We specifically focus on AM of plastic polymers, metal materials and ceramic materials. Many other printable materials used in AM systems including fibers, sand, plasters, glass, wood filament and other bio-materials are beyond our focus and therefore are not reviewed in this paper.

3.1. *Additive manufacture using engineering materials*

3.1.1. *Material extrusion*

In 1988, Scott Crump, the co-founder of Stratasys, Ltd.,[8] developed an AM process that created layers by mechanically

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[8] http://www.stratasys.com/.

extruding molten thermoplastic material (e.g., ABS or PLA) onto a substrate. The method, trademarked as Fused Deposition Modeling (FDM), requires high operating temperatures, and the finished prints typically exhibit high porosities [47,48]. However, the inexpensive and flexible extrusion systems are gaining popularity among the DIY crowds. While the majority of extrusion systems process thermoplastic materials, efforts have been made in processing ceramic [49–52] and metal pastes.

3.1.2. Powder bed fusion

In general, powder bed fusion techniques use an energy beam (e.g. laser or electron beam) to selectively melt a powder bed. Once a layer is scanned, the next layer of powder is spread via a rolling mechanism. The subsequent layer is scanned, and is fused to the previous layer. Polymer powder bed fusion, which was initially developed by Deckard and Beaman [53] in the mid-1980s, typically process polyamides and polymer composites. The process can also be used to indirectly create ceramic [54] and metal [55] melting polymer blends; the resulting parts require high-temperature post-processing to fully sinter the structural powder. Direct metal laser sintering (DMLS), selective laser melting (SLM) and electron beam melting (EBM) are the most popular metal powder bed fusion techniques. They were developed in 1995 and made commercially available since 2005 by EOS GmbH (Germany) and Arcam AB (Sweden), respectively. These processes initially create a powder bed via rolling or raking the powder fed from cassettes onto the built table. Through heating and melting the successive pre-alloyed, atomized powders such as 17-4 PH stainless steel, cobalt chromium and titanium Ti6Al-4V, DMLS and SLM utilize a focused laser beam [56–60] while EBM using a scanned electron beam (up to 60 kV voltage) [61]. The actual building process is done in a vacuum or inert environment in order to avoid metal oxidation. DMLS and EBM parts are fully dense with high specific strength and stiffness.

3.1.3. Vat photopolymerization

In 1984, Charles Hull of 3D system Corp.[9] developed the first commercial AM system using stereolithography method (SLA), where ultraviolet laser was used to selectively polymerize the UV curable resins to create a layer of solidified material [62,63]. Layers are subsequently cured until the part is complete. The building speed using SLA is relatively high (1–3 cm per hour) and minimum layer thickness is dependent on the curing depth [64]. The downsides of this method are the process errors due to overcuring, scanned line shape, and the high costs for the necessary supplies and materials [65]. Due to its reliance on photopolymerization, this technology is inherently limited to photopolymers. By suspending nanoparticles in the resin, some researchers have been able to process ceramic components (e.g., alumina, zirconia, PZT) with this technique [66–71].

3.1.4. Material jetting

Similar to the ink-jet printing technology that transfers ink droplets from the fluid channel onto the paper substrate in a drop-by-drop manner, material jetting AM processes directly deposit wax and/or photopolymer droplets onto a substrate via drop-on-demand inkjetting [72–74]. Phase change of the jetted droplets occurs via heating or photocuring. Researchers have attempted direct inkjetting of nanoink suspensions of ceramics [75–79], metals [80], and semiconductors [81] in order to create final parts with added functionality. However, due to viscosity limitations of processing fluids via inkjetting, the suspensions have a relatively low concentration of solid particles.

3.1.5. Binder jetting

In binder jetting, a liquid polymer is selectively deposited onto a bed of powder. The jetted polymer droplet infiltrates the powder surface, resulting in a printed powder agglomerate primitive. Recoating occurs via powder spreading, as is done in powder bed fusion techniques. Printed parts are composed of bound powder, and thus require infiltration during post-processing in order to have sufficient strength. This method was first studied in MIT and commercialized by Z Corporation and ExOne. Any powdered material that can be successfully spread and wet by the jetted binder can be processed by this technology. Researchers have used this technology to process a variety of metal [82,83], ceramic [84,85], foundry sand [86], and polymer materials [87–91].

3.1.6. Sheet lamination

Helisys Inc. (now Cubic Technologies[10]) developed AM systems using laminated object manufacturing (LOM) in 1986 and this process was patented in 1987. The advantages of LOM include low internal tension and fragility of the parts, high surface finish details, and lower material, machine and process costs [92]. A variety of research work has been looked at lamination [93–95], decubing [96,97] and waste removal [98] processes. The sheet lamination AM process has also been employed to create metal parts by cutting, stacking, and gluing profiled metallic laminates. In 1999, Himmer et al. [99] first presented the rapid laminated tooling for sheet metal manufacture. Extensive research efforts have been made to minimize the stair-step effect [100] and to improve the laminate bonding [101–103] in the processes. Ultrasonic Consolidation, which features the ultrasonic welding of metal sheets, has also been used to produce functionally graded metallic structures [104–106].

3.1.7. Directed energy deposition

In directed energy deposition (DED) AM processes, metallic powder or wire is fed directly into the focal point of an energy beam to create a molten pool. Using a multi-axis motion stage, the processes are essentially three-dimensional welding machines [107–109]. Laser Engineered Net Shaping (LENS) was developed in 1995 at Sandia National Laboratories and is being commercialized by Optomec.[11] Parts fabricated by LENS accommodate graded multi-materials [110] and allow microstructures with complex internal features [111,112]. Wire-fed DED systems have also been realized [113,114]. Lasers and electron beams are the commonly used directed energy source. Directed energy deposition can achieve up to 99.9% theoretical density of the material. Due to the local melting and rapid cooling, the resultant microstructure consists of well-refined grains and parts built by this process usually exhibit 30% higher strength than those built by casting. This process is uniquely applicable to the repair of parts [115] as the damaged portion of a part can be re-stored selectively. Another advantage of these processes is its ability to add coatings (or clad) to existing surfaces [116–120]. This can be used to improve the tribological performance of any engineering products. Its capability of in-situ synthesis of novel materials by mixing various elemental powders is unique to these processes [121].

3.2. Building capabilities of AM

AM technologies' ability to selectively place (multi) materials in space affords unique design opportunities and capabilities that

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[9] http://www.3dsystems.com/.

[10] http://www.cubictechnologies.com/.

[11] http://www.optomec.com/.

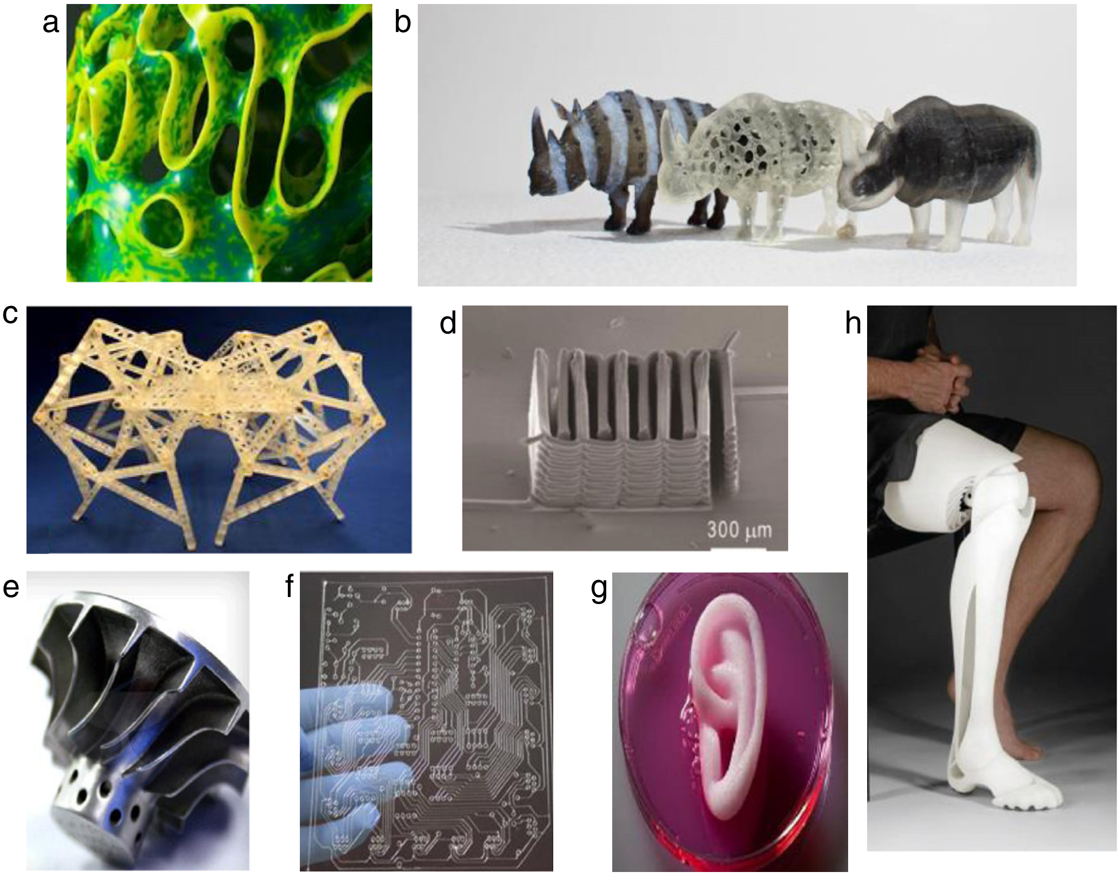

Fig. 3. Examples of objects that can be printed using AM. (a) Pulmonary Series, artistic shapes inspired by nature [122] (image courtesy of Neri Oxman), (b) three rhinos, printed using OpenFab, demonstrating voxelizable objects with gradient material [123] (image courtesy of Kiril Vidimce), (c) Theo Jansen locomotive mechanism [124], (d) 3-D printable lithium-ion rechargeable battery [125] (image courtesy of Jennifer Lewis), (e) metallic turbine printed using DMLS [126] (image courtesy of Solid Concepts), (f) PCB fabricated using liquid metal printer [127] (image courtesy of Yi Zheng), (g) artificial printed ear [128] (image courtesy of Wake Forest Regenerative Institute), (h) printed prosthetic limb [129] (image courtesy of Bespoke Innovations). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are not possible using any other manufacturing processes. From integrating multiple materials to creating functional assemblies and parts with integrated circuits and sensors, AM allows for the realization of multi-functional products. Given this capability, one of the challenges lies in creating software environments capable of enabling a user to efficiently model such complexity.

Multi-material printing. Multi-material AM processes (e.g., LENS, ultrasonic consolidation, vat photopoymerization, material jetting) enable the creation of parts with functionally graded materials. With these techniques, a designer can specify material properties such as hardness, flexibility, adhesive properties, stiffness and color on a voxel-by-voxel basis. Multi-material printing has been used for realizing artistic sculptures (Figs. 3(a) [122] and 3(b) [123]) and multi-component assemblies featuring compliant joints [130].

Printed assemblies. Printing pre-assembled machines and mechanisms requires that the parts are printed with sacrificial support material. The assembly is designed with gaps of a few hundredths of a millimeter between parts such that kinematic components can cooperate with each other to yield certain determinate motion. The parts are printed and then the support is removed leaving a captive assembled linkage. Physical working models [131–135], complaint mechanisms [136,137], articulated models [138,139], locomotive robots [140,141] and prosthetics [142–146], including a variety of pre-assembled and fully-functional kinematics components such as links, joints, tighteners and flexure units, have been receiving extensive reproductions using AM techniques due to its assembly-free and time efficient features. Fig. 3(c) shows the Theo Jansen mechanism printed in a single build. Motion and force issues like friction, hysteresis, compliance, geometric tolerances, and dynamics are still the critical research topics when using additive manufacturing for printing kinematic systems.

Embedding foreign components. A fundamental advantage of the layer-by-layer fabrication approach found in AM technologies is the ability to access the entire volume of the workpiece throughout the build process [147]. By pausing the build, one can embed foreign objects into a priori designed voids, which are then fully encapsulated into the part once printing is resumed. With this capability, AM affords the unique opportunity to embed components such as circuits, sensors and other functional components (e.g. motors, threaded rods, etc.) into a part as it is being fabricated. This allows for the direct fabrication of functional assemblies and mechanisms within the AM machine without the need for a secondary assembly step. This embedding capability provides an opportunity for the realization of such applications as actuated robotic limbs, smart structures with embedded sensors, and energy harvesting devices with embedded piezoelectric materials. Embedding has been demonstrated for shape deposition manufacturing [148,149], stereolithography [150,151], CNC accumulation [152], ultrasonic consolidation [153], material jetting [154], and extrusion [155] AM processes.

Printing circuits, sensors, and batteries. Leveraging the ability to embed components into printed parts, many researchers have explored combining AM and Direct Write (DW) technologies.

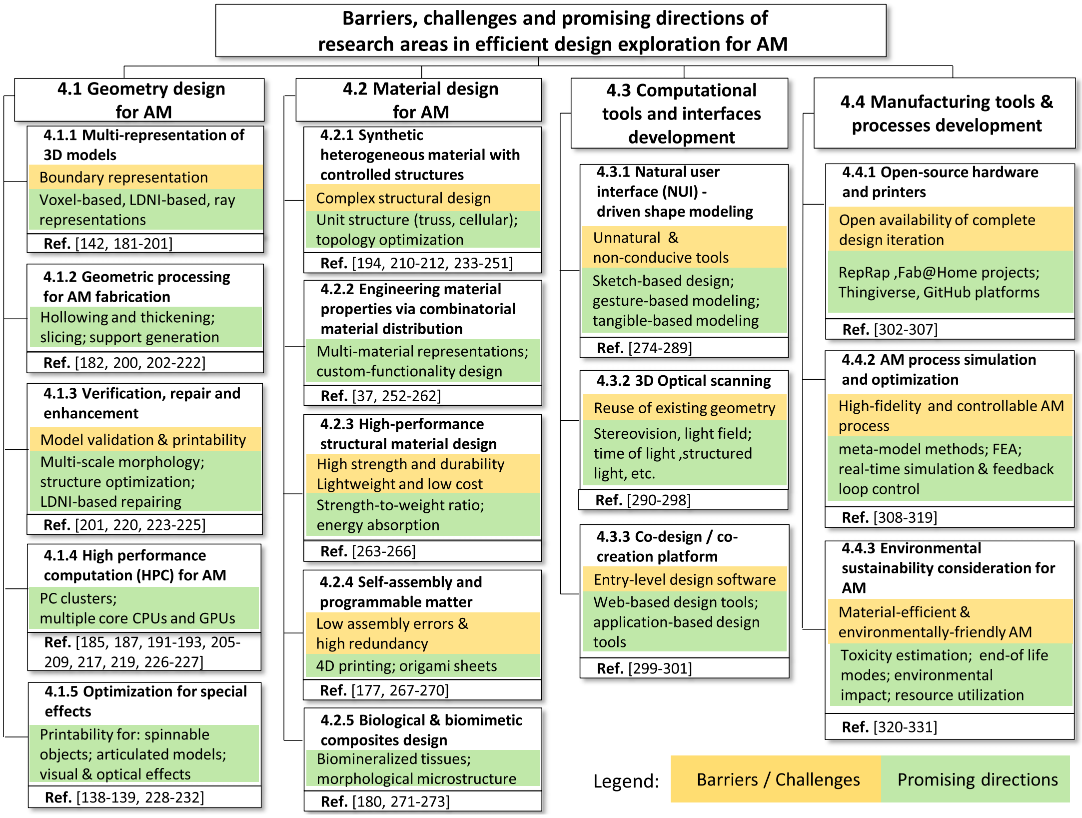

Fig. 4. The barriers, challenges and promising directions of 4 research areas: design of (1) geometry, (2) material, development of (3) computational tools and (4) manufacturing processes in efficient design exploration for AM.

DW technologies enable the selective deposition and patterning of material, and have been used to pattern conductive material onto a variety of printed substrates [156,157]. DW technologies include extrusion [158], ink jetting, aerosol jetting, laser-based systems, and tip deposition [159]. DW processes have been successfully hybridized into ultrasonic consolidation [160], stereolithography [161,162], extrusion [163,164], and polymer powder bed fusion [165] AM processes [166,167]. When combined with AM, DW enables the creation of complex and conformal electronics that are structurally integrated into a finished part. When integrated into an AM process flow, DW can be leveraged to manufacture electronic signal routing, embedded sensors, and integrated power systems in additively manufactured structures. Specific applications include signal routing [160], 3D antennae [168], conformal electronics [169], discrete electronics [170], strain gauge sensors [171], force sensors [172], magnetic sensors [173], and batteries [174,125,175,176]. While embedding of a diverse collection of foreign elements, circuits, and sensors has been demonstrated for multiple AM processes, there remains significant need for computer-aided design software that is able to support the modeling and analysis of these heterogeneous assemblies and their multi-functionality.

4. Rethinking efficient design exploration for AM

The growing opportunities of additive manufacturing arise by exploring new design concepts that would have not been considered due to the limitations of traditional "subtractive" manufacturing processes such as turning, milling and cutting. In some respect, much of machine design elements and structural design occurs based on known manufacturing and shaping processes, and their constraints. This is also true for courses in universities for machine design, kinematics and structures that are based on ways of design thinking that emerged during traditional manufacturing. But AM is now pushing the frontier of new breeds of design approaches and tools. The new areas that are open for such explorations include topologies and geometries that take advantage of AM. For example envisioning new types of mechanisms, materials and structures with multi-scale and multi-resolution, for programmable matters [177], cellular materials [178], deployable structures [179], and biomimetic materials [180]. In this section, we will review how AM enables the creation and control of novel geometry, material, computational and fabrication tools designs that were not possible (or difficult) to obtain with existing technology (see Fig. 4).

4.1. Geometry design for AM

4.1.1. Multi-representation of 3D models

Most of commercial CAD/CAM systems are developed based on the solid modeling kernel using boundary representation (B-rep). One challenge on the B-rep based solid modeling kernel for AM is the problem of numerical robustness [181] specifically, how to compute the intersection between models (or between a model and a slicing plane) by using approximate arithmetic in a reliable way. Currently, main stream AM products still adopt the STL file format to represent models, where the STL file of a model stores the set of triangles representing a water-tight triangular mesh for the boundary of the model. Problems can be caused by the numerical error generated during the computation (e.g., the cracks reported in [182]).

In recent years, many approaches have been proposed using volumetric representation to approximate the operations of solid modeling. The simplest volumetric representation of solid models

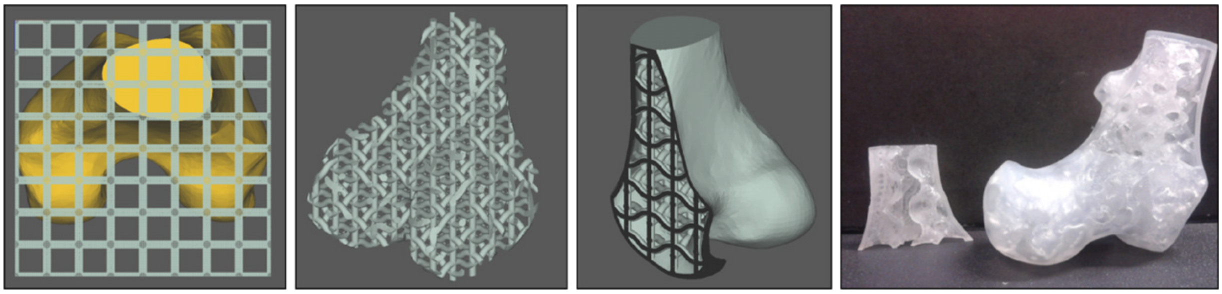

Fig. 5. Models with complex structure can be efficiently and effectively processed by LDNI-based solid modeling kernels [188–190] with the help of high-parallel computation on GPUs.

is voxel-based [183]. As the voxel-representation of a solid model can be directly obtained from volumetric images of CT or MRI, and thereby widely used in medical applications using AM [142]. A major problem of voxel-based representation is its huge memory consumption. Some research approaches only generate such discrete representation in a local computation (e.g., in the current plane under fabrication in [184]). However, the problem still cannot be solved when some operations like offsetting/hollowing are performed. The ray-rep in the solid modeling literature [185–187] is an alternative of voxel-based representation with a better memory-efficiency. The solid models in ray-rep are represented by a set of parallel 1D-solids in a specified direction, allowing only the entering/exiting points to be stored. Recently, a variation of ray-rep (called Layered Depth-Normal Images (LDNI)) [188–190], shown in Fig. 5, was proposed to represent models for AM. LDNI-based representation is robust in high-parallel computation based on GPUs [190] and support multi-materials in a discrete manner [191]. Moreover, LDNI can be compactly stored, thus models with complex topology can be processed on consumer level GPUs [192–194]. There are other approaches that employ the distance-field [195,196] for designing continuous heterogeneous objects realized by AM. However, adaptive sampling strategies [197] are required to overcome the aliasing problem due to the large shape approximation error at regions with large curvature. To support computational material design in AM, a multi-scale representation based on implicit function is proposed in [198,199]. Besides, research work in [200] employs the point-sampled geometry (e.g., moving least-square (MLS) surfaces) to represent the boundary of a scanned model and directly fabricate it using AM.

The input 3D models prepared for additive manufacturing are usually represented by polygonal meshes, such as STL and OBJ file formats. These polygonal models are supposed to be water-tight and manifold [201]. However, those with unstructured triangulated surface have issues such as degenerated triangles, self-intersections, gaps and cracks. On account of the layer-upon-layer printing process in AM, self-intersection and non-manifold models often make the slicing algorithm instable and even fail the fabrication. Nevertheless, it is difficult for users to prevent and resolve the aforementioned problems in the early design stage using CAD software. It thereby becomes essential to apply geometry regularization process onto the 3D polygonal models before printing. There have been research endeavors striving to solve the issues using proposed methods. Chen and Wang [201] proposed a geometry regularization approach which adopts a layered depth normal image (LDNI) representation. Based on LDNI representation, the 3D models can be repaired robustly and efficiently. Huang et al. [182] presented a robust slicing approach based on implicit sold. Their method extracts the contours in a binary image domain, and guarantees no self-intersection.

4.1.2. Geometric processing for AM fabrication

Several geometric operations are universal for the AM processes including hollowing, thickening, slicing and support generation:

Hollowing and thickening. To save the time during fabrication and/or reduce the weight (as well as the material usage), 3D models are usually hollowed before slicing [202]. To improve the efficiency and the robustness of offset computation, dexels are used as the intermediate representation for hollowing [203]. The methods presented in [204,205] first generate a self-intersection B-rep by offsetting vertices, edges and faces, and accordingly self-intersected surfaces are trimmed off. To enhance the robustness of computation, LDNI-based representation [205,206], signed distance-field [207] and CSRBFs [208] are adopted to compute the intersection-free offsetting. Besides of hollowing a solid model, a thickening operation was recently introduced in [209] to convert an open surface model into a shell model with user-specified thickness for AM. Besides, many methodologies [210,211,194,212,213] have been proposed recently to address infill and conformal lattice generation issue in modeling.

Slicing. Given a model ready for AM, a significant preprocess is to convert the model into data used to guide the operation of AM machines. A widely used method is to slice the model into a set of parallel planar shapes [214]. The process of AM in this manner is called layered manufacturing. Some approaches [215,216] conduct sophisticated adaptive slicing strategy to generate layers with different thickness according to the variation of curvature. These methods could result in misclassification of inside/outside regions caused by self-intersecting contours. A different method using a reliable contouring in image space is proposed in [182] to fabricate topologically faithful objects.

Support generation. Support structures are usually generated during printing to support overhangs and large flat walls, retain parts stability, and prevent excessive shrinkage. Different AM processes produce supports in different ways. In FDM, the supports are generated mainly through computing the area difference between neighboring layers [218]. SLA method adds the support structure by identifying the overhanging regions and linking the anchor points with bars [200]. Huang et al. [217] presented the method of support generation in the image space (see Fig. 6) for both FDM and SLA. GPU-based implementation has also been developed along with LDNI representation. Recently, Vanek et al. [219] proposed a shape and topology optimization approach which can generate much less support structures meanwhile successfully supporting overhanging shapes. Finite-element analysis (FEA) based methods have been used to optimize supports and internal structures of a model during AM (e.g., [220,221,213,222]).

4.1.3. Verification, repair and enhancement

In recent literature, efforts have been made to verify the manufacturability of a given model in AM. For example in [223], the

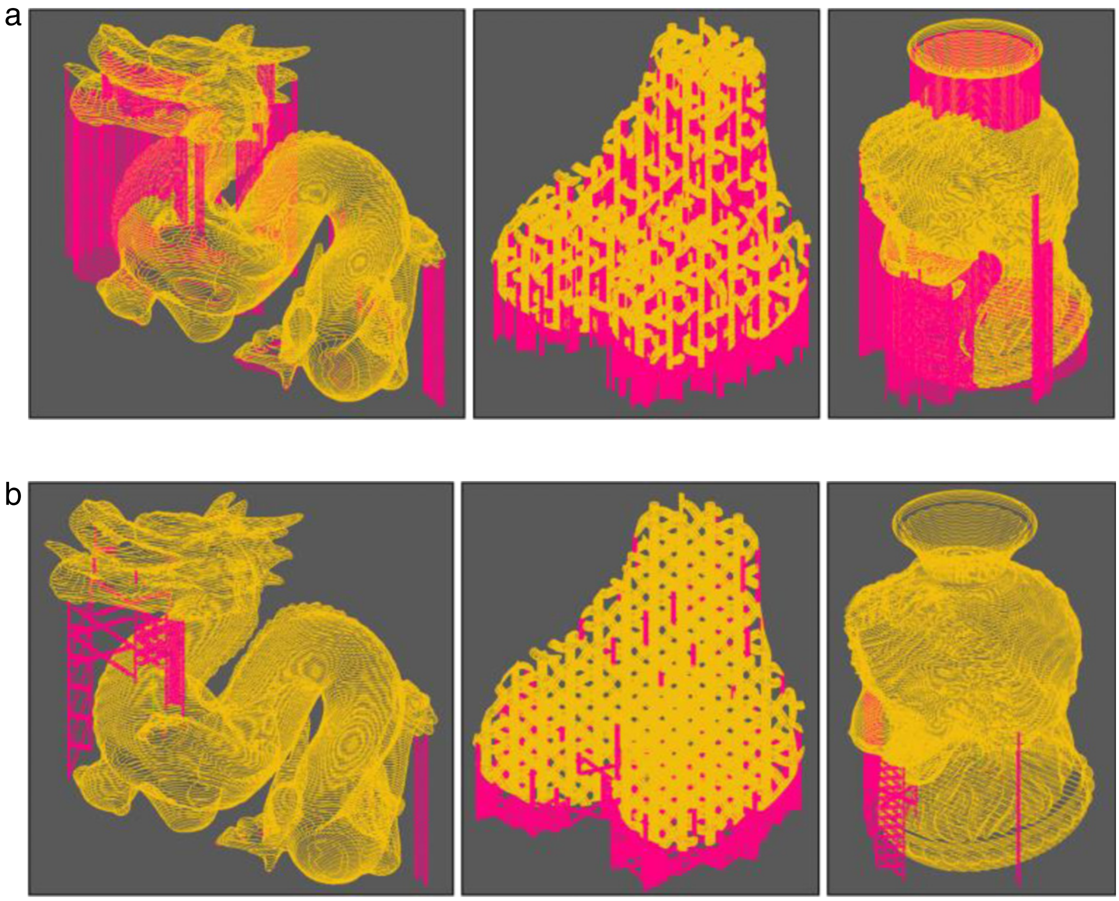

Fig. 6. Support generation in image space [217]: (a) supports for FDM and (b) supports for SLA.

printability of a 3D model is analyzed using tools from multi-scale morphology and geodesic analysis. Apart from manufacturability, the strength of a model can also be verified and corrected in a simulation system [220]. In [224], the stiffness of a printed model is optimized by applying the hollowing and structure optimization approach. Their approach results in a hollowed model enhanced with truss-network structures. Recently, a more challenging problem required to be solved is to apply the inverse elastic shape optimization for compensating the unwanted deformation [225]. On the other hand, many models prepared for AM have the validation problem of non-watertight, multiple overlaps and self-intersections. Chen and Wang [201] proposed the LDNI representation to repair models with such problems.

4.1.4. *High performance computation (HPC) for AM*

Bulk of research efforts have been made to improve the modeling efficiency for high degree of geometric complexity. HPC techniques including PC clusters, multiple core CPUs and GPUs were introduced to speed up solid modeling, slicing and support generation.

As aforementioned, solid modeling including Boolean and offsetting operations represented by LDNI can be accelerated by PC clusters [188,205], multiple core CPUs [190], and highly-parallel GPUs [190,192,206]. GPU-based hardware acceleration was also studied in sampling procedures for LDNI/LDI [193]. Other parallel offsetting methods were proposed and performed on multiple core CPUs with signed distance field [207], triangular mesh representation [209], and GPUs [226] with voxel representation. Wang [191] proposed a surface modeling approach from multi-material volumetric data.

Besides solid modeling, other time-consuming geometric operations for AM, such as slicing [208,217,227] and support generation [219], have also been accelerated by multiple core CPUs and GPUs.

4.1.5. *Optimization for special effects*

There are also some research approaches dedicated to generate special effects of fabricated products via geometric optimization on input models. To print large models, a segmentation method was introduced in [228] to decompose a 3D model into printable parts and allow assembling to achieve the final construct. Some other works focus on creating models with particular dynamic properties. Prevost et al. [229] proposed an approach to generate models which can stand alone by deforming the initial inputs. Other interesting works involve printing spinnable objects by optimizing moment of inertia of the 3D model [230] and articulated models [139,138]. For representing different visual effects, multi-material models with textures or shadows [231], and models with optical fibers for sensing and displaying [232] are also presented very recently.

4.2. *Material design for AM*

It is envisioned that 3D printing will provide a powerful tool to analyze the synergetic role of material properties of the constituent materials, combined with geometry, hierarchy and size scales on the different characteristics. For this objective to be successful, the analysis needs to be combined with computational modeling, nano- and micro-mechanics, and state-of-the-art in-situ microscope mechanical experiments to yield meaningful results.

A key successful aspect of 3D printing in this combined computational/prototyping/experimental approach is that it serves as the basis for proof-of-concepts of many mechanisms. As such it helps one to understand and connect the different material composition and fracture mechanisms across length scales. Researchers try to pursue the answer to questions such as (1) "Can modest materials be used as building blocks for synthetic heterogeneous, remarkably strong/tough and programmable materials?" (2) "Can we obtain the same level of improvement in mechanical properties as Nature does?" Fortunately, previous studies have been positive, indicating that the scaled-up artificial architectures can indeed be established to obtain quantitative information on the design principles of different material composites.

4.2.1. Synthetic heterogeneous material with controlled structures

By building physical models layer upon layer, different AM processes can build complex geometries with little cost penalty. This opens up tremendous opportunities for complex structure design which may have a wide range of applications including bioengineering, aerospace and automobile. The performances of structures design correspond to certain geometric configurations of individual elements such as struts and beams. However, for given design requirements, the complex structure design with optimized design performance is challenging. The current structural design approaches for AM processes can be generally classified into the bottom-up or top-down approaches.

Bottom-up approaches: using designed unit structures. Uniform truss, a simple type of structure, is a pattern of unit cells (microstructure) repeated in every direction uniformly. Molecular Geodesic Inc. had pioneered the manufacturing of periodic cellular structures by using AM approaches back in 1990s. However, as pointed out in Wang et al. [210], it takes significant computational resources to directly compute the Booleaned models of truss structures using a solid modeling kernel (e.g. ACIS from Spatial Corporation) and the maximum strut number is limited. To address the problem, Wang [233] proposed a hybrid geometric modeling method by dividing truss structures into a set of unit trusses and semi-struts. Chen [211] presented a general structure configuration approach for various structure designs using point-based method. Other than meshes, implicit representations can also be used. For instance, Pasko et al. [212] demonstrated how to model lattice structures using periodic trigonometric functions. Extending from uniform trusses, heterogeneous structures can easily be generated by varying connections, shapes and sizes of the microstructures used in individual cells of a given model (e.g. using sets of voxels as cells). Designed geometry from a unit-cell structure library can then be populated in each unit cell [194,234]. Chang et al. [235] and Nguyen et al. [236] used heuristic optimization methods such as size matching and scaling (SMS) in optimizing the parameter sizes of lattice structures. In addition, multiple unit cell topologies can be selected and placed in different cells to achieve heterogeneous material properties [237,238]. Several commercial software systems have been developed based on the unit cell design approach, such as Selective Space Structures from netfabb,[12] Meshup from Uformia,[13] and Magics structure module from Materialise.[14]

Top-down approaches: based on topology optimization. Topology optimization is a type of structural optimization where the overall shape, arrangement of shape elements, and connectivity of the design domain are determined. The complex shapes fabrication capability provided by AM processes presented tremendous opportunities for topology optimization to be wider used in product design. Two broad categories in the structural optimization include the topology optimization of discretized and continuum structures: The well-known discrete structure optimization method developed for truss topology design is the ground structure method [239,240]. The numerical computational theories [241–243], as well as linear/nonlinear programming techniques [244,245] on ground structure approach are mainly established on the minimization of compliance or maximization of stiffness. On the other side, continuum based material optimization methods such as Homogenization [246] and Solid Isotropic Material with Penalization (SIMP) [247,248] have been developed to design structures for various design requirements. In this design domain, intermediate density values indicate fictitious materials with densities and stiffnesses that scale monotonically between zero and the stiffness of the solid material. However, since the density map is not manufacturable, an extra step is required to convert the density map into the structures that can be adopted using AM processes. In addition to rigid structures, the topology optimization methods have also been used in the compliant structure design [249–251]. However, problematic issues such as unnatural interpretation of design needs, and expensive computation remain to be addressed.

4.2.2. Engineering material properties via combinatorial material distribution

Geometric modeling deals with the problem of representing objects in 3D space, while material modeling gives the material information for each portion inside the objects. In addition, it is desired to directly compute material distribution in an object based on the following approaches.

Multi-material modeling and editing. Many types of material heterogeneity like multi-material, FGM or even irregular material distribution can be used for the representation of material sets or material space. Based on the data representation of the model as well as the distribution methods of material, Kou and Tan [252] classified heterogeneous object representations into three main categories: (1) evaluated model, (2) unevaluated model and (3) composite model. Evaluated models present heterogeneous objects through intensive space subdivision. Two typical models are voxel model and volume mesh based model. Voxel based model is suitable for medical data collected through CT or MRI scanning. Volume mesh based model uses a collection of polyhedrons to represent 3D models and the material distribution inside of the polyhedron is interpolated from the vertices. Unevaluated models use rigorous mathematical expressions, such as analytical functional representation, single feature based model [253], and multiple feature based model [37] to represent heterogeneous material distribution and therefore are compact and mathematically rigorous.

Custom-functionality design. Parts often made of single material and satisfying predetermined functionality as a basis of design is usually not questioned in current industrial practices. However, AM provides new affordances of heterogeneous and multi-functional design and many examples are developed in a special issue on material ecologies [255]. For example, Duro-Royo et al. [256] introduced a computational approach to generate articulated armored surfaces of a fish that negotiate between functions of protection and flexibility. Doubrovski et al. [257] developed a voxel-based method for digitally fabricating custom prosthetic sockets. Heterogeneous objects with various mechanical, electric, and optical properties can also be fabricated using multi-material 3D printers [258]. It is desired for designers to directly specify the functionality of the designed components instead of directly specifying the material composition the objects. An open research question is how to translate functional requirements given

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[12] http://www.netfabb.com/.

[13] http://www.uformia.no/.

[14] http://www.materialise.com/.

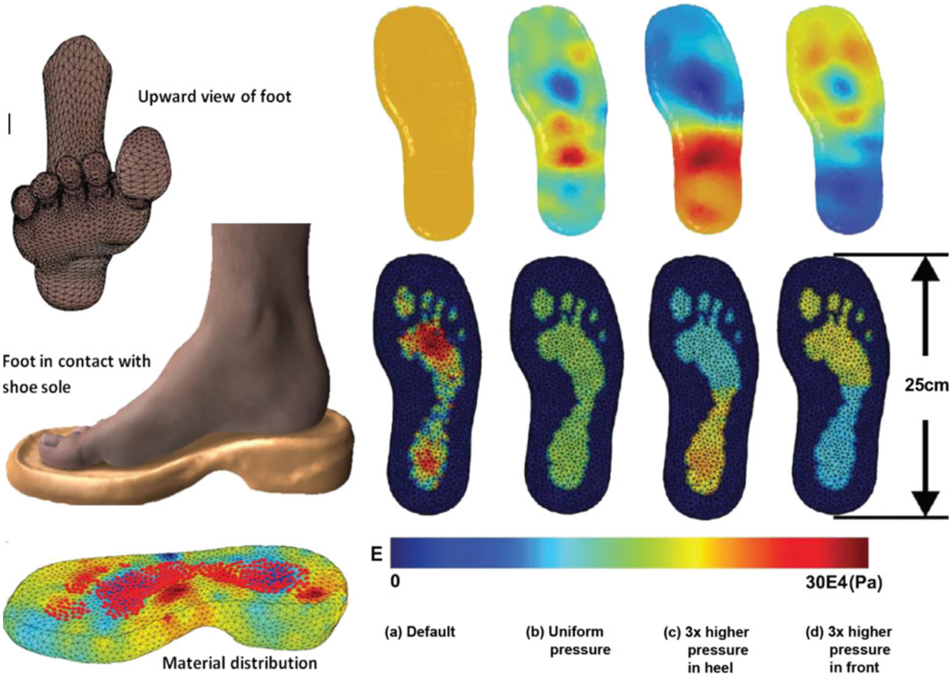

Fig. 7. Controlled shoe contact pressures: Top row: volume rendering of the material distribution. Bottom row: Contact pressures. Left column is the input obtained under a homogeneous material distribution. Second, third and fourth columns give results under a target constant pressure distribution, 3x higher distribution in front and heel, respectively [254].

by designers to the desired material distribution within a CAD model. Data-driven modeling approaches were used to collect sets of force–deformation measurements of interested non-linear materials [259,260]. Xu et al. [254] developed an interactive method to edit the material properties of three-dimensional deformable objects (see Fig. 7). In addition to structural performance, other design performances such as appearance can be designed based on multi-materials additive manufacturing processes [261,262]. In future research, various heuristics need to be developed for specific additive manufacturing processes in order to speed up the searching in large design spaces.

4.2.3. High-performance structural material design

One of the promising areas for AM is designing and synthesizing functionally gradient materials (FGM). The concept of FGM is to change the microstructure and composition gradually such that the performance of the built part is optimal. Such FGM can impart local properties as needed so as to custom-tailor the mechanical, thermal and electrical properties within the same part. FGM material can be designed in discrete or continuously varying manner. For the former, each layer will have a different material or composition when a part is built such that its properties are gradually changed. For the latter, such a gradual change will be achieved by continuously varying the constituent material composition. Fig. 8 shows an example of functionally gradient metal matrix composite built by AM [263]. Such material design capabilities of AM will drastically alter the future design of engineering products as designers will have more freedom as their shape design is no longer governed by the properties of the material being used.

Another opportunity for the AM in material design is the synthesis of high performance material in-situ. There is a strong demand for new paradigms of design and development of advanced high-performance structural materials with high strength and durability while lightweight and low-cost with novel combinations of properties [264]. Often times the use of high performance material for engineering products is limited by its processing capability of generating complex 3D shape. Post-processing of these high performance materials by machining or other processes is very difficult and costly, and impossible sometimes. AM is an effective way of realizing such material design in engineering products. Recently a Boston startup Mark Forged[15] released the first 3D printer capable of printing in carbon fiber, which has a higher strength-to-weight ratio than 6061-T6 Aluminum. China's Avic Heavy machinery, in May, displayed an AM titanium aircraft major load-bearing parts being used in the stealth fighter. In the industrial realm, GE Aviation claimed that more than 100,000 structural parts are aimed to use AM by 2020, including building improved fuel nozzles for the Leap engines [265]. More often AM has made a niche to manufacture tooling such as injection molds with conformal cooling to make casting cores and molds for lost wax processes. Molds with cooling channels that are close to the surface can have complex shapes, resulting in saving of cycle time and heat energy each cycle [266]. Companies have reported large savings in energy and cycle time using conformal cooled molds made by AM.

4.2.4. Self-assembly and programmable matter

Current AM techniques are extensively used in printing complex-in-shape but static-and-individual parts, while users still spend hours of manual labor to actually assemble parts. Active materials with adaptive, self-assembly and reconfigurable properties can be programmed and reprogrammed for variable shapes and forms, such as thermoelectric material [267]. As these capabilities progress during fabrication, the mechanical properties and structural features of the material change and adapt when confronted with outside stimuli like a change in temperature and pressure. Crane and Tuckerman [268] pointed out that the lower possibility of assembly errors, increased redundancy, and accommodation of large-scale system are the key challenges in producing high-performance self-assemblies integrated with

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[15] http://markforged.com/.

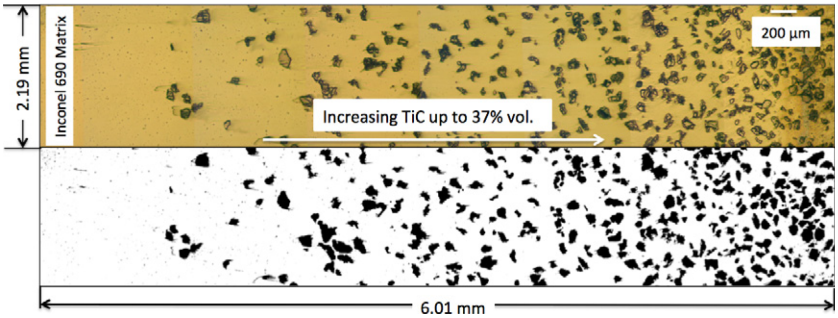

Fig. 8. Original functional gradient TiC/IN690 micrograph on top with the binary image on bottom transitioning from 0 to 37 vol% [263].

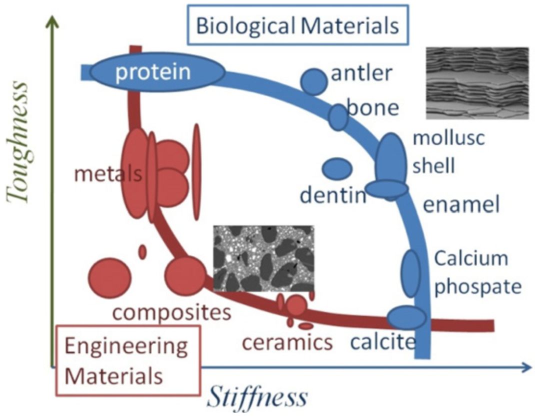

Fig. 9. Normalized toughness vs. stiffness for engineering material and biological materials.
Source: Adapted from [180,271–273].

AM processes. Tibbits et al. [177] from MIT proposed "4D printing scheme" where bendable properties are geometrically coded inside a water-absorbable printed material. Liu et al. [269] presented an approach for fabricating self-assembly structure by printing black inks onto a Shrinky-Dinks film via 2D inkjet printing. Deng and Chen [270] presented a 3D-printing-based approach to design and fabricate 3D self-configurable structures from 2D origami sheets.

4.2.5. *Biological and biomimetic composites design*

Nature has evolved through millions of years efficient strategies to synthesize materials that often exhibit exceptional mechanical properties that significantly break the trade-offs often achieved by man-made materials. Fig. 9 shows the map of biomineralized materials in terms of normalized toughness and stiffness [271,272]. The biological composite materials achieve higher toughness without sacrificing stiffness and strength comparing to typical engineering material [273]. Devising how nature employs these strategies, investigating their fundamental mechanical behavior and contributing with the necessary knowledge and tools for AM, many environmentally friendly, ultra-high-performance and multifunctional biological materials have been investigated. Early work has focused on biomineralized tissues of gastropods and bivalves over multiple length scales. 3D printing was first used to test hypotheses about the morphological features of the microstructure of nacre to determine an optimal geometry and size scale of the microstructural building blocks that increase energy dissipation [180].

4.3. *Computational tools and interfaces development*

With the rapid increase in lower cost 3D printers, it is harder for common people to create complex 3D models that can leverage the potential of the new 3D printers. This requires a lot of training in design tools, and furthermore the design and production of the objects are also separated unlike the real world of craft. The following sections review the current research endeavors in developing 3D modeling and scanning tools for AM.

4.3.1. *Natural user interface (NUI)-driven shape modeling*

AM would not have flowered without major advances in 3D shape modeling. Limitations that exist within conventional modeling tools impede the advancement of AM paradigm. Such computational tools are highly procedural in natural and usually require elaborate training and practice before they can be effectively utilized. As a result, they are cognitively too difficult for novice designers and common public as well as kids, who lack specialized knowledge about technical design. Moreover, such tools are unnatural and non-conducive towards early-stage design. With the marriage of cognitive learning, computer vision and human–computer interaction, computational modeling and simulation researchers have been looking into the NUI-driven design and modeling tool development in a multi-representative and multi-modal manner.

Sketch-based design. In traditional WIMP (Window, Icon, Menu, Pointer) interface systems, dating back to Sutherland's Sketchpad [274], 2D sketching often plays a role of nascent pictorial representation in the conceptual design stage before the depicted design converts into a 3D model. Over the last decade, sketch-based interfaces for modeling (SBIM) are becoming ubiquitous using natural and expeditious interaction of sketching to create and edit the digital models. Olsen et al. [275] categorize the stroke-based SBIM into "evocative" systems [276–278] by searching and template retrieval, and "constructive" systems [279–281] by reconstructing and deforming objects directly from sketches. Pen, bimanual and multi touch-based interactions vastly evolve to provide designers easier support in the sketching and modeling workflow.

Gestured-based modeling. With the recent commercial success of low cost 3D input devices such as depth sensing cameras (Kinect [282], Leap Motion [283], PrimeSense [284]), NUI-driven design and modeling tools using gesture-based platforms facilitate the creation of 3D object ready for printing. The naturalistic integration of human hand gestures with the 3D modeling scheme make the designer an integral part of the creative and exploratory shape design process without the need for extensive training. Recently, Holz and Wilson [285] presented data miming as a voxel representation approach using hand gesture towards descriptive shape modeling. Vinayak et al. [286] proposed Shape-it-up, a gesture-based 3D shape creation system using a paradigm called shape-gesture-context interplay (SGCI). The challenges, in human shape interactions (HIS) still exist in the recognition and interpretation of hand gestures to allow the robust interaction for shape modeling.

Tangible-based shape creation. Holding, manipulating and modifying real-world objects, with hands and hand-held tools, are natural tasks which human learn to perform from an early age. Latest literature shows that by merging traditional fabrication approaches of artifacts, engineers and scientists have also used tangible and haptic devices for creating and modifying free-form 3D shapes. Schkolne et al. [287] demonstrated the modeling of organic shapes using a glove-based wearable device. Inspired by carving and sculpting, Zoran et al. [288] proposed a tangible interaction approach with handheld tools to carve the complex spatial objects, as well as to interpret and edit the virtual model. Oe et al. [289] presented the Scan Modeling technique by scanning the cross section of physical objects and reconstruct the 3D models.

4.3.2. 3D optical scanning

The ability to scan enables reuse of previous geometries for personal making, serve as a model for repair or enable technologies tailored towards customization. Hence scanning technologies are important for fueling the growth of 3D printing technologies. Scanning has, in parallel to 3D printers, undergone a revolution in the past few years. Laser scanning technology has become cheap with hand-held and desktop devices. They range in cost between a few hundred dollars to several thousand for desktop models. Low-cost depth cameras such as the micro-soft kinect are also being adapted and special applications are being developed to transform multiple images to 3D models in both research and commercial domain [290]. 3D optical scanning technologies have been experiencing tremendous growth over the past few decades for providing quantitative measure of physical objects that can be digitized, modified and reproduced by additive manufacturing.

Numerous techniques have been developed including photogrammetry [291], stereovision [292], light field [293], shape from shading [294], time of flight [295], structured light [296], and digital fringe projection [297]. These techniques can be broadly classified into two categories, the passive method (e.g., photogrammetry, stereovision, light field imaging), and the active methods (time of flight, structured light).

Passive photogrammetry method has been extensively employed in remote sensing to determine planar coordinates of the scene. Stereovision technique uses two cameras to capture two 2D images from different viewing angles, simulating the same process as human vision. It is difficult for this technique to achieve high accuracy if an object surface does not have strong natural texture variations. Light field imaging method recovers 3D information using a microlens array without worrying about the correspondence problem of the stereovision method. In general, passive methods work well for reproducing objects where accuracy requirement is not high. Time of flight requires emission of light for 3D reconstruction and it is suitable for long-range measurements. Active methods based on triangulation are more extensively studied and used for close-range measurement. Depending upon the nature of the structured patterns, these methods can achieve different spatial resolutions, speed, or accuracy.

Instead of using discrete dots, the laser scanning system typically uses a structured line to increase both speed and resolution. Since a line is continuous in one direction, its spatial resolution is substantially improved to the camera pixel resolution along line direction. Another popular laser-based method is called fringe projection where sinusoidally varying structured patterns are generated by laser interference or a digital computer. Unlike all aforementioned intensity based methods, fringe projection techniques use the phase information to establish correspondence which is typically quite robust to surface texture variations, thereby allowing for high accuracy measurements. In addition, because fringe projection technique requires a small number of patterns for 3D reconstruction, it allows for high-speed measurements [298] of the physical objects.

4.3.3. Co-design/co-creation platform

As AM continues to lower the barrier of manufacturing via desktop-scale 3D Printing platforms, there is an ever-increasing need for entry-level software to guide a user through the solid modeling process. One manner to address this need is the paradigm of co-creation. Broadly, co-creation is the joint creation of value by the company and the customer [299]—essentially, it is providing the opportunity for a customer to influence the design of an artifact based on his/her specific needs. Within the context of CAD and AM, co-creation will take the form of a web-enabled software tool that will allow users to modify the dimensions of a pre-designed part. Essentially, the technical aspects of the design are completed a priori; the user is using "sliding bars" to adjust design parameters to tailor the final shape to his/her needs. For example, a team from Loughborough University's School of Design Research developed software (leveraging the Grasshopper plug-in for Rhino design environment), coined "PenCAD" that enables any user to easily develop geometric variations of a ballpoint pen. After a base design is created by an experienced Rhino user, anyone can make a custom variation of it using slider bars to change its dimensions, color, and overall shape [300]. In addition, "Uformit" software from Uformia is an online 3D model repository that permits users to make modifications to any uploaded 3D model [301]. The overall goal of these web/app-based design tools is to enable non-specialists to design products to meet their needs. Research opportunities exist to broaden this concept to the design of functional artifacts. Such a tool would require a virtual environment and user interface to interact with a parameterized model and an intelligent design tool to quickly validate each design iteration against a set of design constraints to evaluate performance.

4.4. Manufacturing tools and processes development

4.4.1. Open-source hardware and printers

3D printers are widely discussed as the enabling technology for extending open source processes to physical product development. 3D printers offer the possibility of sharing designs on an open platform that can be used and modified by anyone. At the same time, open source 3D printers represent some of the earliest experiments with open source hardware development. For example, in 2004, Adrian Bowyer launched the RepRap (Replicating Rapid Prototyper) [302] project from Bath University. In subsequent years, Hod Lipson at Cornell and Windell Oskay at Evil Mad Science developed the Fab@Home [303] and CandyFab [304]. These early experiments on developing open source 3D printers provide rich information about the success factors and the limitations of open source processes.

Open source processes are fundamentally unique because they are driven by evolutionary processes, as compared to traditional hierarchical design processes. According to the open source hardware association (OSHWA), the defining characteristic of open hardware is that "design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design" [305]. Different open source projects provide different levels of information. Some projects provide final design documents that can be used by anyone to replicate the project, while other projects document design information throughout the design process. For example, for the RepRap project, the evolution of the entire project is well documented online; the detailed design documents, such as CAD/CAM files, are openly available for download on platforms such as Thingiverse[16] and GitHub.[17] Using these files, the evolution

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[16] http://www.thingiverse.com/.

[17] https://github.com/.

of the product can be analyzed to determine which parts are added, which parts are modified, or removed. A detailed analysis of the evolution of RepRap is provided by Le et al. [306].

Although sharing of the final design documents enhances innovation related to these products, recently, Yanamandram and Panchal [307] showed that the current open hardware projects are not truly open, as per the definition. Most of the open hardware projects are designed by one person or by a small group with close collaborations, and the designs are used by many individuals. In addition to the open availability of the final designs, the above definition also implies that open source hardware must be suitable for making modifications by interested individuals. Further, derived works, manufacturing, sales and distribution of the technology need be permitted. However, such modifications and derived designs are currently difficult because complete knowledge associated with the design, such as constraints, models, analysis, and iterations is not captured. This is partly due to the lack of tools to support holistic knowledge capture within open hardware projects, creating a barrier for individuals who have good ideas but lack complete (engineering) knowledge about the product, thereby limiting the evolution of open hardware products. These issues in open hardware are not only relevant to open source 3D printers but also to all other open source physical products that 3D printers are expected to support.

In addition we note that the early innovation of 3D printing came because of university level projects that co-developed both the process and machine concurrently. However recent open hardware systems for 3D printing are lower cost and lack the functionality for advancing the precision and material compositions because of simpler machine design and control algorithms. We see the lack of availability of more advanced open architecture printers as a deterrent of advancements of process materials and design tools outside the commercial environments.

4.4.2. AM process simulation and optimization

Process simulation capabilities of planning and optimization are crucial for AM systems to provide relevant physical properties such as droplet sizes, shape accuracy, degree of curing, and temperatures with certain fidelity. Researchers have developed simulation methodologies for various AM processes and specific applications, such as the droplet impingement simulation [308] for inkjet-based multi-jet modeling process, the light energy convolution simulation [309] for digital-micromirror-device-based stereolithography process, and the laser energy and material temperature simulation [310] for selective laser melting process.

Compared to conventional manufacturing processes, AM systems require more controllable process parameters and more active interaction between material properties and process parameters. This presents significant challenges in developing AM process simulation and optimization with high fidelity, especially for heterogeneous material deposition. For instance, different build parameters in FDM [311] and SLS [312] processes result in different material properties of fabricated AM parts. Studies have been conducted in [313,314] to incorporate AM process selection with the process planning in the early design stage for designers.

Concurrent process simulation models and approaches are limited in the variety of scope and scale, as well as different levels of fidelity. Response surfaces (meta-models) methods [315] and finite element analysis have been widely used for empirical data and physics-based simulation. To achieve an even higher fidelity, Kai et al. [316,317] presented how to select simulation parameters based on real-time measurement of AM fabrication process. The integration of real-time simulation and feedback loop control in AM systems is critical in achieving controllable fabrication performances. Recent work [318,319] presented a technique that combines the multiscale simulation of material properties and fabrication process to analyze the effects of temperature stress and distortion in the resulting structure. On the commercial side, currently there exists no simulation system that can be directly used by AM developers and users. Some start-up companies such as 3DSim[18] and Sigma Labs Inc.[19] are developing process simulation and analysis software for metal AM processes. However, significant efforts and time are still required to develop simulation systems that are similar to VERICUT for CNC machining process and MoldFlow for injection molding process.

4.4.3. Environmental sustainability consideration for AM

Additive manufacturing techniques have the potential to alter existing models for the product development process. Consequently, we can hypothesize that it will have a significant impact on sustainability considerations within each lifecycle stage of the AM-based production model. A cursory analysis might lead to the thought that AM processes are more benign because of higher efficiencies in material and manufacturing utilization. However, the advent of a new manufacturing process brings different process consumables, workable materials and production techniques. Research has shown that in some cases, processes such as Construction Laser Additive Directe (CLAD), LASER Engineered Net Shaping (LENS), and Direct Metal Deposition (DMD) are more environmentally friendly than conventional manufacturing processes with an impact reduction of about 70% [320–323]. However, AM might not have an edge over traditional manufacturing processes when considering energy consumption [324]. Drizo et al. [325] point out those current models for estimating the environmental, social and economic impacts for technologies are deficient in that they contain too many unknowns.

The use of a variety of chemical solvents, input materials and production consumables poses a significant challenge towards estimation of the toxicity, end-of-life modes, carcinogenic effects, and human health hazards to operators [326]. Although AM technologies are marketed as more material efficient, comprehensive data on the quantity of primary or secondary material wastes is unavailable. The potential toxicity, environmental hazards, and chemical degradability of materials and solvents in AM remain a topic of considerable research potential. A related concern is that additive manufacturing technologies can have “shadow effects” due to their impacts to the design process. For example, an increase in early prototyping may lead to fewer failures in latter stages of product development leading to positive contributions towards reducing the environmental impact of production [327]. On the other hand, reducing the barrier to prototyping may result in unnecessary testing and evaluation causing a negative effect on sustainability.

AM can make design processes such as DFM and DFA redundant allowing for more complex, topologically optimized designs. Such designs would theoretically use lesser energy and material resources compared to traditional designs whilst retaining similar functionality. Therefore, an important future direction for research in AM is optimizing resource utilization. Along these lines, Strano et al. [328] developed a novel approach for optimizing support structures for AM applications such as SLM, EBM and SLA. Bourhis et al. [329] present a novel method for predicting environmental impacts of AM processes that considers flows from material, fluids, and electricity. The authors develop an optimization strategy that reads data from G-code (generated from a CAD representation) and allows users to choose the manufacturing strategy with the least

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[18] http://3dsim.com/.

[19] http://sigmalabsinc.com/.

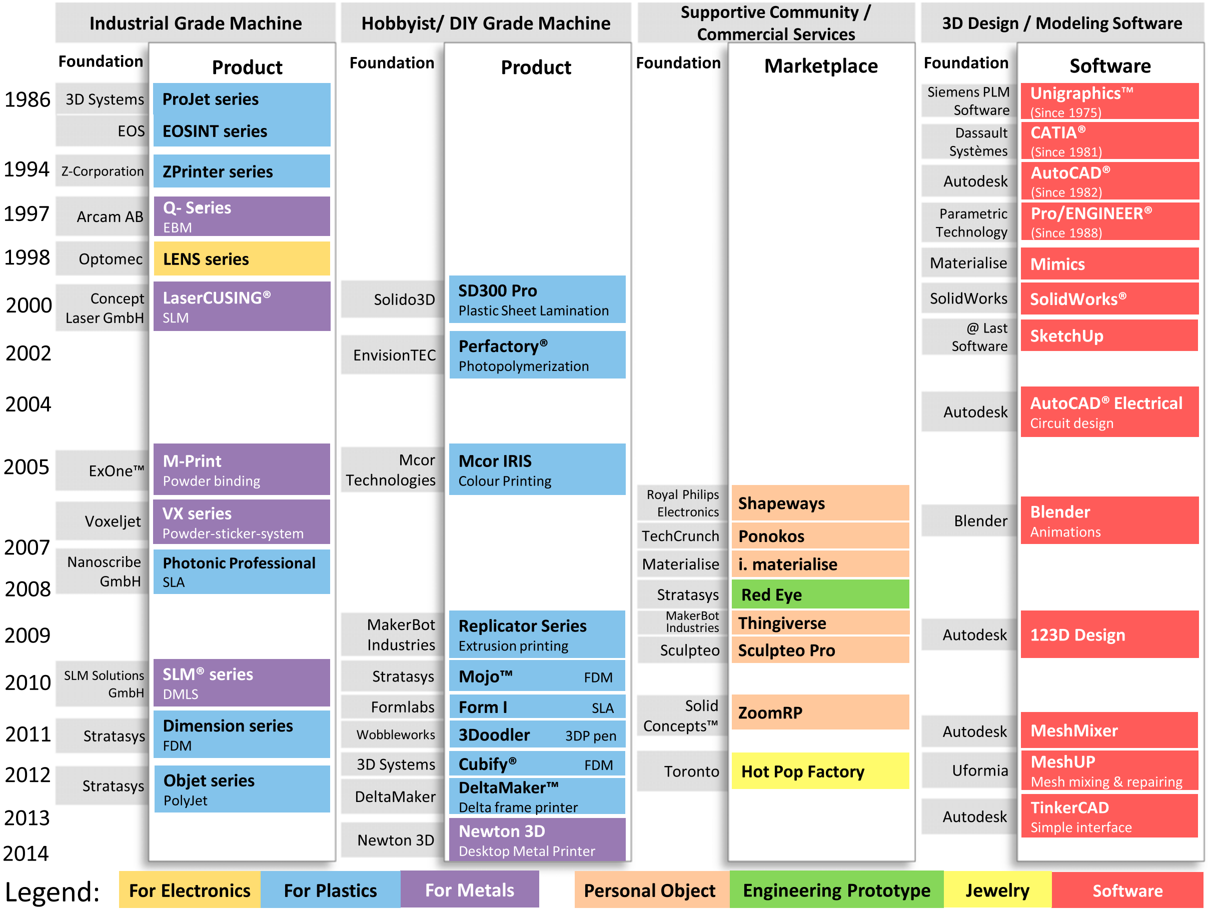

Fig. 10. Integration of solutions for AM industry academic view of foundation and development of products among industrial grade machines, hobbyist grade machines, supportive communities and commercial service, and 3D design and modeling software.The list of the table is no comprehensive, but represents the industry trend.

environmental impact. To fully realize, the potential benefits of AM technologies, future research should look into multi-domain optimization approaches that bridge modeling aspects such as material microstructure, mechanics, heat transfer, part topology, and environmental assessment [330].

AM offers the potential for developing complex, customized products that is prohibitively expensive to produce in current manufacturing settings. AM's ability to revolutionize personalized healthcare, custom-fit safety equipment, and bio-engineering promise to have a positive effect with regards to societal impacts [324]. Diegel et al. [331] suggest that AM's ability to customize a product according to a user needs, has the potential to influence the desirability and therefore the longevity of a product. A joint effort by all involves stakeholders such as designers, manufacturers and environmental specialists can help further our understanding of the potential environmental, societal and economic impacts of AM technologies.

5. The broadening impacts of AM industry

5.1. A commercial view of AM

Early developments in 3D printing were intended to improve the time and cost efficiency of the industrial-scaled manufacturing [16]. This is mostly being explored and supported by the giant leading manufacturers all over the world for use in aerospace, defense, power generation, and medical device manufacturing industries. They include not only flight hardware, but also for jet-powered boats, land-based power generators, and other applications of gas turbine engines [332].

For instance, Optomec developed the Laser Engineered Net Shaping (LENS) systems; 3D Systems developed the ProJet series of printers; e-Manufacturing Solutions (EOS)[20] developed the EOSINT series for laser-sintering systems; Z-Corporation (acquired by 3D Systems in 2012) developed the ZPrinter series; ExOne[21] developed the M-Print systems; Objet Geometries (now merged with Stratasys) developed Connex systems. Nowadays, the AM systems and machines tend to be accessible to more small businesses, supportive communities and even individual designers.

A timeline of significant developments and the resulting products are shown in Fig. 10 for four groups of different AM solution: industrial grade, hobbyist/DIY grade, supportive community/commercial services, and 3D design/modeling software shown in Fig. 10. It is interesting to note the parallels in their timelines: the gradual expansion from open source and multi-material printing capacities, to the various applications such as art, electronics, fashion, engineering prototypes and personal customerization. Most of these are through various acquisitions and partnerships with other organizations. In the third column, we list a list of worldwide supportive business communities and marketplaces for 3D printing, including Shapeways from Netherlands, i.materialize[22] from Belgium, Ponoko[23] from New Zealand,

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[20] http://www.eos.info/en.

[21] http://www.exone.com/.

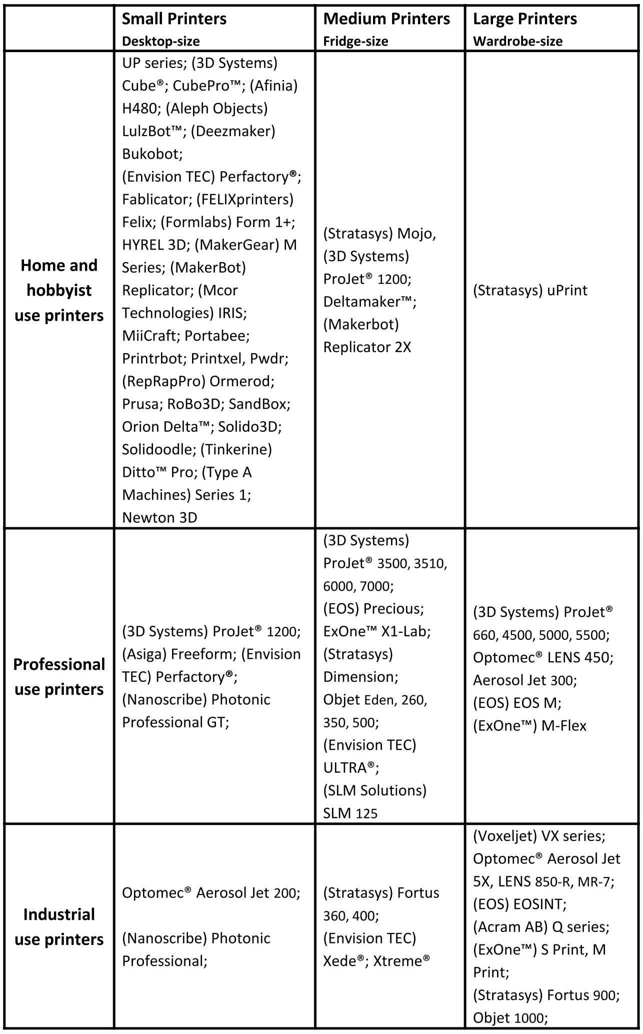
[22] http://i.materialise.com/.

[23] https://www.ponoko.com/.

Sculpteo from France, ZoomRP[24] and RedEye[25] from US. These facilities allow designers to upload their designs, have them made, and then shipped the finished product back. Designers can also set up an online "shop" through the website and sell their products.

Existing computational support tools that generate digital files ready for printing can be divided into two categories: creating virtual models using Computer-Aided-Design (CAD) software, and capturing physical objects using 3D scanner. The first refers to geometric modeling methods which use parameters, dimensions, features, and relationships to capture intended geometric features of a 3D object design. The development of CAD has evolved over decades and the four organizations garnering the highest market share include Autodesk (major product solutions: *AutoCAD*® and *Inventor*®), Dassault Systemes (major product solutions: *CATIA*® and *Solidworks*®), Parametric Technology Corporation (major product solution: *Pro/ENGINEER*®), and Siemens PLM Software (major product solution: *Unigraphics*™). 3D scanning methods were initially expensive and available only for industrial-level use. Nowadays affordable ways include (1) using RGB cameras and depth sensors (*Microsoft Kinect*™, *Asus Xtion*® and Leap Motion[26]), and (2) using Image-based mesh generator like 123*D Catch*®. The point cloud of an object is first generated and then mesh edited using software like *Netfabb*®, MeshLab[27] and Pleasant3D.[28]

Fig. 11 shows the classification of different commercial printers against their build volume during use. 3D Printers like Cubify, Printex, Nanoscribe focus on building the coin-scale or even smaller objects in the fields from customized jewelry, ornaments to professional electronics and medical instruments. A majority of companies on the market develop their own printers that can print palm-scale object and they are mostly towards the hobbyists and home tinkerers. Typically for the research and industrial manufacturing purposes, leading manufacturers like Stratasys and 3D Systems develop AM systems that are capable of producing larger components (∼90 cm in length). Sciaky DED systems are capable of producing even larger components (∼580 cm), but only at a near-net shape resolution. Many printers such as *Replicator*™ use X/Y axis table with belt transmission and step motors for the motion feeding, while Delta robot inspired printers such as *DeltaMaker*™, Rostock and Orion use three nimble arms driven extruder.



	Small Printers **Desktop-size**	**Medium Printers** **Fridge-size**	**Large Printers** **Wardrobe-size**
Home and hobbyist use printers	UP series; (3D Systems) Cube®; CubePro™; (Afinia) H480; (Aleph Objects) LulzBot™; (Deezmaker) Bukobot; (Envision TEC) Perfactory®; Fablicator; (FELIXprinters) Felix; (Formlabs) Form 1+; HYREL 3D; (MakerGear) M Series; (MakerBot) Replicator; (Mcor Technologies) IRIS; MiiCraft; Portabee; Printrbot; Printxel, Pwdr; (RepRapPro) Ormerod; Prusa; RoBo3D; SandBox; Orion Delta™; Solido3D; Solidoodle; (Tinkerine) Ditto™ Pro; (Type A Machines) Series 1; Newton 3D	(Stratasys) Mojo, (3D Systems) ProJet® 1200; Deltamaker™; (Makerbot) Replicator 2X	(Stratasys) uPrint
Professional use printers	(3D Systems) ProJet® 1200; (Asiga) Freeform; (Envision TEC) Perfactory®; (Nanoscribe) Photonic Professional GT;	(3D Systems) ProJet® 3500, 3510, 6000, 7000; (EOS) Precious; ExOne™ X1-Lab; (Stratasys) Dimension; Objet Eden, 260, 350, 500; (Envision TEC) ULTRA®; (SLM Solutions) SLM 125	(3D Systems) ProJet® 660, 4500, 5000, 5500; Optomec® LENS 450; Aerosol Jet 300; (EOS) EOS M; (ExOne™) M-Flex
Industrial use printers	Optomec® Aerosol Jet 200; (Nanoscribe) Photonic Professional;	(Stratasys) Fortus 360, 400; (Envision TEC) Xede®; Xtreme®	(Voxeljet) VX series; Optomec® Aerosol Jet 5X, LENS 850-R, MR-7; (EOS) EOSINT; (Acram AB) Q series; (ExOne™) S Print, M Print; (Stratasys) Fortus 900; Objet 1000;

Fig. 11. Benchmark of different printer sizes versus the areas of use.

5.2. *Intellectual property considerations*

The first patents in the area of plastics AM were hold by Ross Housholder (1981) later assigned to DTM corporation and from United Technology Corporation (tourtelotte 1981 and Brown 1982). The invention of Stereolithography by Charles Hull [2] was in 1984 (Hull 1986). Early AM processes patented in the 1980s were selective laser sintering [3], sheet lamination [333], material extrusion [4] and 3-D printing [5] all with the support of the National Science Foundation. The number of patents published in this area grew gradually until 2000, and increased to about 500 in 2013. Many of the patents in the mid 90s have expired now and as a result many new machines have appeared in the market using derived technologies. A detailed listing of 70 patents issued between 1970–2012 is given in [334]. 3D systems (including Z Corp acquisition) and Stratysys (including MakerBot) own the largest number of patents. Among the universities, MIT has about 30 patents since 1975 [6]. As more patents expire as did in SLS and FDM patents, we can expect cost of the 3D printers will fall down for consumers. It can be expected that litigation in this area will grow with better technologies that may build from earlier experiences. The new printers have very high resolution and layer marks are hardly visible to the eye. New technologies that are more capable and have patent protection will continue to cost more for consumers.

5.3. *Educational view of AM*

Due to the rapid acceleration of industrial interest and recent adoption of AM technologies, there exists a significant need for educating a workforce knowledgeable about how to employ AM. In addition, as outlined in the "2009 Roadmap for Additive Manufacturing", unfamiliarity with AM technologies is seen as a barrier to adoption. The roadmap urges the development of university courses and "programs for educating the general population to enhance the interest in AM applications and generate some societal 'pull' for the technologies" [332]. Given this need, a recent National Science Foundation workshop on AM Education was held, wherein attendees from industry, academia, and government met to discuss the educational needs and opportunities for the AM engineering workforce [335]. Following presentations from industrial attendees, it was determined that the future AM workforce need to have an understanding

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[24] https://www.zoomrp.com/.

[25] http://www.redeyeondemand.com/.

[26] https://www.leapmotion.com/.

[27] http://meshlab.sourceforge.net/.

[28] http://www.pleasantsoftware.com/developer/pleasant3d/.

of (1) AM processes and process/material relationships, (2) engineering fundamentals with an emphasis on materials science and manufacturing, (3) professional skills for problem solving and critical thinking, (4) design practices and tools that leverage the design freedom enabled by AM, and (5) cross-functional teaming and ideation techniques to nurture creativity. A variety of AM-centric pedagogical experiences have been explored as a means of achieving these learning objectives. Dedicated AM courses at the undergraduate and graduate levels are emerging (e.g., [336–338, 124]), but their limited quantity does not match the recent interest in, and suggested national importance of, the technology. In addition to these formal learning opportunities, there exist several opportunities for students across all educational levels to engage with AM in informal learning environments—extracurricular activities such as internships, design competitions, and student engineering professional societies. Typically characterized as unstructured, socially-based educational environments wherein students collaborate autonomously on a project, informal learning environments, these opportunities have been shown to positively contribute to students' engineering education [339].

K-12 STEM outreach. The broad availability and accessibility of desktop-scale AM systems has resulted in its dissemination into K-12 STEM classrooms and related events [340–342]. For example, Kid's Tech Enrichment Connection (KTEC) hosts annual 3D printing camping which allows children to practice CAD modeling skills using Google Sketchup and Tinkercad, and igniting design ideas for printing real objects. Pennsylvania Cyber Students are given access to create printed parts but also building 3D printers with constructable kits. High schools are at the early stages of learning and adoption of 3D printing technologies in their informal programs such as first robotics and formal technology oriented electives. Training programs for high school teachers including examples of curricular uses of it through potential integration of courses with design as well as informal opportunities through programs such as first robotics can be used as channels for exposure.

"Maker" community. Through its continual garage-scale technology advancements, the DIY "Maker" community has significantly broadened access to AM technologies. Every summer Maker Faire offers platforms and opportunities to entrepreneurs for selling their personal AM printers and organizes expos to the worldwide do-it-yourself crowds. The Exploratorium in San Francisco, as an educational museum, brings concurrent 3D printing technology to the life through kinetic art, inquiry, and plays, such as the sugar printer CandyFab.

University-level informal learning environments. Inspired in part by the Maker movement, several universities have engaged their students in "maker spaces" that feature several digital fabrication tools. These spaces, such as Georgia Tech's Invention Studio [343], feed a culture of entrepreneurship and innovation across the campus while providing opportunities for students to learn about AM. Virginia Tech's 3D Printing vending machine [344], which provides access to AM in a 'vending machine' user experience, has lowered the barrier to AM while also advancing understanding about CAD, AM, and design for manufacturing [345]. Similarly, AM student design competitions (e.g., [346]) have shown to improve understanding about the technology and how to design products for it.

Research opportunities. Engaging students in graduate and undergraduate research provides opportunities for undergraduate and graduate students to work on multiple interfaces of computational design, geometric and mechanistic properties, as well as creative application contexts ranging from consumer products to toy designs (STEM, DARPA's MENTOR project). In addition, K-12 STEM teachers have engaged in AM research, and later developed AM curriculum for their classrooms, via Virginia Tech's Research Experience for Teachers program [347]. The nature of the projects that are being investigated through the NSF funding are diverse, shown in Fig. 12. Typical projects in the geometry structure area investigate new process development, integrated fabrication of the device and embedded electronic sensors, fabricating structured artificial materials, and demonstration of designed microstructures. Materials design classified projects range from fiber reinforced ceramics, using nano-suspension binders for fabricating copper cellular materials, and design of new creep resistant titanium alloy via additive manufacturing. Projects in the computational hardware and software combinations include a new printer for fabricating textiles involving multiple materials. In the machines and hardware development area new machines that enable research on the fabrication of products from different materials, intricate features and mechanical properties have been proposed. Even a pen that can draw in 3D directly with overhangs and high visual appeal has being proposed. New approaches to integrate optical, mechanical and software designs by using a projection image that can be continuously moved in high speed without losing its native resolution is also being developed in the methods and processes categories. This category had a high growth of funded projects. Most projects had an educational component, and many in the undergraduate education category included a strong maker community development.

6. Discussion and future trends

We are poised and on the brink of "a third industrial revolution" [348] when many emerging companies are rethinking how traditional manufacturing will be transformed. Some of the driving factors that are already bringing about this change, or are likely to do so in the next few decades, are discussed below along with some challenges they bring. These trends and challenges in additive manufacturing ecosystem are discussed from the perspective of researchers, manufacturers, and end consumers.

Additive manufacturing for "desktop fabrication". Although AM devices are being perceived as desktop commodities by the public, such developments are currently restricted to specialized demographics. These "makers" are consumers of diverse age groups that actively contribute towards the design and creation of personalized products, ranging from tiny trinkets to large prosthetic devices. AM technologies can help in customization of products by directly involving customers in the design stage. However, such technologies are at a nascent stage due to the cumbersomeness associated with design and printing software. Web-based design tools such as 3DTin,[29] TinkerCAD, and Shapeways are a step in this direction. Natural user interfaces including pen-based and gesture based interactions have the potential to help democratize design of shapes for 3D printing. In recent times, low-cost optical sensors for gaming are being adapted for 3D scanning. Methods including passive photogrammetry and laser-based approaches provide different spatial resolutions, speed and accuracy; and will see continued growth and ease duplication, modification and production of 3D content. Hobbyists are also spawning start up industries that develop machines at different scales, costs, performance, and materials. However, the number of printing options due to the diverse nature of AM is confusing to the customer. Education and training in 3D printing will be critical for the future customer to adapt and innovate in AM, which is in very early stages of growth.

Research at the intersection of products, processes, and machines. Design for additive manufacturing (DfAM) is an emerging field in engineering design. Currently the benefits of using AMs unique capabilities such as unlimited geometric

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[29] www.3DTin.com.

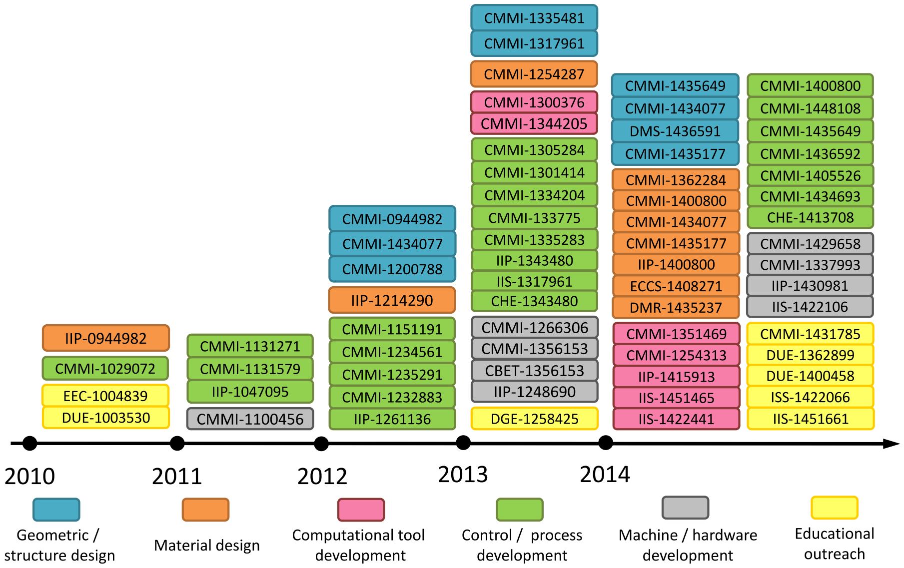

Fig. 12. NSF awards on AM technologies in the last five years.

capability and heterogeneous material property for better design performance are still untapped. There is limited knowledge regarding how to use such capabilities in achieving improved design performance. For the establishment of DfAM, there are many promising research directions that can be further explored. In future DfAM systems, designers may generate complex multi-materials objects by simply specifying design performance. Hence efficient and high fidelity simulation algorithms will be required in order to analyze and synthesize complex shapes, constraints and specifications in physics, motion, and other functionality.

Generating designs that can have increasingly complex shapes and material composition is an open research question. Consequently, new methods for geometric computation such as layered depth normal images using distance fields and adaptive strategies are being developed for representations of 3D models for AM. New geometric modeling and computation methods are required for future product components whose shapes and material composition would be orders of magnitude more complex than our current product designs. Many open research areas in self-assembly and biologically and ecologically inspired printing approaches since there are various complex volumetric structures in nature that can serve as an inspiration for developing these new methods. Novel geometric representations are also required for optimizing material support during manufacture, designing for specific physical properties, and AM-based repair/remanufacturing.

The advantages that AM claims to differentiate itself from traditional manufacturing need further research for it to become a more practical alternative. New research towards these developments is slow (especially at the interfaces of research laboratories and commercial machine manufacturers) due to traditional gaps between academia and industrial settings. The industry-academic exchange faces further challenges since industry has now developed capabilities to produce machines that are complex, expensive and are not open architecture.

Fragmentation of research investments and trends towards the "print-it-all" paradigm. Although additive manufacturing is very attractive for research, especially after recent surge in interest after the expiry of the base patents, we see significant problems in organizing, integrating and having realistic impact with the research. The primary reason is that the research is fragmented and mechanisms for integration do not exist. In particular because of the large variations in additive manufacturing methods and representations, it becomes difficult to repeat or reuse research. Although one may want standards to emerge, commercial entities with larger revenues will resist this change. One way to overcome this is to have open academic research platforms, but also significant expertise and federal investments in organizing these topics will be required. Additive manufacturing currently evolves under the context where researchers are investigating different printing techniques individually in multi-disciplinary fields. We envision that in the near future the integration of 3D shapes, mechanical joints, electronics and actuators will provide affordance and enable a "print-it-all" fabrication process for building more functional products. However, this pathway of further development will likely be confined to laboratory uses and demonstrations, rather than be used commercially until many areas of reliability, repeatability, robustness and performance under different environmental conditions are considered. Substrates (2.5 D) may be manufactured using ink jet printing or cut from sheet materials using laser cutting. Directly printing conductors on substrate constructions is possible using existing techniques with adaptations. Conductors can be directly printed on the substrate by screen printing, ink-jet printing, or selective wetting of pre-patterned surfaces (patterned by composition or texture via lithography, sputtering, and/or vapor deposition).

The need for rethinking and reorganizing manufacturing. Intellectual property considerations, especially with key patents that have expired, have played a very important role in the sudden upsurge in commercial interest with respect to AM. If the future of manufacturing floors transit to rows of 3D printers that sit amongst lathes, planers, mills and drilling machines, new operations and scheduling systems will be required for supporting mass production. These changes will inevitably result in a new production models in design and processes that will eventually percolate throughout the product life cycle. AM can support decentralized production at low to medium volumes allowing companies to drive significant changes within the supply chain. These changes include, cost reductions, the ability to manufacture products closer to customers, reduction in logistical complexities, involving consumers in design processes, and reduction in capital deployment. We envision the future of manufacturing to leverage such advantages offered by AM and evolve into a model that integrates AM techniques with more conventional manufacturing processes. For this, new business models at the hobby level, prototyping level, and short run production will have to be developed while identifying those niches that consumers will support.

Acknowledgments

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