SCIENCE AND TECHNOLOGY POLICY INSTITUTE

Additive Manufacturing: Status and Opportunities

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Executive Summary

Additive manufacturing (AM), also referred to as 3D printing, is a layer-by-layer technique of producing three-dimensional (3D) objects directly from a digital model. With markets including prototyping, tooling, direct part manufacturing, and maintenance and repair, the industry has grown significantly to $1.3B of materials, equipment, and services in 2010. Despite significant progress in the field, a number of technical challenges remain. Issues such as material characterization and availability, among many others, have been identified by various groups as areas for improvement. Though many issues are being examined by groups in academia, industry, and government, some challenges would likely benefit from increased coordination and funding opportunities.

While some topics, such as achieving better material properties, have been around since the early days of additive manufacturing, new ideas have emerged in recent years. These topics involve basic science including materials, lightweight and exotic structures, bioprinting, and conformal electronics. They also include more applied areas, such as the environmental impact of additive manufacturing and 3D scanning.

Many areas of AM R&D and associated technical challenges could benefit from incentive competitions that aim to spur and accelerate innovation. Some competitions involving additive manufacturing have already taken place but more could potentially benefit, especially in areas such as design software and web-based design tools.

There is interest at several Federal organizations in advancing research and procurement of additive manufacturing for many types of components. Amid this growing use of additive manufacturing, the government has several opportunities to act as an early adopter to accelerate market adoption, especially in aerospace, defense, and medical applications.

Over the years, the number of regular conferences aimed at advancing AM technologies has grown, with events that now take place annually throughout the globe. In addition to conferences, a number of workshops and roadmapping events have also taken place, covering topics spanning from R&D areas to educational needs.

Standards play an important role in the adoption of many technologies and, as of 2009, there has been significant activity in developing AM standards through the ASTM International F42 committee. There are currently four technical subcommittees working towards standards in materials and processes, terminology, design and data formats, and test methods. They have produced four standards to date and also charted new territory in a partnership with the ISO, signing a cooperation agreement that governs ongoing collaborative efforts between the two groups.

Additive manufacturing holds great potential to engage a broad population—not just students—in science, technology, engineering, and mathematics (STEM) topics in formal and informal settings.

Key findings from this work include:

- Many technical challenges, including process control and modeling, would benefit from new or additional Small Business Innovation Research funding or other R&D funding opportunities.
- Challenges and prizes could be organized in areas such as design software and web-based design tools to broaden accessibility to a larger set of non-expert users.
- Two pre-competitive opportunities have been the subject of numerous discussions in the AM community and include the development of a database of material properties and the establishment of a national testbed center.
- A government agency or group of stakeholders could sponsor an AM-specific "maker faire" for the technical community in which representatives from the government and OEMs, service providers, and academia convene to share ideas and hands-on experience in the spirit of information exchange.
- Supporting the expansion of programs such as Walter Reed National Military Medical Center's pioneering design and use of custom medical implants, surgical guides, and medical models could accelerate wider adoption throughout the public and private sector.
- Due to fragmented coordination of the AM community, there is a need to engage all stakeholders–including individuals from government, academia, and industry–at a workshop to discuss common issues of importance that span all organizations and markets.
- Inherent differences in additive manufacturing compared to traditional manufacturing techniques will likely necessitate modifications to standard validation, verification, and certification procedures.
- Additive manufacturing enables new ways of teaching topics that can further engage young people and adults in STEM.

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A. Introduction

Additive manufacturing (AM), also referred to as 3D printing,[1] is a layer-by-layer technique of producing three-dimensional (3D) objects directly from a digital model. Unlike conventional subtractive processes that cut away material from a larger workpiece, additive manufacturing builds a finished piece in successive layers, each one adhering to the previous. Since its emergence 25 years ago, additive manufacturing has found applications in industries ranging from aerospace to dentistry and orthodontics. Across all industries, additive manufacturing accounted for $1.3B in worldwide sales of materials, equipment, and services in 2010 and is poised to exceed $3B by 2016 (Wohlers 2011).

In recognition of the potential for innovation and job creation in the field, The Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute to identify potential policies, programs, and partnerships that the Federal government could employ to advance additive manufacturing. Methods included a literature review and several discussions with experts and stakeholders in the AM community.

This paper is organized in two parts. First, we present a brief description of the AM industry, including its most prominent near-term technical challenges. Also presented are emerging research and development (R&D) topics that show promise for significant advancement of the field. Second, we explore the Federal Government's potential role in advancing additive manufacturing, including opportunities in pre-competitive R&D, early government adoption, workshops and technical roadmaps, standards development, and education.

B. State of the Industry

Although the AM industry originated 25 years ago, it has transformed significantly from its early days, when the primarily market was rapid prototyping. Today, the AM industry is changing at a rapid pace. In this section we present the now-prevailing categorical views of additive manufacturing processes as developed by the ASTM International Committee F42 on Additive Manufacturing Technologies. Also detailed in this section are typical material application areas and emerging trends that will affect the overall market for additive manufacturing.

[1] 3D printing is technically a subset of additive manufacturing, which was recently established as the prevailing term to describe the industry. Other terms include rapid prototyping, direct digital manufacturing, and solid freeform fabrication.

1. Processes

The field of additive manufacturing encompasses a variety of unique processes with varying characteristics. These processes were previously categorized by a variety of researchers (Hopkinson 2010; Gibson, Rosen, and Stucker 2010; Hartke 2011), and have now been standardized by the ASTM International Committee F42 on Additive Manufacturing Technologies into the seven classes in Table 1. The table presents an overview of process classes, examples of leading companies that make machines for each process, typical materials classes, and the most popular markets for use.

Table 1. Additive manufacturing process types and attributes, including example companies, materials utilized in machines, and typical markets

Process	Example Companies	Materials	Market
Vat Photopolymerization	3D Systems (US), Envisiontec (Germany)	Photopolymers	Prototyping
Material Jetting	Objet (Israel), 3D Systems (US), Solidscape (US)	Polymers, Waxes	Prototyping, Casting Patterns
Binder Jetting	3D Systems (US), ExOne (US), Voxeljet (Germany)	Polymers, Metals, Foundry Sand	Prototyping, Casting Molds, Direct Part
Material Extrusion	Stratasys (US), Bits from Bytes, RepRap	Polymers	Prototyping
Powder Bed Fusion	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Polymers, Metals	Prototyping, Direct Part
Sheet Lamination	Fabrisonic (US), Mcor (Ireland)	Paper, Metals	Prototyping, Direct Part
Directed Energy Deposition	Optomec (US), POM (US)	Metals	Repair, Direct Part

Each of the processes has associated strengths and weaknesses related to the following characteristics (Wohlers 2011; Hartke 2011):

- The materials they can utilize (typically different polymers or metals but also waxes and paper for some niche applications)
- The speed at which they can build parts (build speed)
- The dimensional accuracy and quality of the surface finish of the produced parts
- The material properties of the produced parts
- Machine and material costs

- Accessibility and safety related to complexity of operation
- Other capabilities, such as multiple colors

As a result of these attributes, each process has particular markets in which it is used. While many of the above-mentioned processes are commonly employed in prototyping, others are well suited for markets that include tooling, direct part production, and the repair of damaged parts, as detailed below:

- **Prototyping**. Some of the earliest AM parts were created for the rapid prototyping market, first employed as visual aids and presentation models (ASM International 2012; Wohlers 2011). These are still compelling applications, as 3D models tend to increase comprehension of a product design over their 2D counterparts. As material properties initially improved, AM parts began to be used for functional models and for fit and assembly, ultimately leading to a long phase of rapid prototyping. As lower-cost, office-friendly systems were introduced, AM-produced prototypes became an integral part of the iterative design process. Companies would print the part, evaluate it, revise the design, and print it again. In many engineering and design organizations today, 3D printers are used for such rapid prototyping as a standard operating practice.
- **Tooling**. Another broad class of applications for AM parts is patterns for tooling. For years, investment castings[2] have been made with the aid of additive manufacturing. These patterns are made from materials or with build styles that are compatible with the investment process. AM patterns are also used extensively in silicone rubber tooling, which produces urethane castings. These castings are used mostly as prototypes but also as parts that sometimes go into final products. Sand casting is another application for AM patterns.
- **Direct part manufacturing**. The fastest growing application for AM parts is as end-use parts, (i.e., direct part production). As opposed to rapid prototyping and tooling, where AM is used as a step in the design or production process, in direct part production, additive manufacturing creates a final good for sale or use. This application category has grown from 4 percent of total AM revenues in 2003 to nearly 20 percent in 2010 (Wohlers 2011). This rise in direct part production has been made possible by increasing material quality from AM processes, decreasing cost, and growing awareness of the potential of additive processes. Examples include dental copings for crowns and bridges, surgical implants, environmental control system ducting for military and commercial aircraft, parts for unmanned aerial vehicles, and consumer products such as jewelry.

[2] Investment casting is a process by which a pattern of the desired part is first created. A mold is then taken of the pattern and the material inside the casting is burned or melted away. It is commonly employed in instances that require intricate detail.

- **Maintenance and Repair**. Additive manufacturing is increasingly being used for maintenance and repair of damaged parts, particularly for products where a long lead time or expense is associated with procurement of new parts. The ability to repair metal parts to near-net shape has significant advantages over manufacturing new parts, particularly large parts where only a small portion has been damaged (Mudge and Wald 2007). Additive manufacturing also excels where traditional maintenance and repair approaches are not enough to replace worn or damaged parts. It provides a metallurgical bond to the base material as opposed to a mechanical bond, which reduces the "heat affected zone" in the nearby material. It thus leads to a stronger bond with fewer nearby residual stresses, making it ideal for parts that have a high sensitivity to heat distortion (e.g., gas turbine engine blisks) (Hedges and Calder 2006).

2. Applications

The range of applications for parts made by additive manufacturing has grown significantly over the course of the industry's history, fueled in part by the introduction of new materials, incremental improvements to existing materials, and improvements in system process control, speed, cost, accuracy, and reliability. A handful of characteristics dictate current and potential applications:

- **Small production runs.** Additive manufacturing techniques and materials tend to be more expensive than traditional counterparts for large production runs, and thus they are most competitive for applications where flexibility and fast product development cycles are needed. Examples markets include those for customized parts and small production runs down to one (ie, prototypes or fully custom products).
- **Small part size.** Presently, low build speeds and technical limitations tend to limit additive manufacturing to areas where relatively small parts, such as one cubic foot or below, are needed.
- **High-value products**. Given its comparatively low build speeds and high materials costs, additive manufacturing competes well in high-value markets.
- **Products with high complexity.** Creation of some complex shapes and geometric features is difficult, if not impossible, to achieve using traditional methods. Additive manufacturing is more competitive where part complexity is desirable, because any part that can be modeled digitally can be built with little or no additional cost related to complexity. It is also possible to use AM to consolidate several parts without the need for assembly.
- **Elimination of tooling.** Any time a part, or a batch of parts, can be produced without tooling, substantial savings are possible. This usually occurs in situations

where the production volume, part size, and part complexity combine to give AM an advantage over tool production on a cost per part basis.

3. Recent Trends

Additive manufacturing is a fast-moving industry that is currently generating significant attention in the popular media—see, for example, *The Economist* (2011). A number of recent trends indicate that the field is still rapidly developing with new markets emerging, patents expiring, and international interest growing, as highlighted below:

- **Growing personal use**. With the introduction of AM machines selling for under $2,000, it is becoming increasingly possible for individual or groups of hobbyists, sometimes called “makers,” to purchase and operate additive manufacturing machines (Campbell et al. 2011).
- **Patent expiration**. Early AM patents are expiring, which is beginning to affect development of new machines as well as their applications in the United States and abroad (Bourell, Leu, and Rosen 2009).
- **International growth**. While additive manufacturing techniques have mostly been developed in the United States and Europe, other countries are increasingly becoming interested in using and further developing these techniques. For example, Australia recently produced a roadmap for metals additive manufacturing to move down the supply chain in its rich mining and metals sectors (Wohlers Associates 2011), and the government of South Africa is supporting the development of a large, laser-based AM machine for the production of titanium parts that promises to be eight times faster than other laser-based machines on the market (ASM International 2012). Japan was historically among the leaders in AM technology but has recently produced relatively few machines that sell outside its domestic market. China represents a rapidly growing market for AM design services, with several companies producing machines and offering services that utilize additive manufacturing (Wohlers 2011).

C. Technical Challenges

AM technology has made significant strides over the past 25 years, but technical challenges related to materials, equipment, and applications remain. Many of the challenges described in this section, which have commonly been discussed in workshops or publications, are the focus of ongoing research in government agencies or industrial organizations. In some cases, the topics may be underfunded by the private sector and could benefit from new or additional Small Business Innovative Research funding.

1. Materials Characterization

Information is needed on material properties for different processes, but who would maintain such a database and which data should be publicly available are unclear. Before the AM industry can fully transition to offering viable manufacturing solutions, specifications are needed that provide mechanical properties data for available materials, as well as more detail on how parts made from these materials perform (Campbell et al. 2011). Engineers and designers cannot design without fully understanding the properties of the materials used to manufacture the parts being designed. If the properties for AM materials are not available, designers will not consider additive manufacturing as a method of manufacturing. With so many AM processes and materials currently available, the creation of comprehensive specifications is a resource-intensive endeavor, requiring the involvement of research organizations and system and material manufacturers (Kinsella 2011).

2. Materials Development

Though a wide range of homogenous and heterogeneous material mixtures have been employed in additive manufacturing, there is still a need for developing additional materials. This includes a better understanding of the processing-structure-property relationships of materials that are already in use to help understand their limitations and benefits (Bourell, Leu, and Rosen 2009). Furthermore, there is demand for developing testing procedures and methods of qualification to help expand the variety of materials available.

3. Process Control

Methods are needed for in-process monitoring and closed-loop feedback to help improve consistency, repeatability, and uniformity across machines (Kinsella 2011). In situ sensors are an area that should be examined to provide nondestructive evaluation and enable early defect detection, particularly related to thermal control (Bourell, Leu, and Rosen 2009). Better process controls could also lead to decreased downtime, currently a major issue for many machines and processes (Bourell, Leu, and Rosen 2009).

4. Process Understanding and Modeling

New physics-based models of AM processes are needed to understand and predict material properties such as surface roughness and fatigue (Frazier 2010). A better understanding of the basic physics could then potentially lead to predictive modeling, allowing designers, engineers, scientists, and users to estimate the functional properties of the part during design and tweak the design to achieve desired outcomes.

5. Machine Qualification

Machine qualification standards could help machine-to-machine and part-to-part repeatability. Government qualification procedures can lead to further requirements on top of industry specifications; thus, streamlining these necessary processes as much as possible could help achieve greater uptake of additive technologies (Kinsella 2011). Along with a standardized materials properties database, qualification at a machine or process level could help reduce qualification time and effort (Frazier 2010).

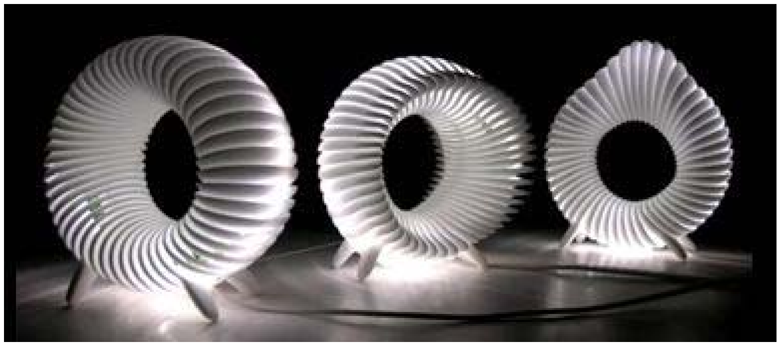
6. Machine Modularity

Many of the controllers and machine modules used for additive manufacturing have a closed architecture, making it difficult for users to test new build routines, materials, and so forth. Open architecture controllers and reconfigurable machine modules would enable a more manufacturing and research flexibility, similar to the path of computer numerically controlled (CNC) machining systems (Bourell, Leu, and Rosen 2009).

7. Design Tools and Software

Additive manufacturing requires the development of, and widespread access to, easy-to-use and affordable computer-aided design (CAD) tools at multiple levels. Solid-modeling software is required to use AM technologies, and estimates of total solid-modeling installations are surprisingly low, with only about 2.7 million commercial seats at the beginning of 2011 from the four major suppliers of CAD solid modeling software (Wohlers 2011). For direct part production, new tools are needed that can simultaneously optimize both shape and material properties (Frazier 2010) and design complex lattice structures that optimize reductions in material and weight.

For the nonprofessional markets, new web-based design tools could potentially allow nonspecialists to creatively design products to meet their needs. New, web-enabled co-design environments would bring together the talent of professional designers with novice users to personalize designs, as evidenced by the easy-to-manipulate lamp designs in Figure 1. Furthermore, Loughborough University's School of Design Research developed software that demonstrates the idea of co-creation. Using the Grasshopper plug-in for the popular Rhino design software, the university created PenCAD, an environment for developing 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.



Note: Photo courtesy of Digital Forming Ltd.

Figure 1. Three versions of a lighting design made possible by co-creation.

D. Emerging R&D

While some topics, such as achieving better material properties and higher throughput, have been around since the early days of additive manufacturing, new ideas have emerged in recent years. These topics involve such basic science as materials (metals, plastics, and composites), manufacturing systems, lightweight structures, conformal electronics, and conformal energy storage. They also include more applied areas, such as the environmental impact of additive manufacturing and improvements to the "back-end" of AM processes (e.g., support material removal, finishing, heat treatment, and inspection). The following subsections explore some of the most prominent emerging R&D areas across the field.

1. Energy and Electronics

The production of conformal electronics with additive manufacturing shows potential. The types of components that might be printed to conform to the shape of a product include energy storage devices (batteries), electronic sensors (e.g. RFIDs, strain gauges, and thermocouples), and electronic controls. The materials for these electronics would be deposited within the body of the housing, enclosure, or another section of a part as it is being manufactured. While no commercially available additive manufacturing process currently prints conformal electronics, the concept was demonstrated in 2005 in a joint project between Sandia National Laboratory and the University of Texas at El Paso (UTEP).

Cornell University has created parts that embed electronics, such as conductors and LEDs, using its Fab@Home system. The system was also used to produce a zinc battery and a polymer actuator. The battery powered the actuator, causing it to move.

In January 2011, UTEP opened the Structural and Printed Electronics Center, a facility that will conduct research to combine additive manufacturing and printed electronics technologies. Several other university researchers are conducting R&D or seeking funding in this area.

2. Exotic Structures

A variety of novel structural types are in various stages of development. For instance, researchers have already demonstrated functionally graded materials (Hascoet, Muller, and Mognol 2011), nanostructures (Ivanova, Williams, and Campbell 2011) and epitaxial metallic structures including single-crystal superalloys (Bansal et al. 2011).

Micro- and nano-additive manufacturing are also emerging. A project led by Lawrence Livermore National Laboratory is contributing to the significant improvement of additive manufacturing capabilities and advanced material design. The team is using a variety of techniques, including projection microstereolithography, direct ink writing, and electrophoretic deposition to engineer high-strength, low-density materials at the microscale (Meissner 2012).

3. Lightweighting

A topic with high potential impact is the development of lightweight structures. Additive manufacturing affords a novel manufacturing technique, wherein a structural member can be built with the requisite strength and stiffness but can be considerably lighter than its conventionally manufactured counterpart. One approach is to create a lattice structure, comprised of trusses or scaffolds, for the interior of a part. This has significant implications for improving energy efficiency in transportation since lighter structures require less energy to move. Further, building parts in this way uses less material compared to traditional manufacturing processes, which can significantly reduce material costs. Processing less material requires less build time, so higher throughput is another benefit to this approach. Further research and development needs include the enhancement of CAD software to automate the generation of complex lattice structures. Also, there’s a need to streamline the removal of the unsolidified build material from the interior volumes.

The use of topology optimization is another approach to producing light but strong parts. Airbus, for example, is using it to design metal brackets that are 50–80% lighter than their CNC-machined counterparts. When machining the brackets, about 80–90% of the expensive aerospace aluminum becomes scrap in the form of chips. The new process is not yet in production, but the company has dedicated significant resources to the development of this approach.

Approaches to building strong, lightweight structures are also used to create new, innovative designs. Figure 2 is a cutaway view of a heat exchanger built using additive manufacturing. The combination of special design software and metal additive manufacturing holds the potential for dramatically increasing efficiency in heat exchangers and considerably reducing production costs. However, currently only two companies—Netfabb and Within Technologies—offer commercial software products that create these internal structures, and both are in Europe. In the United States, a process called Conformal Lattice Structures is being developed by Paramount Industries in collaboration with Georgia Tech. This novel method of design—when combined with AM technology—could become a game-changing approach to the manufacture of many types of products.

Note: Photo courtesy of Within Technologies.

Figure 2. Heat Exchanger Cutaway View

4. Three-Dimensional Scanning

The efficient creation of 3D designs is a significant obstacle to the growth of additive manufacturing. Three-dimensional (3D) scanning has long been an option for "copying" physical objects and recreating them in a computer. Old parts that were designed before CAD became popular can be digitized in this way and then manufactured, often by additive manufacturing or other digital manufacturing techniques.

Recently 3D scanning has become less expensive and easier to use. For example, it is now possible to produce relatively crude 3D models from objects, such as faces, using Microsoft's inexpensive Kinect sensing device for the Xbox 360 video game console. A higher resolution approach to using the Kinect device, expected sometime this year, will produce better quality data, and thus, better 3D scans for less than a few hundred dollars. Using new algorithms can transform relatively crude scans into quality 3D surface mapping (Newcombe et al. 2011). This and other developments provide the opportunity to create far more 3D content than ever before. A number of additional 3D scanners and processing software options are available and affordable. Over the past several years, many organizations have integrated them into their product development processes.

5. Bioprinting

Custom medical implants and devices represent a market for additive manufacturing. For example, the Walter Reed National Military Medical Center demonstrated early success in producing and implanting porous cranial plates and cutting guides for bone grafts that are less expensive than existing alternatives and better matched with the patient.

One of the ultimate promises of additive manufacturing is the printing of human tissue. For many years, organizations have successfully printed bones that have survived and thrived in animals. The shape and size of a body part is captured and modeled in 3D on a computer using computed tomography (CT) or magnetic resonance imaging (MRI). This data is used to drive an AM machine that prints a porous scaffold structure made of an absorbable material such as hydroxyapatite. Living cells, preferably taken from the patient, are printed within the porous scaffold structure. Some soft tissue, such as that for a bladder, has been produced. The eventual goal is to manufacture complete organs, such as kidneys and hearts. One hurdle is printing blood vessels; without vascularization, organs will not survive.

6. Environmental Impact

Equitable metrics for measuring the environmental impacts and sustainability of AM processes are needed. To date, few studies have examined the variety of environmental impacts of additive manufacturing. Potential benefits over conventional manufacturing include the following:

- Efficient use of raw materials/feedstock as compared to conventional processes that often start with a solid billet of material, which is then machined down to specifications. When machining parts, scrap rates can be as high as 80–90 percent. Using additive manufacturing to produce the same part in metal reduces the scrap rate to 10 percent or less.
- Displacement of energy-inefficient processes such as casting and CNC machining to reduce environmentally unfriendly fluids and metal debris.
- Reduced need for fixed asset tooling as manufacturing shifts to more adaptive processes that require fewer pieces of specialty capital equipment.
- Lighter parts as a result of complex structures and concomitant transportation and fuel efficiencies
- More efficient heating or cooling channels, fluid paths, and other internal features that are not producible using conventional techniques.

- Potential for more localized production that could reduce the need for shipping. 3D models can be easily downloaded and printed, thereby supplanting long-distance transport and associated fuel.
- Dramatically reduced inventory and warehousing because additive manufacturing makes on-demand manufacturing possible.
- Consolidation of many parts into one, thus reducing tooling and manufacturing, part numbers, assembly, certification paperwork, and maintenance.

Agencies including the Department of Energy and the Environmental Protection Agency would be well suited to oversee the study of these topics. Resulting reports could provide support the business case needed by private industry and government agencies to adopt additive manufacturing.

E. Prizes and Challenges

Many of the aforementioned areas of R&D and technical challenges could benefit from incentive competitions that aim to spur and accelerate innovation. Prize competitions allow the public and the government to engage and co-create. Recognizing that prize competitions can allow the government to harvest the ingenuity of the public, the Obama administration has established policies and supporting tools to encourage innovation. In September 2009, the administration established the Strategy for American Innovation,[3] which encourages Federal agencies to increase their use of prizes (White House 2009).

These policies have spurred AM prize competitions such as the direct fabrication challenge sponsored by the Defense Advanced Research Projects Agency (DARPA) and made available through Challenge.gov. The 2011 Digital Manufacturing Analysis, Correlation, and Estimation (DMACE) Challenge asked participants to submit predictions and model descriptions for the maximum compressive load for a titanium sphere and cube configuration based on DARPA-provided data. DARPA's motivation for the December 2011, $50,000-prize competition was to challenge the science and engineering community to begin to understand the properties of structures created by additive manufacturing (DARPA 2011).

One industrially sponsored example is the Extreme Redesign 3D Printing Challenge by Stratasys. This competition has two engineering categories (secondary school and college levels) and an art and architectural category (open to all students) and tasks

[3] About the strategy: http://www.whitehouse.gov/administration/eop/nec/StrategyforAmericanInnovation/. This strategy was accompanied by a formal policy framework for prizes issued by the Office of Management and Budget in March 2010 (http://www.whitehouse.gov/sites/default/files/omb/assets/memoranda_2010/m10-11.pdf).

participants with developing innovative product designs, redesigns of existing products, or original works of art and architecture (Stratasys 2011).

One area that is especially well suited for a competition is innovative design software and web-based design tools. The challenge, possibly sponsored by an independent software vendor, could focus on the development of web interfaces that allow the co-design and co-creation of new products. Web tools would allow a professional designer to develop and make available a design that a novice could change and personalize within preset limits.

F. Pre-Competitive Opportunities

As already discussed, additive manufacturing still faces many technical challenges. Though the industry continues to grow, R&D budgets for many government agencies and Federal laboratories are shrinking, making it difficult to invest in AM research. One model that has been used in other industries to increase the effectiveness of R&D dollars is pre-competitive collaboration. Europe recently employed this approach in additive manufacturing when it established an Engineering and Physical Sciences Research Council Center in 2009 for Innovative Manufacturing in Additive Manufacturing. Hosted at Loughborough University, the center aims to provide a collaborative research environment that can benefit the UK industry in developing AM technologies, including multi-material processes and design systems. It is also aimed at fostering collaborations for the mutual benefit of small- to medium-sized enterprises, suppliers, and equipment manufacturers.

In the United States, one early benefit from collaboration in the AM industry was an early 1990s consortium that benchmarked the speed, cost, and accuracy of different AM systems. The consortium, funded by ManTech, was organized by the National Center for Manufacturing Sciences (NCMS) and involved United Technologies, Baxter Healthcare, and Texas Instruments. A benchmark part was designed, and many copies were built on several different AM systems by different independent organizations. The consortium compiled the results, and shared the speed and cost comparisons publicly with the user community. The effort also involved pilot demonstrations and case studies using AM technologies installed in industry and DOD depot locations. More than 30 case studies documented savings of over 600 man days and $2.2 million (NCMS 2003).

Due to the amount of intellectual property at stake, coupled with investments in experience and know-how that gives a company a competitive edge, some members of the AM industry have been hesitant to collaborate. One example of this is an attempt in early 2011 to bring the CEOs of the major AM companies together to move the industry forward as a whole. The goal of the Additive Manufacturing Branding Initiative (AMBI) was to create a better and stronger brand to increase awareness of the vast potential of the technology. Eighteen companies from the United States and Europe were represented.

The effort eventually failed, mainly because the participating companies were unwilling or unable to justify funding the work. This is an example of where matching funds from government might have been the difference between success and failure.

Despite the unsuccessful attempt of the AMBI, other members of the AM community have previously suggested two opportunities that would facilitate pre-competitive collaboration: a shared database of material properties and a national testbed center.

A shared database of mechanical properties for materials created by additive manufacturing was voted the most highly desired need at the Air Force AM workshop in 2009. Though the Edison Welding Institute is pursuing the development of a database for Titanium-6 Aluminum-4 Vanadium (Ti-6Al-4V) and Alloy 718 (a nickel-based alloy) produced by electron beam and laser additive manufacturing, other materials and process combinations need to be examined for other use cases outside of aerospace. After developing appropriate testing methods and protocols, the large amount of work required to document process, material grade, and other characteristics, demands coordination across government, academic, and industrial organizations. If successful, the payoff would be significant in providing an effective database and tool for screening candidate applications across multiple industries.

The establishment of a national testbed center to improve accessibility to expertise and equipment has also been discussed at AM events, including the 2009 Roadmap on Additive Manufacturing. Such a center, or network of sites, could provide the opportunity to expand the reach of additive manufacturing to small businesses and enable existing AM users to experiment with a range of materials and processes. This idea has also gained traction as a result of the President's recent announcement on March 8, 2012 to support a National Network of Manufacturing Institutes. One of the suggested areas of focus for an institute was 3D printing (*President Obama to Announce New Efforts to Support Manufacturing Innovation, Encourage Insourcing* 2012).

In order to identify other opportunities for pre-competitive collaboration, a group of government agencies such as NIST, DOE, and NASA, could co-sponsor an AM-specific "maker faire" for the technical community in which representatives from the government and OEMs, service providers, and academia convene to share hands-on experience and ideas in the spirit of information exchange. Such a setting could generate ideas similar to the RepRap[4] project, which is an example of pre-competitive collaboration that extends beyond industry and into the academic and personal-use communities.

4 RepRap, or replicating rapid prototyper, is an open-source project initiated in 2005 at the University of Bath to develop a 3D printer that can print its own components. More information on the project can be found at http://reprap.org.

G. Early Government Adoption

There is interest at several Federal organizations in advancing research and procurement of additive manufacturing for many types of components. For instance, the Air Force is conducting research on forms of additive manufacturing including metal parts for aircraft and heat exchangers, and plastic resins for remotely piloted vehicles. NASA is conducting research into fundamental materials science and tool development with an eventual goal of demonstrating additive manufacturing in remote locations like the international space station. The Navy is conducting research on how to rapidly qualify parts produced using new techniques like additive manufacturing to reduce acquisition times from between 8 and 28 months to between 2 and 7 weeks (Frazier and Pagett 2011).

Given the rising interest of Federal organizations and needs of the AM community, the government has several opportunities to act as an early adopter to accelerate market adoption. Examples of these opportunities, obtained through discussions with experts at various Federal organizations, are provided in the following sections.

1. Aerospace and Defense

A major opportunity is in combat and aerospace applications in the Department of Defense (DOD), Department of Energy (DOE), National Institute of Standards and Technology (NIST), National Aeronautics and Space Administration (NASA), and the intelligence community. Additive manufacturing has significant potential in combat and aerospace due to relatively low production runs, importance of lightweighting (producing lightweight products using less or lighter weight material) for many applications, and the potential for replacing physical inventories with digital parts inventories when space is at a premium, such as in underwater or space missions.

Within the aerospace industry, AM can help significantly reduce the high buy-to-fly ratios of cast, forged, and machined components. In these cases, the causes of higher costs are time, highly skilled labor (e.g., moldmaking), and high levels of scrapped material. AM can reduce and sometimes eliminate the need for tooling, thus helping to accelerate the development cycle for new parts.

a. Spare Parts

Managing spare parts for military weapon systems and space missions is a complicated, time-consuming, and expensive task involving large inventories (GAO 2008). Many military systems, including aircraft, are increasingly being used beyond their designed life expectancy, resulting in parts that are in danger of failure. Given that many of these parts are out of production, remaking them using traditional methods of manufacturing can often take multiple years, not including additional time for qualification and delivery. These problems not only require billions of dollars to support vast inventories but may necessitate long-term grounding of systems, threatening national security (GAO 2008).

Additive manufacturing has been identified as a potential solution to the spare parts inventory problem (Frazier 2010). The types of parts most likely to use on-demand additive production in the near term are parts smaller than 1 cubic foot and made of high-value materials. Shipping digital designs instead of parts could increase the efficiency of defense logistics and the infrastructure to support them, particularly by reducing inventories kept in the field. Less energy would be used to transport, package, and store the spare parts. This reduction of storage would have a large benefit for space-constrained systems such as submarines, which require a large number of spare parts when in service.

b. Maintenance and Repair

One emerging use of additive manufacturing is the repair of valuable, damaged parts and tools. Since the processes used for repair can work locally outside of a build chamber, repairs can be performed on parts and tools that are substantially larger than can be built by most AM machines. For instance, the Army has used the laser engineered net shaping (LENS) process developed by Sandia National Laboratories in the 1990s to repair turbines on M1 Abrams tanks (Fink 2009).

2. Medical Uses

Another opportunity is in the use of AM medical devices, including models and devices for planning and conducting surgery and custom surgical implants (Christensen 2011). The Army, through the Walter Reed National Military Medical Center (WRNMMC), has been a pioneer in the design and use of custom medical implants, surgical guides, and medical models.

a. Medical Models and Surgical Guides

Walter Reed established a center for additive manufacturing in 2002. Originally, the team had only one stereolithography machine and was only using it for medical modeling purposes. Each medical model is usually a unique representation of what was often severe damage from the battlefield. The model offers major cost savings by cutting an average of six hours off surgery time. This reduces operating room time and the associated risk to the patient involved with being in surgery for so long. It also reduces the number of repeat surgeries that are needed because they can be done right the first time (Rouse 2012). WRNMMC has also used additive manufacturing to create custom surgical guides, which, for example, allow surgeons to take exact cuts from bones to create the kinds of grafts they need.

b. Custom Metal Implants

The main use case in medicine for metal parts made from additive manufacturing are for complicated custom implants such as cranial plates. WRNMMC routinely designs implants almost half a skull in size, which often cannot be made well by any other means. These types of plates are not just for wounds from bullets and improvised explosive devices but also injuries from car accidents, motorcycle accidents, and other noncombat purposes. WRNMMC strives to also use additive technologies in ways that could be transferred to the civilian space (Rouse 2012).

Manufacturing custom implants can be as cost effective as other techniques for certain applications, with the added advantage of providing a better fit. For instance, a recent cost estimate for a cranial implant was around $15,000 for a conventional cranial implant, plus $200 for a plate and $100 for five screws. When using additive manufacturing to produce a cranial implant at WRNMMC, the plates and screws are not needed because they are all integrated into the design, and the material cost is only about $75. Of course, the capital cost of the AM machine must be depreciated to make a fair comparison. Even so, a custom implant offers several advantages such as making the operation less complex and reducing operating room time (Rouse 2012).

c. Prosthetics

Another potential early adoption opportunity for additive manufacturing in the medical field is custom prosthetics. Prosthetics and orthotics were relatively early uses of additive manufacturing due to the ability to produce custom-fit parts for highly variable joints, amputated limbs, and cavities (such as ears for hearing aids) (Lipson 2011). Additionally, for areas where aesthetics are important, additive manufacturing can be used to create a custom fit prosthesis that matches its surroundings while still achieving high strength-to-weight ratios.

H. Workshops and Technical Roadmaps

Over the years, the number of regular conferences aimed at advancing AM technologies has grown. Some of the most prominent examples include the Society of Manufacturing Engineers RAPID conference and exposition in the United States as well the EuroMold trade fair in Germany. Both events are focused mostly on industry while other events, such as the annual Solid Freeform Fabrication symposium at the University of Texas, are aimed at the academic community. In addition to the aforementioned meetings, there have been workshops and roadmapping events dedicated to additive manufacturing, as highlighted in Table 2, that have covered a rather comprehensive range of issues.

The World Technology Evaluation Center played a big role in mapping the field during its two studies, one in 1997 on what was then called rapid prototyping and one in

2003 that focused on Europe and additive as well as subtractive processes. These two reports helped benchmark the technology during its early days, focusing on the U.S. position relative to other countries that utilized AM processes.

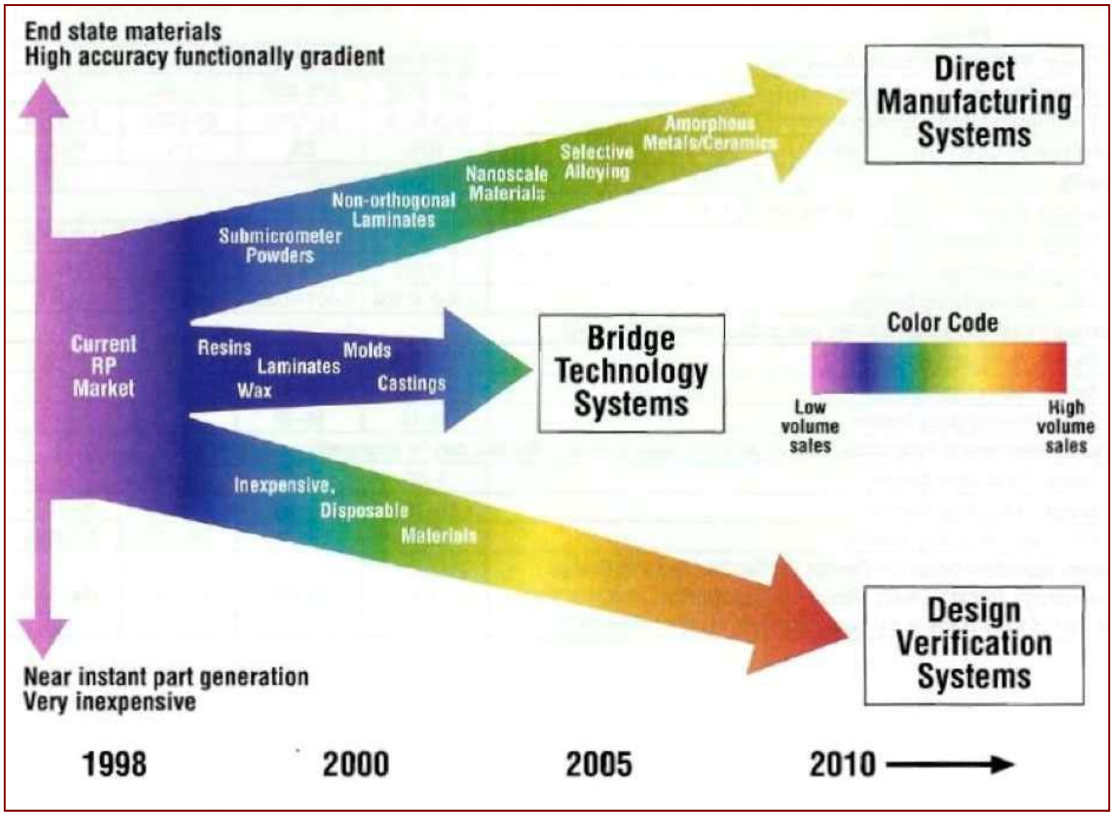
Table 2. List of Previous Additive Manufacturing Workshop and Roadmapping Events

Year	Event Name	Sponsor(s)
1997	WTEC Rapid Prototyping in Europe and Japan	NSF, DOE, DARPA, ONR, DOC
1998	The Road to Manufacturing:1998 Industrial Roadmap for the Rapid Prototyping Industry	National Center for Manufacturing Sciences
2003	WTEC Workshop on Additive/Subtractive Manufacturing R&D in Europe	NSF, DARPA, ONR, NIST
2009	Roadmap for Additive Manufacturing Workshop	NSF, ONR
2009	Additive Manufacturing Workshop	Air Force ManTech, Metals Affordability Initiative
2010	Direct Digital Manufacturing of Metallic Components	ONR, NAVAIR
2010	Additive Manufacturing Consortium Kick-Off Meeting	Edison Welding Institute
2011	Direct Part Manufacturing Workshop	Society for the Advancement of Material and Process Engineering-Midwest Chapter
2012	Additive Manufacturing Workshop	Oak Ridge National Laboratory

Another of the earliest gatherings was the 1998 National Center for Manufacturing Sciences-led development of a roadmap for the additive manufacturing industry, then referred to as “rapid prototyping” The effort was supported by many industrial, government, and academic organizations in the United States and culminated in a roadmap report. The roadmap divided the industry into three subcategories: design verification systems, bridge technology systems, and direct manufacturing systems. It then predicted an evolutionary path of the industry, as shown in Figure 3. The now 14-year-old graphic remains reasonably accurate as the industry has evolved mostly as mapped. The primary difference is that the terminology has changed.

In more recent years, one of the most well-known activities was the 2009 Roadmap for Additive Manufacturing (RAM) Workshop, which included 65 experts from academia, industry, and government. Its purpose was to develop a roadmap for research in additive manufacturing for the next 10–12 years. Participants were invited to submit white papers before the workshop that present their thoughts on the future of additive manufacturing and how research might impact the path to that future. The workshop summary document included 26 specific recommendations spanning a range of categories and ultimately focused more heavily on a research agenda than providing a specific roadmap.

The 2009 RAM Workshop was the primary inspiration behind the formation of the Additive Manufacturing Consortium (AMC), an important effort launched in 2010 by the Edison Welding Institute, a nonprofit organization that operates centers and consortia for the advancement of various technologies. The AMC has become a forum in which to continue many of the topics of discussion from the original 2009 workshop and to share best practices across the 33 participating government, university, and industry members and partners.



Note: Diagram Courtesy of National Center for Manufacturing Sciences.

Figure 3. "Evolutionary Path of Rapid Prototyping" from the 1998 roadmap "The Road to Manufacturing."

In 2009 and 2010, the Air Force and Navy held AM workshops, respectively. Though both workshops involved participants from government, academia, and industry, their workshop goals remained mission oriented. In 2011, the Society for the Advancement of Material and Process Engineering hosted a workshop that also brought together a diverse set of participants but with the stated focus of direct part manufacturing. Lastly, Oak Ridge National Laboratory, together with the Scientific and Technical Intelligence Committee, hosted an additive manufacturing workshop in February of 2012, assembling a mix of industry experts and analysts, technology developers, researchers, and end-users from the defense and aerospace industries to discuss the state-of-the-art in the field.

While these events helped advance additive manufacturing in many ways, most activities were assembled around specific agency or organizational interests. Coordination across the AM community remains fragmented. Thus, there is a need to engage all AM stakeholders—including individuals from government, academia, and industry—at a workshop to discuss common issues of importance that span all organizations and markets. The White House Office of Science and Technology Policy is ideally suited to sponsor such a workshop to take the focus away from individual agencies or groups and emphasize the opportunities for increased collaboration and coordination. Possible topics for discussion include the technical challenges presented in Section C and the needs of emerging R&D in Section D. Regardless of the topics chosen for the workshop, it is important that participants be interested in moving the entire industry forward, not just the work of their own organizations.

I. Standards Development

Standards and technical specifications are unanimously recognized as being critical to the growth and maturity of any industry. Technical compatibility and standards setting have been central to the adoption of technologies, ranging from household appliances to electronics and computing software. Reference and minimum quality standards indicate that the product conforms to a certain specification, while interface or "compatibility" standards indicate that a product can be inserted into systems provided by different suppliers who conform to the same standards (David and Greenstein 1990). Material properties are a classic example of reference standards, while fuel economy standards are a minimum quality requirement in the automobile industry. Standards ensure good product quality, and thereby market acceptance, driving the adoption of new technologies. They also provide a foundation for companies to innovate and compete by ensuring a level playing field (Phelps 2006).

Recognized industry standards have been lacking in the field of additive manufacturing. The ASTM International Committee F42 on Additive Manufacturing Technologies was formed in 2009 in response to the need for industry standards. The launch of this standards initiative was driven by a cooperative effort between ASTM International and the Society of Manufacturing Engineers (SME). The committee's goal is to develop consensus standards that will support the adoption of AM across multiple industry sectors (Manufacturing Engineering 2009; Nelson 2009) by:

- Establishing standards to allow manufacturers to measure and compare the performance of different AM processes and materials

- Accurately specifying and standardizing part-building requirements to give purchasers and suppliers a common set of parameters to work with, improving vendor relationships
- Helping new users adopt AM technologies
- Developing comprehensive standards to provide users with uniform procedures for the calibration of AM machines and testing the performance of these machines

The ASTM International F42 committee has four main technical subcommittees that develop standards: materials and processes, terminology, design and data formats, and test methods.

1. Progress to Date

One of the first activities of the F42 committee was to establish standard terminology for the field of additive manufacturing, including processing technologies and other terms associated with the domain (ASTM Standard F2792 2012). The effort is intended to "help clarify communications" within the AM community, especially in industries like medical manufacturing and aerospace where consistency is essential (Canadian Plastics 2010). Material types and characteristics such as orientation and grain structure are particularly important in areas such as aerospace (Brice 2012) and medical devices where products and parts produced by additive manufacturing undergo significant qualification and regulatory testing processes.

The National Institute for Standards and Technology (NIST) is playing a role in the development of AM standards. At NIST, the program for Materials Standards provides the measurement science for the AM industry to measure material properties in a standardized way. Material characterization test methods for powders used in additive manufacturing would provide the industry with an established method for verifying and confirming properties of powders used in AM, and therefore instill confidence in the properties of the final product. The program, started in October 2011, has assisted with the recently developed ASTM standard specification for the additive manufacturing of Ti-6Al-4V for powder bed fusion systems.

The NIST project for Fundamental Measurement Science for Additive Processes is establishing standardized methods for evaluating AM processes and equipment, with current and planned research activities directed at evaluating errors and variability in equipment functioning (e.g., thermal errors, alignment and positioning accuracy of laser motion and repeatability of powder delivery for layers of various thicknesses), process characteristics within the build chamber (e.g., uniformity of heat distribution and gas flow), and in situ process measurement.

The ASTM F2915 "Specification for Additive Manufacturing File (AMF) Format" was approved in July 2011. It serves as an alternative to the STL file format, which has been in use to transfer 3D model data to AM systems since 1987. AMF is based on XML (an open standard markup language) and supports units, color, textures, curved triangles, lattice structures, and functionally graded materials—features that the STL format does not support. Also, an AMF file is about half the size of a compressed STL file.

Four ASTM F42 standards have been published to date. Meanwhile, several new ASTM standards are in progress and can be expected soon. The following is a sampling of the work that is underway:

- Material qualification and traceability of metals using powder bed fusion
- Metrics for initial machine conditioning
- New specification for polymers, including polyamides, using powder bed fusion
- New test method for tension testing of additive manufacturing materials
- New specification for additive manufacturing Nickel Alloy (UNS N07718) with powder bed fusion
- New terminology for lattice structures

2. International Developments

In 2011, ASTM International and ISO signed a cooperation agreement to govern ongoing collaborative efforts between ASTM F42 and ISO Technical Committee 261 on Additive Manufacturing. The agreement means that ASTM standards will be fast-tracked into the ISO final draft and the two bodies will mutually reference their standards in the publications of the other organization's directives (Langau 2011). It is expected that new and existing ASTM standards on additive manufacturing will be "co-branded" and published by both ASTM and ISO. This is seen as a significant development because it should reduce, perhaps even eliminate, conflicting and competing international standards on additive manufacturing. The agreement is the first of its kind between the two organizations.

3. Barriers

Additive manufacturing has the ability to create geometrically complex parts, making it attractive for medical devices that require a high degree of customization, as well as products produced in small or variable batch sizes. But the growth of the additive manufacturing industry is contingent on product, process, and material certifications that conform to internationally recognized standards (Bourell, Leu, and Rosen 2009).

Aerospace companies have a need for parts that are manufactured in low quantities and require repair and replacement frequently, which makes additive manufacturing an economically attractive option for use by this industry. However, the lack of standards in additive manufacturing impedes its use for parts production. The U.S. Federal Aviation

Regulations have stringent requirements for material performance factors ranging from fatigue, creep, and tests of flammability and toxicity to process sustainability and cost. Manufacturers in the aerospace and defense industries depend on established standards in materials and processes to ensure the consistency and quality that would allow their products to be certified for use (National Academy of Engineering 2012). Furthermore, the inherent differences in additive manufacturing, compared to traditional manufacturing techniques, will likely necessitate modifications to standard validation, verification, and certification procedures.

Parts produced by additive manufacturing will need to meet the levels of performance established by traditional manufacturing methods to be qualified for use. Related to this is the need to establish repeatable processes and reproducible parts, particularly in medical, aerospace, and automotive industries. Systems will need to be in place to track the source of a problem in the event of product failure.

J. Education

Additive manufacturing holds great potential to engage a broad population—not just students—in science, technology, engineering, and mathematics (STEM) through formal and informal settings. However, most of the AM literature to date has focused on technical challenges, R&D, and applications rather than the educational potential of the technology. As discussed in the following sections, advancing the field of AM could challenge traditional manufacturing pedagogy by requiring new methods of design. Additionally, increased accessibility to AM tools could have profound impacts on STEM engagement through increased visualization and hands-on experiences.

1. Educational Needs

Most products built today are designed for manufacturing and assembly, meaning that designers tailor a product to minimize processing or assembly difficulties. For example, if it is impossible to remove a part from a mold, the part is redesigned. This has been the traditional paradigm for product design over the course of the last century. Thus, many of today’s product engineers lack the tools and knowledge to take full advantage of the ability of additive manufacturing to alleviate many of the constraints of traditional design approaches. Taking full advantage of additive manufacturing will require educating the current workforce, recruiting a new generation of students, developing proper design tools, and implementing appropriate changes in longstanding procedures such as verification and validation of components.

Community colleges are an excellent gateway to exposing students to additive manufacturing techniques, and their courses tend to be adaptable to recent trends. Encouraging partnerships with regional companies could provide an excellent means of recruiting the workforce required to advance additive manufacturing. Through the

Advanced Technological Education initiatives aimed at two-year colleges, the National Science Foundation (NSF) is developing curricula through its Technician Education in Additive Manufacturing (TEAM) program.[5] As part of this work, two ATE centers—MateEd at Edmonds Community College and RapidTech at Saddleback College and housed at the University of California, Irvine—are developing core competencies and curricula. RapidTech and MatEd are pioneering AM curricula, and can serve as models for expansion. To date, few educational institutions have developed or have access to books, instructional guides, and other educational materials needed for courses and lab activities in additive manufacturing.

2. Broadening STEM Engagement

A recent initiative related to formal secondary education includes the DARPA Manufacturing Experimentation and Outreach (MENTOR) program in which 1,000 high schools will receive 3D printers (DARPA 2010). Curriculum development is also part of the program, which aims to expose high school students in design concepts and collaboration. The program is still in its initial phases but is planned to be fully rolled out over the next four years.

Another way that additive manufacturing has engaged students and adults in STEM is through "makerspaces."[6] Worldwide, there are about 500 active or planned makerspaces that often include one or more 3D printers as part of an arsenal of machine tools. Similarly, libraries are beginning to offer various equipment, including CNC machines and the like, where do-it-yourselfers can work on ideas and learn through short courses they offer (Kalish 2011). "Techshops," a fee-based version of makerspaces, are also beginning to serve as pilot centers and incubators as a result of the dramatic expansion of access to tools. As a result of the reduced costs of access to high-priced equipment, a increasing number of people can now make prototypes or finished products.

One area where additive manufacturing excels is in presenting standard, 2D information from textbooks in tangible, 3D format. Ultimately, this helps students better comprehend complex, difficult-to-understand topics such as chemical and biological phenomena. For instance, a professor at the University of Rhode Island uses 3D printing to produce physical models of molecules that help teach the basics of drug interactions and the effects of diseases (Lavallee 2011). Examples such as these demonstrate how additive manufacturing can bring design education to a new level of immediate

[5] More information on TEAM can be found at the following website: http://www.materialseducation.org/educators/team/.

[6] A makerspaces is a shared facility that provides the tools and forum for tinkering and collaborating among the members of the space. "Maker" is borrowed from the movement that has given rise to workshops such as these. Typically, membership dues are used to pay building rent and buy or maintain equipment.

recognition of a physical model, thus bringing the manufacturing experience to a personal level.

The availability of low-cost additive manufacturing and 3D printing is creating the opportunity for multi-disciplinary labs and makerspaces at primary, secondary, and postsecondary schools across our nation. These programs can include traditional engineering and manufacturing, as well as biological sciences (molecular modeling), medicine (orthopedic implants and tissue engineering), fashion design (clothing, footwear, and jewelry), sports science (protective gear), law enforcement and forensics (recreation of crime scenes), archaeology (bones and artifacts), interior design (space and facilities planning), and architecture (scaled models). Also, AM presents the opportunity to bring back manufacturing programs at our nation's universities, but in the form of advanced product development and additive manufacturing.

As prices of consumer-level, desktop AM machines decrease, there may also be an opportunity to create 3D printers for children. A prototype design, expected to be priced at around $800, has already been designed by the European company, Origo. Similar to the way that makerspaces give adults a space to tinker and experiment with STEM concepts, a 3D printer at home could offer children the same opportunity to explore their ideas and learn by doing.

K. Conclusion

Over the past three decades, additive manufacturing has emerged from its early days as a prototyping process into a set of advanced processes that are becoming increasingly accessible to businesses, government organizations, and individual consumers. Although the industry has grown significantly in recent years, opportunities remain for advancing the state of additive manufacturing and furthering its economic, educational, and environmental benefits. In this work, a number of opportunities were highlighted:

- Many technical challenges, including process control and modeling, would benefit from new or additional Small Business Innovation Research funding or other R&D funding opportunities.
- Challenges or prizes could be organized in areas such as design software and web-based design tools to broaden accessibility to a larger set of non-expert users.
- Two pre-competitive opportunities have been the subject of numerous discussions in the AM community and include the development of a database of material properties and the establishment of a national testbed center.
- A government agency or group of stakeholders could sponsor an AM-specific "maker faire" for the technical community in which representatives from the

government and OEMs, service providers, and academia convene to share ideas and hands-on experience in the spirit of information exchange.

- Supporting the expansion of programs such as Walter Reed National Military Medical Center's pioneering design and use of custom medical implants, surgical guides, and medical models could accelerate wider adoption throughout the public and private sector.
- Due to fragmented coordination of the AM community, there is a need to engage all stakeholders–including individuals from government, academia, and industry–at a workshop to discuss common issues of importance that span all organizations and markets.
- Inherent differences in additive manufacturing compared to traditional manufacturing techniques will likely necessitate modifications to standard validation, verification, and certification procedures.
- Additive manufacturing enables new ways of teaching topics that can further engage young people and adults in STEM.

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