Roadmap for Additive Manufacturing
Identifying the Future of Freeform Processing

2009
Roadmap for Additive Manufacturing
Identifying the Future of Freeform Processing

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At the 2008 meeting of the International Solid Freeform Fabrication Symposium, a small number of attendees, considered established leaders in the field, met to discuss the future of freeform fabrication. Including the three organizers of the workshop serving as a basis for this document, that group concluded that the time was right for a workshop specifically devoted to this subject with a roadmap theme. The workshop would gather experts in the field and selected practitioners with the goal of defining a future path for expeditious development of freeform technologies. This was the basis for this workshop.

The Roadmap for Additive Manufacturing (RAM) Workshop was held in Alexandria VA at the NSF Stafford Building on March 30-31, 2009. The meeting was attended by 65 persons representing universities, industry and the US government [NSF, ONR, DARPA, NIST, NIST-MEP, NIH, AFRL, and NASA (Langley)]. The objective of the workshop was to develop a roadmap for research in the area of additive manufacturing (AM) for the next 10-12 years. The results are formulated as topical recommendations for research in areas associated with the chapter titles in this report. It is arguable that the outcome is more a research agenda than a roadmap per se. Nonetheless, we are convinced that the results of this effort serve to define a direction for AM research pointing our best understanding of where the technology needs to be in the midterm. The principal outcomes of this effort should be acceleration of integration of freeform technologies into the marketplace; identification of potential, fruitful research areas for freeform fabrication for the next 5-10 years; networking of leading experts in the field from industry, academia and government with synergistic results; and thoughtful, systematic layout of a plan for freeform fabrication research for the near and medium term.

The workshop consisted of keynote briefing presentations with ample time for discussion. Breakout sessions served as the foundation for chapters in this document. Participants were invited to submit two-page white papers prior to the meeting on what the future of AM might be and how research might impact the path to that future. These white papers are included as an appendix to this document.

The PIs are grateful for participant support funding from the National Science Foundation under Grant Number CMMI-0906212 and the Office of Naval Research under Grant Number N00014-09-1-0558. We would also like to thank once again the keynote speakers and the breakout chairs who wrote first drafts of the chapters. Finally, we are grateful for the 65 persons who took time to contribute to this effort.

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EXECUTIVE SUMMARY

Modern additive manufacturing (AM) traces back to the mid 1980s with the advent of stereolithography. In the late 1980s and early 1990s a plethora of AM processes appeared. Over the ensuing twenty years, the research community has applied these processes and process variations in novel ways to attack a wide variety of research problems in a diverse number of technical areas. The impact of additive manufacturing continues to grow, in terms of both commercial and scholarly activities. Two WTEC studies were performed on AM in Europe and Japan in 1996. An NCMS roadmap study on AM was completed two years later, which emphasized industrial applications of the technology. In 2003, another WTEC study was performed to assess the level of activity in Europe in additive/subtractive technologies. The reports from these events provide key data points and serve as the basis for the present roadmap study.

The objective of the present workshop “Roadmap for Additive Manufacturing (RAM) Workshop: Identifying the Future of Freeform Processing” was to develop and articulate a roadmap for research in the area of additive manufacturing for the next 10-12 years. The workshop was intended to: accelerate the integration of AM technologies into the marketplace; identify potential, fruitful research areas for additive manufacturing for the next 5-10 years; network leading experts in the field from industry, academia and government with synergistic results; lay out a thoughtful and systematic plan for additive manufacturing research for the near and medium term.

The workshop was attended by 65 key people in the AM field from academia, industry and government. It included four keynote presentations with follow-on discussions to broadly identify trends, barriers, opportunities, milestones, and vocabulary of additive manufacturing. This was followed by seven breakout sessions to simultaneously develop research needs and issues on: Industry Targets, Technological Goals & Barriers, Design and Analysis, Processes & Machines, Materials & Processing, Bio-Additive Manufacturing, and Energy & Sustainability. This workshop report summarizes the discussion results, with one chapter for each breakout topic and the last chapter providing recommendations for future research.

The main recommendations from the workshop are summarized below:

**Design**

- Create conceptual design methods to aid designers in defining and exploring design spaces enabled by AM.
- Produce a new foundation for computer-aided design systems to overcome the limitations of existing solid modeling in representing complex geometries and multiple materials.
- Provide a multiscale modeling and inverse design methodology to assist in navigating complex process-structure-property relationships.
- Create methods to model and design with variability: shape, properties, process, etc.
Process Modeling and Control

- Develop predictive process-structure-property relationships integrated with CAD/E/M tools.
- Create closed-loop and adaptive control systems with feedforward and feedback capabilities. Control system algorithms must be based on predictive models of system response to process changes.
- Produce new sensors that can operate in build chamber environments and sensor fusion methods.

Materials, Processes and Machines

- Develop a better understanding of the basic physics of AM processes to capture the complexity in the multiple interacting physical phenomena.
- Create scalable, fast line or area material processing methods to greatly increase machine throughput.
- Create open-architecture controllers and reconfigurable machine modules.
- Exploit unique AM characteristics to produce epitaxial metallic structures, fabricate parts with multiple and functionally gradient materials, and embed components during fabrication processes.
- Develop screening methodologies to answer the question as to why some materials are processable by AM and some are not.
- Develop tools for AM fabrication of structures and devices atom by atom and design for nanomanufacturing.
- Develop and identify sustainable (green) materials including recyclable, reusable, and biodegradable materials.

Biomedical Applications

- Create design and modeling methods for customized implants and medical devices.
- Develop viable Bio-AM (BAM) processes for fabrication of “smart scaffolds” and for construction of 3D biological and tissue models using living biologics.
- Create computer-aided BAM including modeling, analysis and simulation of cell responses and cell-tissue growth behavior.

Energy and Sustainability Applications

- Design energy system components to take advantage of AM capabilities.
- Pursue Maintenance, Repair, and Overhaul (MRO) as a potential AM application.
- Develop equitable indicators for measuring sustainability in AM processes and products.
- Identify sustainable engineering materials for AM processes.
Education

- Develop university courses, education materials, and curricula at both the undergraduate and graduate levels, as well as at the technical college level.
- Develop training programs for industry practitioners with certifications given by professional societies or organizations.

Development and Community

- Reduce machine, material and servicing costs to ensure the affordability of AM in relation to conventional manufacturing.
- Develop and adopt internationally recognized standards (such as those recently initiated by ASTM Committee F42) which are useful to product, process and material certification.

National Testbed Center

- Establish a national testbed center with distributed AM machines and/or expert users to leverage equipment and human resources in future research and to exemplify the cyber-enabled manufacturing research concept.

Successful completion of the above recommendations will lead to significant benefits on affordability, maintainability, reliability, rapidity and functionality in practical applications of AM. Not only will the technologies become more adopted by the technical community with AM expertise, but there is a great potential for catalyzing the use of AM technologies by a broad population of entrepreneurs. The combined economic impact could be very compelling.
CHAPTER 1 – INTRODUCTION

1.1 Additive Manufacturing Research and Technology

Modern additive manufacturing (AM) may trace back to the mid 1980s with the advent of stereolithography [1]. Critical enabling developments included the advent of desktop computers and the economic development and availability of industrial lasers. In the late 1980s and early 1990s a plethora of AM processes appeared including but not limited to selective laser sintering, laminated object manufacturing, fused deposition modeling and 3D printing. Over the ensuing twenty years, the research community has applied these processes and process variations in novel ways to attack a wide variety of research problems in a diverse number of technical areas including automotive, aerospace, biomedical, energy, and consumer goods. The impact of AM continues to grow, in terms of the total number of parts generated, the number of machines sold, and the amount of scholarly activity in the form of publications and patents [2].

A series of previous events and reports provides a context and historical trajectories of progress in AM. Two WTEC studies were performed on rapid prototyping in Europe and Japan in 1996 [3]. Subsequently, a roadmap study for rapid prototyping was completed two years later [4]. Sponsored by the National Center for Manufacturing Sciences, this roadmap emphasized rapid prototyping with a strong industrial bent. In 2003, a second WTEC study was performed to assess the level of activity in Europe in additive/subtractive technologies [5]. The reports and roadmap from these events provide key data points from which trends can be extrapolated for the proposed roadmap study. By way of contrast, the present workshop effort differentiated itself from these earlier activities by being up to date, by emphasizing domestic rather than foreign activity and by assessing broad application and future potential with emphasis on the role of manufacturing research as an enabling activity.

Over the lifetime of the technical field, numerous terminologies have been used to describe it: freeform fabrication, direct digital manufacturing, rapid manufacturing, additive fabrication, additive manufacturing, etc. Partially in deference to the recently formed ASTM F42 Technical Committee on Additive Manufacturing, the last term in the list was chosen for this document. It is taken in its broadest terms to include AM of prototypes, tools, patterns, and concept parts as well as functional devices for direct application and service.

1.2 The Present Workshop Effort

To develop an encompassing vision of the challenges and opportunities in AM, the workshop brought together a highly diverse assembly of persons whose commonality was AM. Represented were expert practitioners (end-use customers, service bureaus), machine builders (OEMs, company executives), technology contributors (in reverse engineering, inspection, modeling), advanced manufacturing industry watchdogs, academics with strong industrial ties to AM, inventors of AM processes, creative AM researchers with long track records, leading experts in sustainability and energy, and government stakeholders invested in the field.

A pictorial view of the progression of activities and information at the Roadmap Workshop is shown in Figure 1.1. Keynote presentations addressed where the AM field is, where it should be in 10-12 years and where the obstacles/challenges are. Additionally, the group identified the vocabulary with which to articulate key concepts in each area and also classified those concepts according to their causes and effects. The key notes and speakers were:
The workshop attendees participated in one of seven breakout groups that addressed specific topics listed in Table 1.2. From each group, a chapter in this document was drafted by the respective breakout chair that summarizes the group discussion with regards to targets, barriers, milestones, vocabulary, trends, etc.

Table 1.2 Breakout Sessions and Chairs.

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<th>Breakout Number</th>
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<td>B1</td>
<td>Industry Targets</td>
<td>Terry Wohlers, Wohlers Associates</td>
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<tr>
<td>B2</td>
<td>Technological Goals, Barriers</td>
<td>Richard Hague, Loughborough Univ.</td>
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<tr>
<td>B3</td>
<td>Design and Analysis</td>
<td>David Rosen, Georgia Tech</td>
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<tr>
<td>B4</td>
<td>Processes and Machines</td>
<td>Brent Stucker, Utah State Univ.</td>
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<tr>
<td>B5</td>
<td>Materials and Processing</td>
<td>Dave Bourell, Univ. Texas, Austin</td>
</tr>
<tr>
<td>B6</td>
<td>Nano and Biotechnologies</td>
<td>Wei Sun, Drexel University</td>
</tr>
<tr>
<td>B7</td>
<td>Energy and Sustainability</td>
<td>Hong-Chao Zhang, Texas Tech</td>
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Finally, Figure 1.2 embodies graphically the vision of the workshop participants for AM research. The tree model is effective. At the base are the various AM processes. The trunk of the tree represents the research and development efforts which spring from these technologies. The branches are representative samples of outcomes and benefits of these efforts, reflected in the research needs and opportunities in this document. It is expected that new applications and benefits will grow in time, and that other applications will branch into significant subcategories similar to the Medical and Art Branches.
1.3 References


CHAPTER 2  INDUSTRY TARGETS

2.1 Introduction
Additive manufacturing (AM) technology cuts across a large number of industries and applications, and that is part of what makes its potential so compelling. Aerospace, automotive, medical and consumer products will drive AM into the future. From these core industries alone, vast amounts of research and investment will propel AM technology to new heights. Other industries, including the military, dentistry, jewelry, video game avatars, collectables, construction, furniture and home accessories and toys, will also play an important role in the future development of AM technology and its application.

Many of the parts produced by additive manufacturing will go into or become custom, semi-custom, and limited edition products. Others will serve as replacement parts for weapon systems, marine products, land and air vehicles and other products. New types of businesses will unleash new types of products that were previously impractical due to cost, risk, or manufacturability. Many companies will discover that AM can serve as a strategic bridge between a finished design and production tooling, allowing them to deliver products to customers more quickly than before. Other companies will find that AM will be the manufacturing process of choice, even for relatively large production runs.

2.2 Barriers and Challenges
The cost of machines, materials, and maintenance is seen as an obstacle to wider adoption of AM technology. According to Greg Stein of Northrop Grumman, aerospace companies often require a 3:1 return on its investment, meaning that for every dollar spent on AM, it must receive $3 in return to cover implementation and maintenance costs. For companies that are comparing an existing manufacturing process to AM, it is believed that many must realize a gain of at least 30-40% when replacing the old with the new. Anything less is usually not worth the risk and hassle of replacing a proven method with one that is new and uncertain. The perceived risk and expected returns vary widely from company to company.

Cost is only one factor that influences the adoption of an entirely new process or the launching of a new business based on a new process. Time to market is another important one. Some companies are willing to pay a premium if the time savings are significant. Additive manufacturing presents the opportunity to reduce the part count in a product by consolidating two or more parts into a single design. Additionally, complex parts can often be produced in less time with AM. Additive manufacturing integrates very well with design tools and CAD software. This approach can significantly impact both time and cost savings, as well as inventory, supply chain management, assembly, weight, and maintenance.

For many industries, the breadth of materials available—or the lack of them—is a barrier. This is especially true in the aerospace industry where it needs materials that can withstand high temperatures. Stein reported that one aerospace program requires materials that can operate at a continuous temperature of 132º C (270º F).

Currently, AM is not viewed by most industries as a viable method of manufacturing. Improving the technology to the point of changing this mindset is a critical target for the next 10-12 years. Also, organizations must be able to manufacture products with AM that are consistent across machines, operators, and manufacturing facilities. Today, this is a serious shortcoming. To
overcome this problem, the industry must develop process standards (e.g., for machine calibration), and standards for performance-based testing of parts. There is also a need for AM systems that can produce large parts for aerospace, marine, and other industries.

2.3 Needs and Potential for Industrial Impact

**Aerospace:** The aerospace industry desires parts that are lightweight and strong and sometimes electrically conductive. They are seeking a standard set of AM materials, as well as a design manual for the materials and processes, but neither are currently available. Furthermore, they require material and process standards that ensure part quality and consistency across machines and builds.

According to Stein, his company has identified 1,400 parts that could be manufactured by AM for one of its military aircraft programs if the right materials were available. The challenge, therefore, is to develop AM plastics and metals, along with testing standards to ensure quality and consistency that meet the needs of leading aerospace manufacturers. Successfully meeting this challenge would result in AM being used more aggressively for the testing of new air foil and turbine blade designs.

Already, turbine blades made by direct metal laser sintering (DMLS) from EOS (a German manufacturer of laser sintering/melting systems) have found their way onto test rigs. Morris Technologies believes that a variety of metal parts made by additive manufacturing will initially make their way onto flying aircraft in 2-3 years and will become common in 10 years. Morris Technologies has extensive experience with producing turbine blades and other parts for gas turbine engines using additive manufacturing technology. The opportunity is not only for flight hardware, but also for jet-powered boats, land-based power generators, and other applications of gas turbine engines.

**Military:** Many products for the U.S. military are of high value, complex, and produced in relatively low volumes. Some are custom, and the need for replacement parts is ongoing. Among them are unmanned aerial vehicles (UAVs), lightweight gear and armor for soldiers, portable power units, communication devices, ground-based robots, the production of spare parts in remote locations, mobile parts hospitals, and legacy parts such as those needed for the B-52 aircraft. There is an opportunity to transition to AM for the production of many of these parts. With AM improvements that are expected in 10-12 years, the military will likely become a major user of additive manufacturing.

**Automotive and Motorsports:** The opportunity to use AM to manufacture parts for vehicles is substantial. Production runs of high-end, specialty cars are relatively small. Consequently, these products are candidates for using AM for part production. Already, companies such as Bentley and Rover have shown that it is feasible and have used AM for small, complex parts. Likewise, the motorsports industry (both cars and motorcycles) will benefit greatly from improved helmet design brought about from AM. This includes aftermarket products that are custom, semi-custom, and standard.

**Electronics:** The production of 3D circuits has been demonstrated by Sandia National Laboratories and the University of Texas at El Paso. They perform a function similar to traditional printed circuit boards, but they wrap around the contours of the product. This makes it possible to design the electronics around the optimum shape and styling of a product, rather than...
designing a product to fit the inconvenient shape and size of conventional printed circuit boards. The opportunity for 3D circuits is interesting and expected to develop further in the future.

All portable electronic devices require a self-contained power source and that is almost always batteries, either disposable or rechargeable. The worldwide portable battery market exceeds $50 billion. However, hydrocarbon fuels have 50-100 times higher energy storage per unit mass than batteries, so electrical power generators using fuel rather than electrochemical reactions as the “energy feedstock” could yield electrical power sources that are much lighter for the same energy storage, or have more capacity for the same weight. However, at the small scales required for such devices, heat losses and thus extinguishment of reactions is a major problem. One method for minimizing these losses is with heat recirculation, but this requires complex geometric features with multiple intake and exhaust passages in a compact space. AM is ideally suited for fabricating such reactors. The potential to use various materials is also attractive because some parts of these reactors/generators should be made of low conductivity materials (e.g., plastics) whereas other parts require high conductivity and/or catalytic properties (e.g., metals).

**Biomedical:** Many universities and research institutes are exploring ways in which AM can be applied to medical implant design and manufacturing, tissue engineering, and regenerative medicine. Two companies in Italy have used AM to manufacture more than 10,000 metal hip implants, thousands of which have been implanted into human beings. Meanwhile, Walter Reed Army Medical Center has produced 37 cranial implants using electron beam melting, an AM process from Arcam of Sweden.

**Dentistry:** The market for the production of dental products using AM is on the verge of explosive growth. Already many dental labs are using DMLS from EOS and other direct metal AM processes for the production of copings for crowns and bridges. EOS has reported that the dental business is currently its fastest growing area of AM for production applications.

**Jewelry:** In the future, jewelers will use AM to manufacture custom and limited edition products. Lionel Dean of FutureFactories is currently manufacturing impressive pendants in titanium alloys. Lena Thorsson, formerly of Particular AB, showed that it is possible to laser sinter gold alloys to produce beautiful chains and necklaces that normally require complex and expensive machinery.

**Game avatars:** In the past 18 months, new AM businesses have emerged around the popular World of Warcraft, Spore, and Rock Band computer games. Already, thousands of custom products are being manufactured by AM for this fast-growing consumer market. In the future, it is believed that video games could drive the development of AM systems, similar to how they have driven computer hardware developments over the past several years.

**Collectables:** The freeform shapes that are possible make AM suitable for a wide range of consumer products. Furniture, lighting designs, and home accessories have been produced by AM and sold at extraordinary prices because of their unique qualities. Artistic pieces and plastic and metal sculptures made on AM systems demonstrate the worldwide market potential for these types of products. A number of organizations have used AM to produce commemorative gifts, awards and trophies as well as corporate gifts that clients, employees and others appreciate and treasure.
Toys: It is believed that in the near future, someone will produce a consumer 3D printer for kids in the price range of $100-150, a 21st century analog of the 1960s Mattel “thingmaker.” It would be used for play, education, and entertainment, much like Erector sets, Tinker Toys, and the Creepy Crawler thingmaker of the past. Kids like to make things and handle their creations as much today as they did in the past. The major difference is that today, kids are creating 3D digital content, so an inexpensive 3D printer would enable them to manufacture their own creations. AM system manufacturers would recoup their R&D investment through volume sales and recurring revenues from consumables. Websites, many that are open source, will give access to an almost unlimited number of creatures, action figures, structures, machine parts, vehicles, etc., that kids will download, modify if they wish, and manufacture.

Food: Specialty food is said to be a $13 billion industry. With AM systems such as the open source Fab@Home machine from Cornell University, it is possible to make chocolates and cake icing that include 3D figures, company logos, names, and other objects. It is also possible to consider the use of the system, or one like it, to manufacture food products in cheese, peanut butter, and just about anything else that can be extruded through a syringe.

Education: In 10-12 years, it is anticipated that schools will offer courses and programs that include instruction on how to design for the manufacture of parts using AM. Meanwhile, innovative organizations will develop methods of product design that take advantage of AM processes and materials.

2.4 Research Opportunities

It is recommended that the research community:

1. Launch a national user standards testing facility, possibly at a NIST Manufacturing Extension Partnership location or the National Center for Rapid Technologies (RapidTech). The facility would be used to test and refine the testing methods created by ASTM International Committee F42 on Additive Manufacturing Technologies.

2. Create finite element analysis (FEA) software for laser sintering, fused deposition modeling, and other AM processes.

3. Develop high-temperature, low thermal conductivity materials for power sources, heat exchangers, aircraft parts, and other applications.

4. Identify and develop manufacturing applications that are only possible with AM.

5. Create cost modeling software that compares AM with traditional methods of manufacturing.

6. Fund the creation of a set of material “allowables” (mechanical properties) with existing and new materials that enter the market.

7. Develop a set of additive manufacturing design guidelines/manuals for a given industry (i.e., aerospace, automotive, biomedical, etc.)
CHAPTER 3 TECHNOLOGY GOALS AND BARRIERS

3.1 Introduction

The aim of this chapter is to discuss the broad issue of Technology Goals and Barriers in relation to Additive Manufacturing (AM) and to consider what research is required to reach these goals and overcome these barriers.

Though this chapter will mainly focus on the process-related technology goals and barriers, it is important to recognize that the processes are only a small part of the overall AM equation – it is only when the design opportunities and business implementation aspects are considered that the full benefit of AM becomes apparent. For example, for the first time in manufacturing history, it is possible to produce virtually any complexity of geometry with very little implication on the cost of the parts – this is particularly true for polymeric parts, though less so for metallic systems (at present). However, what is not yet in place are the design tools to enable production of these new, complex designs and the analysis techniques to validate these designs prior to manufacture. Therefore, a critical aspect of future research effort should be in design, analysis and simulation tools that are dedicated to additive manufacturing or, potentially, specific AM applications. This has already happened with dedicated design tools being developed for the hearing aid industry that can convert point-cloud scan data into manufacturable (fully customized) hearing aid shell designs in less than five minutes; using conventional design tools, this would take many hours. This concept will need to be taken forward, possibly towards product-specific design tools, for a range of industrial applications.

AM techniques also offer up the intriguing possibility of changing the location of manufacture, and could well become the enabling technology for bringing back manufacturing to high wage economies as found in the West (US and EU). Without the need for production tooling, the flexibility and reconfigurability of the systems means that the same machine can be used for the manufacturing of different components simultaneously and sequentially; therefore, especially for low volume production, even at present, this opens up the potential for localized production. With increases in speed and lower cost systems and materials, the barrier to entry will decrease with the very real potential of local, hub based systems following something akin to the Kinko’s model of document printing, but for 3D parts.

In the end, education will form a key aspect of the drive towards AM adoption both at a college and university level as well as within industry. Without a wider understanding of the potential of AM, there will be more of an organic growth in adoption of the systems. Better education and dissemination will lead to a breaking down of preconceptions, resulting in greatly increased AM adoption. This knowledge transfer, especially of research, has to be a key goal for the next 10-12 years.

This chapter will now mainly focus on what are appropriate technology goals and the associated area barriers and challenges for the additive manufacturing field over the next 10-12 years. Clearly, there is significant overlap with other chapters in this document, particularly with Chapter 5, Processes and Machines and Chapter 6, Materials and Materials Processing. However, this chapter will endeavour to take a helicopter view and will broadly aim to answer the following questions:
• What technical and operating advances are needed to ensure that additive manufacturing processes are as reliable and predictable as conventional manufacturing processes?
• What technical advances are required to ensure that additive manufacturing processes are affordable compared with conventional manufacturing processes?

The thinking behind the answers to these questions came from a collaborative engagement of AM academics and industry specialists.

3.2 Technical and Operating Advances for Manufacturing Repeatability

One of the key needs for a manufacturing system is repeatability and consistency of the manufactured parts. This is required over the build volume and between builds of an individual machine as well as across different machines. Currently, the inability to guarantee material properties for any given process is holding back the adoption of AM technologies as industry does not have the confidence that manufactured parts will have the required mechanical properties which are required to meet specific structural needs. The main reason for this is that existing systems are still predominantly based on rapid prototyping machine architectures where a different mentality exists for the requirements of the produced parts. A machine-tool approach is therefore required.

To achieve this repeatability, there is generally a need for the adoption of closed-loop process control systems to monitor and feedback, on the fly, the various parameters of a particular system (e.g., thermal control, laser power, etc.). On a basic research level, there is also a much greater need for understanding the physics of the interlayer bonding (for all processes). This will lead to a greater ability to control the bonding of the layers to produce more consistent parts.

It is felt that the AM community and industry would also gain significantly by an increased activity in modeling and simulation of the various technological approaches where an increased knowledge and modeling of the process/material interface will lead to greater process control. It is important that this modeling initiative takes full account of the different processes and materials as well as taking into consideration the particular geometry that is being built.

Overall, though not particularly a research issue, the development and adoption of robust standards is of significant importance to the future of AM. Product, process and material certification that conform to internationally recognized standards will, in great measure, along with more repeatable systems, drive the adoption of AM. Specifically, to improve repeatability, much greater certification is required for polymeric materials that are often specifically developed for particular processes; metallic based systems tend to use conventional grades of metal (316 stainless, Ti64, etc.), and these generally have a solid and robust certification trail. In large part, the recent ASTM F42 initiative on AM standards will drive the standards agenda, and this should be vigorously supported by the AM community.

3.3 Technical Advances to Ensure Affordability of AM

One of the keys to ensuring the affordability of AM in relation to conventional manufacturing is the reduction in machine, material and servicing costs. The high costs associated with the industry, again, come from the rapid prototyping legacy where volumes are low and higher margins are acceptable. One train of thought is to produce simpler machines that are cheaper to manufacture, though equally, scale of sales will also drive down costs. Scaleable, continuous-flow and faster systems would be advantageous. Additionally, moving away from point-cure/melt systems, which are inherently slow, to line/mask based systems would speed up processing and lower costs.
It should be recognized that AM is not a panacea, and the correct identification of appropriate parts that can/could be manufactured is essential. There will be parts that are suitable for AM, parts that are competitive with conventional techniques and some parts that can only be manufactured additively – it is these last two categories that should be pursued, but a robust methodology for identifying these applications should be investigated.

Independently gathered material property data (i.e., not by the vendors) is considered essential for gaining confidence of end-users. A proliferation of third party materials manufacturers is also considered desirable to add market forces into material supply.

3.4 Barriers to Uptake of AM

Though technological barriers exist, as in most technology areas, the majority of barriers tend to be non-technical and instead are more focused on human-centric issues. In the case of AM, these include:

- (Lack of) Education
- Cultural differences
- Vested interests that stifle innovation
- Lack of imagination

Expectation management is also an issue, where early promise has not been met by reality and therefore the perception of the potential of AM today can often be clouded by individual experiences of rapid prototyping 10 or so years ago. As highlighted earlier, education and knowledge transfer of research outcomes therefore forms a crucial part of any future AM research drive and should be factored into any proposal.

3.5 Research Opportunities

The following, though not exhaustive, is an indicative list of potential research areas that could be considered under the “Technological Goals and Barriers” area:

- **Modeling & simulation**: This is certainly required to have predictive models for the various processes to enable the performance of manufactured parts to be predicted. To feed into the model, a much better understanding of the basic physics of the systems is required as is accurate baseline data to optimize results.

- **Process control**: The ability to achieve repeatability on a singular process and between processes is a prerequisite for any manufacturing system. Therefore, one of the main areas to investigate is in closed-loop/adaptive control systems. Additionally, a basic requirement is to ensure that there is no variability between systems, potentially even between similar machines produced by different vendors. Connected to this is the optimization of mechanical/material/metallurgical properties for produced parts.

- **Alternate energy/scanning sources**: Though for polymeric systems, mask systems that are able to produce individual layers all at once (i.e., not point laser scanning) are becoming available, there is great potential for research to extend this approach for metal systems, which are universally using single point laser/electron beam scanning. Going away from point processing to line/full mask would provide significant speed and cost advantages.
4.1 Introduction

AM technologies enable new, unique capabilities that conventional manufacturing processes cannot duplicate. Some examples include customization, improvements in product performance, multi-functionality, and lower overall manufacturing costs. These unique capabilities include:

- **Shape complexity:** it is possible to build virtually any shape, including
  - complex cellular structures and hierarchical constructions, as well as optimized material distributions,
  - customized, 1-off designs,
  - integration and consolidation of parts;
- **Material and property tailoring:** material can be processed one point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients;
- **Functional complexity:** with many AM technologies, it is possible to embed components (e.g., hardware, sensors, actuators), fabricate working kinematic joints, and deposit conductive materials, enabling the manufacture of functional devices right “out of the vat.”

A wide variety of industries can benefit from these capabilities, as has been mentioned in earlier chapters. The aerospace and automotive industries could benefit from complex geometries and tailored material and property distributions. In the energy area, components such as heat exchangers, evaporators, and condensers can be designed with complex shapes in order to promote more efficient thermal and mass transport. In the biomedical area, the possibilities are endless since a wide variety of tissue shapes and compositions are needed, shapes of implants are complex and often customized, and surgical tools may take advantage of the embedded component and kinematic joint capabilities of some processes.

In a broader context, the area of design and analysis is intrinsic to some larger efforts in the systems-based integration and cyber-enabled manufacturing (CeM) areas. Engineering design and analysis capabilities are central to product development, which may be widely distributed. Designers must have appropriate tools that enable them to design dependably and without necessarily knowing specifically which manufacturing facilities or machines are used for their products.

Subsequent discussion will focus on three general directions:

- design frameworks
- CAD/CAE/CAM advances
- predictive model-based process control

4.2 Design Frameworks

New design methods are needed in order to take advantage of these capabilities. In the cases of hearing aid shell manufacturing and clear aligners (Invisalign), new CAD systems had to be developed to enable efficient shape modeling and part design. Designers seem to be fixated on the traditional paradigm of design for manufacturing (DFM), which includes a number of formal
and informal rules for assembly, machining, injection molding, etc. This approach is evident in the conventionally fabricated products that most people are familiar with: plastic product housings that are molded in simple 2-piece molds, 3-axis machined parts, and assemblies consisting of many sheet metal parts that are fastened together. However, if suitable design frameworks can be developed, with proper CAD, design-for-manufacturing (DFM) tools, optimization and exploration methods, etc., designers can design devices with significantly improved performance that fully utilize material, and with efficient manufacturing processes. With the shape, material, and hierarchical complexity capabilities, DFM can move from an emphasis on cost minimization to a focus on achieving heretofore unrealizable capabilities. Hence, a new definition of DFM can be proposed. DFM for Additive Manufacturing (DFAM) is the:

Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other lifecycle objectives.

However, it can be difficult for designers to envision all of the possibilities offered by AM, and few products in the marketplace embody those possibilities or serve as analogies. Concept generation and ideation tools are needed to help designers overcome this mental barrier. A collection of best-practice examples would help tremendously. From these examples, a set of design rules could be developed, perhaps specialized for specific processes or materials. Viewed more broadly, a set of methods is needed that enable designers to define new design spaces and to search those design spaces.

Changing topics somewhat, variability of geometric shape, material composition, and mechanical properties is inevitable. As such, it is critical to be able to perform metrology, analyze part designs, and design devices while taking into account this variability. Design and analysis methods are needed that can account for variability as listed. Although this is an area of current research (for non-AM reasons), the wide variety of material compositions and complex geometries possible with AM compel additional investment in this topic.

4.3 CAD/CAE/CAM Advances

Parametric, solid modeling CAD systems are used throughout most of product development in the US and Europe. Systems such as ProEngineer, NX/Unigraphics, SolidEdge, CATIA, and SolidWorks are very good for representing shapes of most engineered parts. Their feature-based modeling approaches enable fast design of parts with many types of typical-shape elements. Assembly modeling capabilities provide means for automatically positioning parts within assemblies and for enforcing assembly relationships when part sizes are changed. Commercial CAD systems typically have a hybrid CSG-BRep (constructive solid geometry – boundary representation) internal representation of part geometry and topology. A tremendous amount of information is represented in these systems, all of which has its purposes for providing design interactions, fast graphics, mass properties, and interfaces to other computer assisted design, manufacturing, and engineering tools (CAD/CAM/CAE).

However, commercial CAD systems are ill suited for modeling parts with complex constructions (e.g., lattices or honeycombs) with thousands of shape elements or with material distributions, such as functionally graded materials or tissue constructs. When more than 1000 surfaces or parts are modeled, CAD systems tend to run very slowly and use hundreds of megabytes or several gigabytes of memory due to the nature of parametric CSG-Brep technology. Similarly,
CAD systems have limitations in representing parts with multiple materials. At most, CAD systems only allow one material to be specified for a part. This is a major barrier to the modeling of composite materials, functionally gradient materials, and biological materials.

For many applications, designers may find it useful to specify distributions of mechanical properties, instead of just shapes or material distributions. Mechanical properties can be varied by varying geometry, as can be achieved by optimizing lattice structures. Alternatively, mechanical properties can of course be varied by adjusting material compositions. If CAD systems can convert mechanical property requirements into distributions of geometry and/or materials, they would greatly aid designers. Furthermore, the modeling of relationships among process variables, material composition and microstructure, geometric constructions, and effective mechanical properties would enable integration with analysis codes and process planning systems. Stated differently, integration of process-structure-property relationships into CAD/CAE/CAM systems is necessary to design, analyze, and manufacture many classes of parts using the full capabilities of AM systems.

With process-structure-property relationships integrated into CAD/E/M systems, additional capabilities become desirable. These relationships are not typically simple, so it is necessary have computational methods for analyzing materials and material combinations (property to structure to process), as well as designing materials and their combinations (process to structure to property). Multiscale modeling, inverse design, and optimization methods are needed for these tasks.

A related issue is ability of materials to perform multiple functions. Multifunctional analysis and design capabilities would enable the development of heat exchangers that support structural loads and structures that absorb vibrations and noise.

From a different perspective, computer-aided design tools for non-experts and non-engineers are needed. This need is evident from the variety of applications emerging in the toy, collectables, game avatar, and food areas, as mentioned in Chapter 2. Simple, intuitive user interfaces are needed for these non-expert users. At the same time, many of these users will be demanding of part quality, such as color for game characters and surface finish for home furnishings. As a result, new non-expert CAD systems will need to hide significant complexity from users, or provide access to sophisticated technologies in an easy-to-use, intuitive manner.

Computer-aided inspection methods that are integrated into CAD/E/M systems would enable potentially the analysis of parts while they are being built, assuming that suitable sensors are installed in AM machines. Quantitative comparisons between the nominal part design (geometry and material composition) and the in-process part could lead to feedback control capabilities in machines. Additionally, quantitative, scientific metrics for part quality would be enabled.

4.4 Predictive Model-Based Process Control

From the CAE and CAM perspectives, high fidelity process models are important in order to enable process planning and analysis of parts with as-manufactured properties. A major challenge in development of such process models is difficulties in process control due to the variability inherent in process conditions. Rather than try to remove variability directly, which may be very difficult, another approach may be possible. The concept is to instrument machines extensively and use an intelligent controller that can learn in order to improve process control. Some barriers and ideas will be presented in this section; more will be discussed in Chapter 5.
Model-based process models and maps are needed to support control systems. Feedforward control methods are needed to anticipate process challenges related to part geometry, scan patterns, and other part-specific conditions. Feedback control methods are needed to compensate for variations in process conditions, local material compositions, and other issues that are difficult to predict.

Given a set of process models and maps, they should be implemented in a computational manner that facilitates construction of process analyses and simulations. That is, a plug-and-play, composable simulation capability should be developed to facilitate the construction of process simulations and process planning methods for new or modified processes, or for situations where new sensors or control methods are to be tested.

Many new sensor technologies are likely to be needed to support the wide range of sensing needs for various AM processes. Sensors are desired for part shape precision, surface finish, and part integrity (e.g., porosity), as well as for process conditions (local temperature distributions, melt pool size, ink-jet droplet splatter). It is not clear if sensors are available for part quality or dimension inspection in a powder bed, or for surface finish in a liquid polymer vat or in support structures. Sensing and inspection systems are needed for the micro-scale, as well as for biological (tissue) constructs. Other sensor challenges can be identified.

With a set of sensors installed in an AM machine, sensor interpretation and fusion technologies are needed to interpret the large sets of data generated by the sensors. Such data sets must be reducible into forms suitable as inputs to machine control systems. Ultimately, machine learning systems may be useful to help AM machine performance improve over time. It is not clear that current machine learning technologies are suitable for the demands of AM machine control in fabricating devices with complex geometries and materials compositions.

### 4.5 Research Opportunities

Recommendations are presented corresponding to the three areas described above.

- Conceptual design methods are needed to aid designers in defining and exploring design spaces enabled by AM. Methods for simultaneous product-process design are needed also.

- Multifunctional analysis and design methods are needed.

- A new foundation for computer-aided design systems is needed that overcomes the limitations of parametric, boundary-representation solid modeling in representing very complex geometries and multiple materials.

- Composable simulation capabilities for primitive shapes, materials, material compositions, etc.

- Process-structure-property relationships should be modeled and integrated with CAD/E/M tools. Multiscale modeling and inverse design methodology is needed to assist in navigating these complex relationships.

- Easy-to-use CAD interfaces will be necessary for use by non-AM experts: such as medical technicians who make prosthetics; maintenance personnel who make replacement fittings; on-line game enthusiasts who make characters; children who make toys; etc. In many cases these CAD interfaces will be designed with pre-defined product scopes that enable end-users to make meaningful product changes within expert-designed constraints.
• Computer-aided inspection methods are needed for integration into the build process, and quality is not measured scientifically.

• Methods are needed to model and design with variability: shape, properties, process, etc.

• Predictive model-based process maps are needed to support feedforward and feedback control, with the goal of embedding process model knowledge into control algorithms. They should be implemented in a manner that enables plug-and-play modules and composable simulations.

• New sensors (process, shape/precision/surface finish, NDE) are needed that can operate in build chamber environments. Sensor fusion and interpretation methods are needed to convert sensor data into control signals. Machine learning technologies should be developed that are suitable for AM machine control and improvement.
CHAPTER 5  PROCESSES AND MACHINES

5.1 Background
Since the commercialization of the first stereolithography apparatus in the mid 1980s, more than a dozen types of processes have been developed, and more than 40 companies from around the world have sold variations of these processes as commercial machines. These processes range from simple, inexpensive devices which use glue to stick paper together into simple shapes; to complex apparatuses that utilize lasers or electron beams to transform materials from powder or liquid states into complex 3-dimensional objects. This diversity of processes is further complicated by the fact that some of these processes have only recently been developed and commercialized, whereas other processes have more than 20 years of research and commercialization history.

Most AM processes are patented technologies. As a result, many of the best improvements to a particular process or machine may only be available to one manufacturer. However, the AM industry is on the cusp of a new set of opportunities, as many of the original process patents are expiring. This will open up new opportunities for competition and process improvement.

There has been a trifurcation of the marketplace for AM machines. The most rapidly growing segment is for low-cost 3D printers, or concept modelers, suitable for the office environment. A second, mid-cost, set of technologies exist for prototyping of parts with varying levels of functionality and/or accuracy. Both low and mid-cost machines typically utilize polymer build materials. High-end machines for polymer, metal and ceramic parts are also available at a cost between $200,000 and $2,000,000. These high-end machines may be optimized for the production of larger parts, higher throughput, multiple materials, or some other end-goal which drives up the cost of the machine.

5.2 Technology Barriers and Limitations
In spite of this diversity of technologies, a number of key barriers still exist across many AM processes. Common barriers include:

• part fabrication times which are significantly slower than mass production processes such as injection molding;
• most machines are designed in such a way that they have inherent trade-offs between part size, accuracy and speed, with part accuracy often being sacrificed in light of speed or size;
• there are significant geometric and property variations between “identical” parts built on different machines;
• many processes require highly skilled operators or need careful periodic tuning to operate well;
• many machines lack hardware reliability;
• most machine vendors have a closed architecture, which precludes researchers from making meaningful changes to processing conditions;
even the lowest-cost platforms cost more than $10,000, which limits adoption by educational institutions and individuals; and

although many processes are inherently capable of multi-material deposition, few have hardware and software implementations which enable simple, effective use of these capabilities.

5.3 Research Opportunities

To overcome these process limitations and barriers, a number of research priorities have been identified. There is a great diversity of AM technologies, and general recommendations for process and machine improvements will be applicable to certain technologies and less applicable to others, nevertheless, this collection of research priorities is broadly applicable to most AM processes.

• The most significant research need is a more complete, fundamental understanding of the basic science behind each AM process. In particular, a better understanding of the interaction between the various energy sources and materials is key. Examples of the types of understanding which are needed include the influence of energy input and distribution on resultant microstructure and part properties.

• Intelligent feedforward control schemes must be developed based upon a basic scientific understanding of the processes, coupled with the specific geometry and material knowledge for the part being built.

• Closed-loop feedback control must be integrated into a greater number of processes. Sensor systems which can be calibrated to new industry-standards must be developed to, in real-time, monitor and modify critical process parameters and/or the part being built. This should be done in such a way that real-time non-destructive analysis (NDA), quality assurance, and process repeatability can be monitored and recorded for each part and/or build.

• Better multi-material hardware must be developed, along with the process controls and software required to effectively create multi-material parts. This could include modifying existing processes and/or developing new processes.

• An increased focus on hybrid systems is needed. These systems will provide new processing capabilities which include: multiple additive processes; layer plus non-layer technologies; additive plus subtractive processing; and the integration of sub-components utilizing automated component insertion. One example of this type of hybrid system could be a collection of additive technologies which create 3-dimensional structural materials with embedded and direct write electronics combined with automated insertion of pre-manufactured components, resulting in a fully integrated electro-mechanical product from a single hybrid system.

• Higher throughput AM machines are needed for high volume manufacturing. This can be partially accomplished through the elimination of process inefficiencies by applying a detailed understanding of the basic science. Process speed also inherently increases when moving from point-processing to line-processing to planar-processing to volume-processing. New additive processes should be developed which move AM technologies up this processing continuum.
• Goal-based design tools are needed to integrate general Design for AM rules with process-specific capabilities to rapidly produce CAD geometry that meet specific design requirements. These tools should enable designers to better utilize the multi-material, pre-assembled, and complex-geometry benefits of AM.

• A new set of design tools are needed which enable non-experts to make meaningful changes to part geometry, without breaking process-specific design rules, part-use safety criteria, or other expert-specified constraints. These tools will enable the general public to utilize AM in the same way that word processing has enabled the general public to utilize computers and printers.

• Lower-cost machines are needed to reduce barriers to entry for individuals and educational institutions. Many AM machines could be redesigned and sold in higher volumes at a lower price if the machines were redesigned with lower cost as a primary design criterion. One potential way to accomplish this might be to modularize portions of AM processes which are shared amongst several diverse technologies, to increase the overall volume of each module, and thus reduce costs.

• Open architecture machines should be developed as test beds for process control, basic science research, and software testing. Equipment manufacturers should be encouraged to provide an “AM developers toolkit” option for researchers, similar to the “software developers toolkit” that is available in the software industry.

• Educational teaching modules should be developed to increase knowledge about AM processes amongst the non-engineering community. These should be targeted at the business community, to increase entrepreneurship and industrial applications of AM, as well as to potential beneficiaries of AM technology, such as architects, biologist, artists, hobbyists, etc. Modules which could be utilized in high school courses should also be developed.

• Current design education is inadequate for AM. Re-training of existing designers should be attempted. More importantly, a significant push to educate the next generation of engineers and designers to utilize AM must become a part of related technical training, community college courses, and university degrees.

• Upper-level engineering courses must be developed to train the next generation of AM researchers. These courses should focus on the science of AM technologies, training engineers to develop better analysis tools, models, control schemes, and software tools for AM.
CHAPTER 6 MATERIALS AND MATERIALS PROCESSING

6.1 Overview

Materials play a key role in all AM processes. Material requirements are impacted by the need to create feedstock, to be processed successfully by the fabricator coupled with post processing, and to manifest acceptable service properties. While individual AM processes are limited to varying degrees based on these requirements, in broad terms, an impressive variety of materials may be processed using AM. Figure 6.1 shows a hierarchy of homogeneous material systems that have been demonstrated using AM. Figure 6.2 lists heterogeneous materials.

![HOMOGENEOUS MATERIALS Diagram]

Figure 6.1 A Hierarchy of Homogeneous Materials Systems for Additive Manufacturing

Intrinsic to heterogeneous materials systems are the use of transient and permanent binders and discrete material support structures. The heterogeneous materials systems are further varied by the potential in many cases to employ post-processing steps including infiltration of porous AM parts.

This diversity has resulted in a highly diverse set of materials, including for example flame retardant polymers, direct metals and ceramic composites. The grand challenge in materials and materials processing is to improve quality, process consistency, repeatability and reliability in a wider diversity of materials at a lower material, machine, processing and finishing cost.

Conventional manufacturing is considered to be consistent and repeatable in terms of the structure and properties of materials thus processed. AM processes are more complicated since machine parameters must be individually “dialed in” to produce acceptable parts, and in some cases, the material structure, properties and performance vary not only from machine to machine but also based on the build location within a single fabricator as well as its orientation at any given location. The recently (January 2009) inaugurated ASTM F42 Technical Committee has
the potential to address this issue and others by developing industrial standards for testing, characterization and properties.

![Figure 6.2 A Hierarchy of Heterogeneous Materials Systems for Additive Manufacturing](image)

### 6.2 Comparison of AM Processes to Conventional Manufacturing Processes

Currently, it is sometimes advantageous to compare AM to conventional manufacturing processes in an attempt to make market share inroads. This is the “We can do it better” categorization of application. For example, 3D Systems has recently introduced a polymer blend that mimics the properties and performance of polypropylene. Parts have been investigated for aerospace applications where the economy of manufacturing favors AM over forging and machining. These examples are repeated throughout the field where process substitution becomes the easiest method for developing inroads of AM into practice. The more long-range impact though, comes from highlighting the unique features of AM processes to address specific problems not solvable by conventional manufacturing processes, a “We can do it and others can’t” approach. In addition to the time-tested advantage of being able to create unique geometries, there are a host of other possibilities in varying degrees of maturity, including cellular structures, gradient structure, directional properties, on-the-fly in-build probing of the internal structure, etc.

For the first category, it will be important to continue to apply materials science analysis (microstructure, properties, performance) to AM like other manufacturing processes (welding, forming, casting, etc.) with the objectives of understanding limitations and exploiting unique features of AM while meeting the requirements of processability and performance. Building on the unique features of AM broadly, there are a number of materials challenges and opportunities that have been identified, most of which take advantage of the unique aspects of AM. These include identification of a shopping list of metallic materials that may be mixed and/or alloyed during AM to produce parts with both homogeneous and heterogeneous composition. The
specific elements making up the feedstock would need to be engineered to maximize the utility of the final product. Exploration of specific novel materials includes self-healing polymers, SLA polymer resins with improved part time stability after fabrication, development of affordable high-temperature polymers, integrated optics gradient materials (diffraction/dispersion/filters...), in-situ sensors, self-assembled single crystals (e.g., aluminum nitride), continuous filament composites, and point-to-point control of materials properties and composition.

Manufacturing of meso-, micro- and nano-sized parts has potential applications in optics, medicine, fluidics, micro/nanoelectronics and elsewhere. Meso-scaled processes tend to be based on macro-scaled processes such as SLS, SLA, etc. Micro-scaled AM processes are more limited in number, the best example perhaps being two-photon polymerization. Nano-scaled processing also has potential in medical/health care industries. The term “molecular manufacturing” describes fabricators or assemblers that can place material specifically on an atomistic level. Biologically, ribosomes perform this function in the transfer of certain amino acids from tRNA to growing polypeptides. DARPA recently initiated a research program for tip-based directed assembly. In general, the research needs center around the need for better tools to fabricate parts atomistically, design and design rules for nanomanufacturing and improved computational tools for product design and modeling. The development of new self-assembly and synthesis methods are needed to create structures complementary to devices produced using tip-based synthesis. [Dr. David Forrest of the Naval Surface Warfare Center provided information for this paragraph.]

6.3 Research Opportunities

Based on the current state of the art, several challenges for AM materials may be identified. These are listed below.

- There is a need to link microstructural evolution back to process properties. The goal in part is to improve the ability to predict performance criteria based on fabricator operating parameters.

- There is a need to understand the effect of thermomechanical exposure on material microstructure and properties and to articulate the constitutive behavior of materials as a function of machine process variables. Such correlation, for polymers particularly, has the potential to enable thermal management models and control systems with the capability to alter processing parameters “on the fly” resulting in uniform thermal exposure at all points in a build.

- There is a need to develop further those features of AM that are unique and differentiated from conventional manufacturing processes. Included but not exhaustive are taking advantage of the anisotropic nature of AM; the ability to produce epitaxial metallic structures; description and manufacture of functionally gradient materials and multiple materials.

- Another advantage unique to AM is the ability to probe internal features. This enables the placement of internal sensors, to finish internal surfaces and to perform in-process inspection. While several of these abilities have already been demonstrated in research settings, more research is needed to mature these prior to transferring this technology to the commercial sector.
• Screening of materials for suitability for AM is an expensive and time-consuming activity. There is a need to develop screening methodologies for advanced manufacturable materials: why are some materials processable by AM and some are not?

• In general, micro and nano AM needs further research for the development of better tools to build structures and devices atom by atom. There is a need for better tools to fabricate parts atomistically, design and design rules for nanomanufacturing and improved computational tools for product design and modeling. Specifically for materials, the development of new self-assembly and synthesis methods are needed to create structures complementary to devices produced using tip-based synthesis.
CHAPTER 7  BIO-ADDITIVE MANUFACTURING

7.1 Introduction

The revolution in biological sciences and bioengineering has created an environment in which the advances in the life sciences are not only amenable to, but require, the active participation of engineering design and manufacturing to achieve solutions for complex biological problems. This revolution, along with the development of modern design and manufacturing, biomaterials, biology and biomedicine, has advanced the additive manufacturing technology to a broad application in biological and biomedical engineering. Bio-additive manufacturing encompasses applications to tissue-engineered substitutes, artificial organs, orthopedic implants, medical devices, and the new generation of micro-vasculature networks and biological chips produced by printing/patterning cells and proteins. This chapter is based on a review of recent advances in bio-additive manufacturing, with attention directed to the state-of-the-art research, development of bio-additive manufacturing processes, the process science and engineering, and emerging biological and biomedical applications. This chapter also addresses novel bio-additive manufacturing processes for cell and organ printing/patterning, drug delivery, complex 3D tissue scaffolds, and computer-aided bio-additive manufacturing and tissue engineering.

The introduction of additive manufacturing (AM) in combination with computer-aided technologies has offered new possibilities for medical modeling: using computer models or additive manufacturing fabricated physical models for representation of patient specific anatomical geometry. The AM approach uses the principle of layered manufacturing to create the model layer by layer. This tomography approach lends itself readily to the freeform sculpture present in human anatomy. Medical modeling has a wide range of applications in anatomical representation, implant and prosthesis design, and surgical planning and rehearsal. With the AM approach, a computer tomography image can be accurately reproduced in a few hours as a physical model, often called Biomodeling, which can be handled by the surgeon, allowing a more intuitive understanding of the most complex 3D geometry used to plan and practice an operative procedure. In addition, the AM approach produces extremely detailed physical models that can serve as excellent templates for the creation of custom implants. A physical model made by AM from X-ray, CT or MRI data can be held and felt, offering surgeons a direct, intuitive understanding of complex anatomical details which cannot be obtained from imaging on the screen. A precise physical model can help determine implant size and type, and provide ‘hands-on’ surgical planning and rehearsal. In addition, AM fabricated anatomic models can be used to display local regions of interest, which may, for example, help a surgeon identify a tumor on the CT image and use it for disease diagnosis. Thus, AM technology offers the surgeon a tool that is not available anywhere else.

Additive manufacturing also contributes significantly to freeform fabrication of tissue scaffolds. In tissue engineering, three-dimensional (3D) tissue scaffolds play a vital role as extra-cellular matrices onto which cells can attach, grow, and form new tissues. Although many indirect methods of fabricating tissue scaffolds, including indirect solvent casting, salt leaching, freeze drying, fiber bonding, melt molding, and gas foaming, have been reported, these methods have limitations in manual interaction, difficulty in control of complicated internal architecture and reproducibility, and toxicity concerns due to using organic solvents. In contrast, direct digital fabrication of tissue scaffold using AM technology is very promising because these processes
allow versatility of using biomaterials and fabrication of scaffolds with complex geometry and internal architecture. Many AM processes have been reported in application to scaffold fabrication, including Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Modeling (LOM), Three-Dimensional Printing (3DP) by TheriForm fabrication, precision extruding deposition (PED), and micro-syringe based polymer deposition.

The convergence of engineering and life sciences has evolved into a new paradigm of Bio-Additive Manufacturing (BAM): biofabrication using cells, biologics or biomaterials as building blocks to fabricate biological and bio-application oriented substances, devices and therapeutic products through a broad range of engineering, physical, chemical and/or biological processes. Biofabrication encompasses enormous applications in tissue science and engineering, disease pathogeneses and drug studies, biochips and biosensors, “tissue/animal/lab on a chip”, drug delivery, in-cell printing, patterning, assembly, and organ printing. Many BAM techniques for cell manipulation have been developed, such as syringe-based cell deposition for tissue constructs, inkjet-based cell printing, laser direct writing of mammalian cells and bacteria, microcontact printing of cell and bacteria, cell manipulation by mechanical, optical, electrical, magnetic, ultrasound, and ionic methods for micro-fluidics, and cell patterning by photo- or electro-etching and soft lithography. Developments in BAM will enable progress from the manufacture of cell-integrated products towards the future goal of manufacturing advanced living parts and/or bio-functional living systems. BAM techniques can also provide biologists with sophisticated engineering and manufacturing tools for studying fundamental biological problems. For example, cell printing methods can be used to deposit cells in precise spatial patterns to enhance cell-to-cell communication, reduce the reliance on cell migration to populate the tissue construct, create artificial tissue structures that more closely resemble their in vivo state, and fabricate bio-mimetic micro-organs for drug metabolism study.

7.2 Challenges

There are considerable challenges in the emerging field of Bio-Additive Manufacturing. For this technology to move forward the following challenges have been identified:

- Lack of capability of making scaffolds with feature size < 100 μm
- Lack of process repeatability and part reproducibility, particularly when using new materials in medical implant application
- Lack of information and assurance from AM machine vendors about the end performance results, and the reliable process window being too narrow
- Poor availability of hardware devices for BAM research (i.e., every lab has to build its own machine for biofabrication research)
- Integration of BAM with micro and nano systems is difficult because of the requirement for a clean environment
- Lack of viable integrated fabrication processes to make heterogeneous BAM structures with cells, growth factors, and scaffolding materials included in the same physical model
- Lack of capability of producing 3D cell biological models and tissue constructs with desired reproducibility and controllability
• Lack of available biomaterials and cell delivery media for BAM
• Lack of standardization for BAM processes, biomaterials and cells
• Rigorous FDA approval required for BAM
• Lack of knowledge of cell behavior in BAM under a 3D structural environment, and lack of understanding of cell behavior under integrative structural, chemical and biological cues
• Lack of taxonomy for communication among researchers from different disciplines (engineering, biology, materials science)
• Difficulty of biological validation after BAM fabrication
• Difficulty to maintain biological viability of BAM materials before and after fabrication
• Lack of understanding of BAM process induced effects on living biologics and on subsequent structural and time-dependent cellular behavior
• Lack of biological science to understand BAM cell assemblies not from Petri dishes
• Lack of computer modeling and simulation of heterogeneous tissues and cell/tissue growth
• Lack of interface between BioCAD and BAM

7.3 Research Opportunities
In the light of the above challenges the following research opportunities have been identified:
• Better scientific understanding of BAM process
• Increase of BAM process robustness
• Integration of multiple BAM processes including printing, extrusion, spraying, electrospinning, coating, etc. for biofabrication
• BAM of scaffolds with controlled shapes, internal architectures, multiple materials and growth factors to provide cells with desired structural, physical and chemical properties for in vitro and in vivo studies
• BAM of scaffolds, implants and prostheses with functionally gradient materials and customized structure to meet patient-specific anatomy, tissue function, and load bearing requirements
• BAM of scaffolds with embedded biocompatible sensors (“smart scaffolds”) to detect biophysical and biological signals
• BAM of 3D cell aggregates and assemblies used as in vitro 3D biological models for regenerative medicine, disease pathogenesis and drug studies
• BAM of human tissues for reducing and replacement of animal testing
• BAM of organs
• Development and manufacturing of low-cost (~$10K) bioprinting devices as standard labware for biological engineering and tissue engineering labs
• Design of porous structures for implants and prostheses with consideration of load carrying and fatigue resistance
• Modeling and analysis of cell/tissue growth in a 3D environment
• Multi-scale modeling: from sub-cellular to tissue level with time dependence
• Development of taxonomy for communication among researchers in different disciplines (engineers, biologists, materials scientists)
• Development of integrated nano and micro BAM fabrication process
• Development of BAM for cell-integrated micro-fluidic devices, biochips and biosensors
• BAM of protein/biomolecule printing and patterning
• Integration of BioCAD and BAM
• BAM of specialty food
• BAM of bioreactor for blood and vaccines

7.4 Milestones
AM technology has been successfully applied to fabrication of customized implants, prostheses, and tissue scaffolds. Research on BAM for cell/protein printing, patterning and assembly has also been explored. This market segment will be ready in 2~3 years. Research on using 3D cell aggregates or 3D cell assemblies as in vitro biological, disease and drug models has also been widely explored. The market for BAM fabricated 3D cell models should be ready in 5 years, and it will be huge since BAM can be a viable technology to provide 3D cell/biological models to meet the ever increasing 3D cell culture and 3D biological studies. With advancement of modern biology and BAM technology, it is possible that functional tissues can be fabricated by BAM technology in 10 years. Organ printing can be possibly seen in 15 years. Figure 7.1 is a milestone chart depicting potential BAM capabilities in the next 15 years.

<table>
<thead>
<tr>
<th>Biomodeling of Implants/Prostheses And Tissue Scaffolds, Cell Printing</th>
<th>BAM with Disease model</th>
<th>BAM with Drug model</th>
<th>Organ Printing</th>
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Figure 7.1: Potential BAM Capabilities in the Next 15 Years

There is a high potential for a multi-billion dollar market for cell dispensing and assembly devices and systems. Within 10 years, every cell culture lab in the United States may be equipped with an easy-to-use, computer controlled Cell-Additive Manufacturing system (i.e., a Cell Dispensing system) as a standard biological labware. Biologists will use this system on daily basis to make 3D cell aggregates or cell assemblies, which will be used as in vitro models for 3D cell culture, disease and drug studies, and/or for regenerating tissue substitutes.
7.5 Major Research Recommendations

The following major research recommendations have been identified for the BAM research community and relevant federal agencies:

- Bio-additive modeling, design and manufacturing of bone scaffolds, implants and prostheses with functionally gradient materials or structures for geometrical and functional customization (to individual patients).

- “Smart” scaffolds, including the design, analysis and BAM of scaffolds with embedded biosensors, biophysical and biological data acquisition and characterization, and application to tissue engineering.

- Development of viable BAM processes for construction of 3D biological and tissue models using living biologics, addressing the issues of process viability, reliability, controllability, reproducibility and quality, as well as the predictability of BAM process effect on subsequent cellular functionality.

- Computer-aided BAM, including modeling, analysis and simulation of cell responses and cell-tissue growth behavior in a 3D fabrication environment. This may require the development of multi-scale modeling, spanning from sub-cellular level to tissue level and with time dependence.

- Automated interface between BioCAD/Biomodeling and BAM, including development of “smart” algorithms and software tools for interpretation of the CT/CBCT/MRI imaging data, customization (i.e., patient-specific) design and analysis, and generation of tool paths for BAM.
Chapter 8    Energy and Sustainability

8.1 Introduction
Significant progress has been made during the last two decades on developing new and innovative design methodologies and advanced manufacturing techniques in additive manufacturing (AM). AM now can offer a viable, functionally feasible, and technologically superior alternative to subtractive manufacturing. AM is particularly suitable for the manufacture of products with complex features using traditionally difficult-to-process materials. Despite this major advancement in materials processing and manufacturing technologies, very little effort has been made in developing sustainability principles and sustainable applications and practices to enable environmentally benign, economically advantageous, and societal benefit-driven AM methodologies. However, recent studies at MIT and elsewhere have shown that currently achievable energy efficiency (power consumption) in a range of AM processes is much lower than that in the traditional manufacturing processes.

8.2 Existing Industrial Practice, Barriers and Demands
Current products are designed for traditional manufacturing and in many cases are sub-optimal. They use excessive material as they are designed for processes such as machining and molding. Moreover, they are made in geographically disparate locations, often dictated by the location of tooling in low labor cost economies.

There are a number of clear, potential benefits to the adoption of AM for part production, which could be driven by the sustainability agenda. These include:

1. More efficient use of raw materials in powder/liquid form by displacing machining which uses solid billets
2. Displacing of energy-inefficient manufacturing processes such as casting and CNC machining with eradication of cutting fluids and chips
3. Ability to eliminate fixed asset tooling, allowing for manufacture at any geographic location such as next to the customer, reducing transportation costs within the supply chain and associated carbon emissions
4. Lighter weight parts, which when used in transport products such as aircraft increase fuel efficiency and reduce carbon emissions
5. Ability to manufacture optimally designed components that are in themselves more efficient than conventionally manufactured components by incorporating conformal cooling and heating channels, gas flow paths, etc.

One of the technical barriers is complete integration of homogenization design with heterogeneous CAD and closed-loop AM. A proof of the concept has been demonstrated, but efficient commercial software with the capability of easy integration with hardware is needed for increased acceptance in the market place. If the integration is successful, customers will have a product with desired performance instead of facing the limitations generally observed by the traditional materials selection approach. When the integration and other technological barriers are overcome, we may witness a major shift in engineering practice where components with desired performance can be ordered “any place at any time.”
However, at present there are a number of barriers to sustainable utilization of AM, albeit these barriers do represent research opportunities. There is clearly a need for more robust process and material property data, which will only be valid if it is collated and disseminated against an established set of standards. Such data (including materials properties and machine capability data) can then be embedded into Knowledge Based Engineering systems. Only then can it be cascaded down to the engineering user community and used to design the next generation of sustainable products. Furthermore, manufacturers do not have readily available metrics to measure the sustainability in their products and processes. It is difficult, nearly impossible, to evaluate the overall impact on the environment and society versus the return on investment.

There is considerable research needed to better understand how AM can be used to realize design products that are more fit for a given purpose. AM has excellent prospects in the manufacturing of lightweight, optimized strength-to-weight ratio, lattice and honeycomb structures. These use less raw materials and provide lighter weight products. This is a key sustainability driver in aerospace and automotive industries. However, to prove the above “superficial” statement quantitatively, significant studies are required in the scope of total product lifecycle analysis.

In principle, some AM processes (such as DMLS, SLM and possibly EBM) use less energy per unit volume of material in the final part than alternative manufacturing processes such as die casting or CNC machining. This appears to have a number of economical and environmental (coupled) benefits. However, very little is known about the waste streams associated with different AM processes. It is known that some polymeric AM processes have very high waste streams (e.g., SLS – powder refresh, FDM/OBJET/SLA – support structure materials). We also know that many metallic processes require significant levels of post-process heat treatment to reduce residual stresses, in addition to considerable energy loss from highly inefficient laser systems and optical tracks. These are waste streams, as they add nothing to the part. Moreover, AM machines are not designed to be efficient. Thermal management is often poor and energy loss is considerable.

8.3 Research Need

The United States consumes 25% of all the oil produced in the world, but has only 3% of the world's oil reserves. As a result of this imbalance, the country has become heavily reliant on foreign oil. Reducing our dependence on oil is not only the fastest and cheapest path to energy security, it is also the best way to keep our planet healthy. Renewable energy seems to be the best solution as it is also sustainable. The key issue to wide utilization of renewable energy is the cost of infrastructure. Fuel cells are considered to be the ultimate "green" energy source, and the key issues in fuel cells are cost and durability. Today, the most widely deployed fuel cells cost about $4,500 per kilowatt. In contrast, a diesel generator costs $800 to $1,500 per kilowatt, and a natural gas turbine can cost $400 per kilowatt or even less. There are therefore ample opportunities for AM to contribute to the area of energy, such as material design to enable lower manufacturing cost and to facilitate mass production.

To reduce the cost of energy, mass production of new energy facilities such as windmills, solar panels and fuel cells are generally desired for renewable and recyclable energy demands. AM technologies will help in developing high-speed forming, stamping, and molding of components for renewable energy generation. AM will permit designs to be modified with a minimum of production line changes. However, there are technical challenges.

There are several sustainability issues that need to be addressed. One of the critical issues that
AM can greatly contribute to addressing is the reuse or remanufacturing of parts or products. If a part or product can be repaired and reused for its initial product function, not only will the material waste and the amount of landfill be reduced, but also the energy and material consumption in manufacture will be reduced. In addition, the utilization of existing components reduces the costs associated with producing new components. Therefore, a greater reduction in environmental impact can be made by product reuse, in which the geometrical form of the product is retained and the product is reused for the same purpose as in its original lifecycle, or for secondary purposes. Many of today’s repair procedures like closing and filling cracks through mechanical pressure or welding, rebuilding worn surfaces using metal spraying and welding, etc., do not lend themselves to automated operations. Manual operations such as tungsten inert gas (TIG) welding add several variables to the repair process that adversely affect the quality and cost of finished product. As AM can add material and recover the functionality, reuse/remanufacturing is an excellent way to help sustain the environment.

Manufacturing companies use high-pressure die-casting or stamping processes to produce large amounts of parts. Due to high-temperature and high-pressure processing, die components are frequently worn out and cracked over time, requiring repair or replacement. Welding-based repair processes exist in the shop, but the capability of these processes is limited and the durability of the repaired die is not predictable. AM processes can be used for repair if they are reliable, timely and cost-effective. An automated remanufacturing process will be able to offer excellent repair quality and part consistency. Since a remanufacturing system often involves both material additive and material removal processes, the study of how to effectively integrate and automate the hybrid process for remanufacturing will substantially provide a positive impact to the environment.

Next-generation AM processes must fully demonstrate their incorporation of sustainability principles including energy efficiency and the following major sustainability targets/goals:

- Reduced manufacturing costs, material and energy use, industrial waste, toxic and hazardous materials and adverse environmental effects;
- Improved personnel health, safety and security in AM processes and use of products made by AM; and
- Demonstrated reparability, reusability, recoverability, recyclability and disposability of products produced from AM.

To achieve one or more of the above sustainability goals, a total lifecycle analysis and a comprehensive sustainability evaluation of each AM process must be made. Analysis of all four stages of product sustainability (pre-manufacturing, manufacturing, use and post-use) will be necessary to reach these goals. Also, product design and manufacture in the 21st century will require a greater integration of lifecycle data, sustainable product/process designs, and their implementation in the manufacture of innovative engineered products. End-of-life products from AM should be recovered, reused and remanufactured. Redesigned next-generation products are expected to utilize most, if not all, of materials from the first life, thus making a “near-perpetual” material flow in AM to enable “near-zero” wastes and minimized adverse environmental effects.

To achieve sustainability, the major research challenges posed for the next 10-15 years are:

- Conducting fundamental studies towards developing sustainable materials for use in AM;
• Increasing the science base for sustainability principles applied to product design for AM;
• Predictive modeling, simulation and control for product and process sustainability in AM; and
• Developing multi-lifecycle models, including economic evaluation of sustainable AM processes.

Finally, a better understanding of product lifecycle and disposal is needed: How will AM parts be recycled or disposed of, and how long will they last?

A holistic view of AM over the entire product lifecycle is needed as depicted below.

In 15 years, perhaps the wide adoption of AM will not be a result of solely displacing expensive and unnecessary tooling, or the ability to manufacture cost-effective personalized products. The adoption may also be driven by legislation and the consumer’s desire for cleaner, greener products, both in their production and usage phases. Perhaps the adoption will also be driven by a global shortage of natural resources, making efficient AM the only viable production process for many parts.

8.4 Research Opportunities
Research opportunities are recommended in the following seven categories:

1. Product design and development:
   ➢ Using AM to produce components in the energy industry
   ➢ Morphing multi-lifecycle products
   ➢ Maintenance, Repair, and Overhaul (MRO) in the aerospace industry and, more generally, remanufacturing in other industries as potentially lucrative applications of AM

2. Manufacturing processes and systems (including reverse manufacturing processes/systems):
   ➢ Separation of heterogeneous materials for efficient recycling in the end-of-life of a product
   ➢ System and methodology to recycle metal alloys and plastic polymers
   ➢ Reuse chips from machining processes in AM (industrial ecology)

3. Engineering materials:
   ➢ Develop sustainable (green) materials to replace eco-toxic materials (e.g., lead, mercury)
   ➢ Enabling technology for passive energy systems
   ➢ Develop next-generation alloys to achieve specific objectives (light weight, high strength, etc.)
   ➢ Explore biodegradable materials

4. Natural resource conservation (including reduced energy consumption):
- Increase efficient use of raw materials in powder/liquid form by displacing machining of solid billets to save energy and reduce solid wastes

5. Enterprise systems:
- Reverse logistics
- Green supply chain
- Theoretical and practical cradle-to-grave lifecycle inventory of engineering materials for AM processes

6. Application tools (including hardware and software tools and related methodologies and technologies):
- Lifecycle value engineering model
- CAD/design methodology and an appropriate set of tools and standard practices for better decision-making
- Design rules for sustainable processes
- Equitable indicators for measuring sustainability in products and AM processes
- Models to quantitatively compare energy consumption and environmental performance between AM and traditional manufacturing processes
- Material performance databases for better design for the environment

7. Governmental regulations and education issues:
- Government-driven incentives for development of sustainability metrics, energy consumption models, and material flow analysis models, and for adoption of ideas that use and leverage AM parts and technologies
- Provide general education/awareness to more groups/people so that they know what is possible
CHAPTER 9 RECOMMENDATIONS

Recommendations from the roadmap for additive manufacturing (AM) report will be summarized in this chapter and categorized into the following four areas: research recommendations, education and outreach recommendations, development and community recommendations, and a national testbed center.

9.1 Research Recommendations

Design: The unique capabilities of AM processes greatly increase the design freedom for designers to explore. However, it is not easy for designers to take advantage of these capabilities. To this end, the following recommendations are offered:

- Conceptual design methods are needed to aid designers in defining and exploring design spaces enabled by AM. Methods for simultaneous product-process design and multifunctional design are needed. Methods are needed to assess lifecycle costs and impacts of parts and products fabricated by AM.

- A new foundation for computer-aided design systems is needed that overcomes the limitations of parametric, boundary-representation solid modeling in representing very complex geometries and multiple materials.

- Composable simulation capabilities for primitive shapes, materials, material compositions, etc. Multiscale modeling and inverse design methodology are needed to assist in navigating complex process-structure-property relationships. Finite element analysis software should be improved to make use of such capabilities.

- Methods are needed to model and design with variability: shape, properties, process, etc.

- CAD systems for non-experts will be necessary for the toy, collectables, housewares, game avatar, and related areas.

Process Modeling and Control: The ability to achieve predictable and repeatable operations is critical. Process variability must be reduced, but also the sensitivity to process variations needs to be reduced as well. To achieve this, research in several areas is needed:

- Process-structure-property relationships are needed for each material and process. They should be modeled and integrated with CAD/E/M tools.

- Closed-loop and adaptive control systems with feedforward and feedback capabilities are needed. Control algorithms must be based on predictive models of system response to process changes.

- New sensors (process, shape/precision/surface finish, NDE) are needed that can operate in build chamber environments. Sensor fusion and interpretation methods are needed to convert sensor data into control signals. Computer-aided inspection systems integrated into control systems would be beneficial. Machine learning technologies should be developed that are suitable for AM machine control and improvement.
AM Materials, Processes and Machines:

- A much better understanding is needed for the basic physics and chemistry of AM processes that capture the complexity in the multiple interacting physical phenomena that are inherent in most AM processes.
- Processes are needed that are based on scalable, fast material processing methods, such as processes that fabricate a line (e.g., ink-jet printing) or area (e.g., mask-projection) to greatly increase machine throughput.
- New, open-architecture controllers are needed for AM machines so that they can follow a similar development path as CNC machining systems did 20-30 years ago. Development of reconfigurable, standard machine modules could have a tremendous impact on the field.
- Unique characteristics that differentiate AM from conventional manufacturing processes should be exploited, which include taking advantage of the anisotropic nature of AM, producing epitaxial metallic structures, fabricating functionally gradient materials and multiple materials, and embedding components (e.g., sensors and actuators) during fabrication processes.
- Screening methodologies are needed for advanced manufacturable materials to answer definitively why some materials are processable by AM and some are not. Material “allowables” (ranges of material properties) should be developed for new materials that enter the market.
- In general, micro and nano AM needs further research for the development of better tools to build structures and devices atom by atom. Better tools are needed to fabricate parts atomistically, and design tools are needed for nanomanufacturing. Funding agencies might work with the National Nanotechnology Coordination Office to structure a university program for Atomically Precise Manufacturing.
- Sustainable (green) materials should be developed to reduce their environmental impact, including recyclable, reusable, and biodegradable materials.

Biomedical Applications:

- Design and modeling methods for implants and medical devices that are customized to individual patients, including software tools to interpret CT/CBCT/MRI imaging data.
- Development of viable Bio-AM (BAM) processes for construction of 3D biological and tissue models using living biologics and for fabrication of scaffolds, including “smart scaffolds” with embedded sensors. The ability to predict BAM process effects on subsequent cellular functionality is critical.
- Computer-aided BAM is needed, including modeling, analysis and simulation of cell responses and cell-tissue growth behavior.

Energy and Sustainability Applications:

- Design energy system components to take advantage of AM capabilities.
- Pursue Maintenance, Repair, and Overhaul (MRO) in the aerospace industry and, more generally, remanufacturing in other industries as potentially lucrative applications of AM.
• Investigate theoretical and practical cradle-to-grave lifecycle inventory of engineering materials for AM processes. Develop equitable indicators for measuring sustainability in products and AM processes.

9.2 Education and Outreach Recommendations
Though technological barriers exist, as in most technology areas, the majority of barriers tend to be non-technical and instead are more focused on human-centric issues. In the case of AM, these include a lack of education of practitioners in AM capabilities, cultural differences, vested interests and potentially a lack of imagination. To overcome these barriers, a three-pronged program of education is recommended:

• university courses, education materials, and curricula are needed at both the undergraduate and graduate levels,

• similar needs exist at the technical college level, and

• training programs for industry practitioners, perhaps with certification by professional societies or organizations (e.g., SME, ASME).

In addition to formal education programs, outreach to non-technical populations is also needed:

• Programs for management or other non-technical business personnel on logistics, lean manufacturing, new business models, etc.

• Programs for educating the general population would enhance the interest in AM applications and generate some societal “pull” for these technologies. Outreach could take the form of museum exhibits, “product placement” in television shows and movies, topical segments on popular shows, or creative advertising and marketing campaigns for new products.

9.3 Development and Community Recommendations
Several other recommendations can be categorized as more developmental, as opposed to research, and more for the larger AM community of vendors and practitioners. Two broad recommendations emerged:

• Ensuring the affordability of AM in relation to conventional manufacturing is critical for the long-term viability of the AM industry, including reductions in machine, material and servicing costs. Higher production volumes of AM machines and manufactured parts will tend to lower prices; additionally, a change in mindset towards production manufacturing may help accelerate cost reductions.

• The development and adoption of robust standards is of significant importance to the future of AM. Product, process and material certification that conform to internationally recognized standards will, in great measure, along with more repeatable systems, drive the adoption of AM. The recent ASTM F42 initiative on AM standards will drive the standards agenda, at least in the near-term, but this should be vigorously supported by the AM community.

9.4 National Testbed Centers
The group recommends that a national testbed center be established. Equipment is expensive and should be leveraged to the greatest extent. The testbed should be a highly visible “showcase” facility or facilities that comprises a critical part of the research and education
infrastructure of the US. This is a concept similar to that of the NSF supercomputer research centers that were established in the 1980s.

The testbed concept is to have one or more sites with AM machines and expert users. The AM machines should be a combination of commercial machines, older commercial machines that can be modified, and research machines. Experimental machines should be constructed that integrate process technologies with sensors and control systems. Additional sensors should be added that enable remote researchers to monitor and interact with the machines. The machines should be used for a wide variety of research, education, applications, and testing. The testbed resource would be available to academic researchers, industry practitioners, users interested in testing to support standards development (as emphasized in Chapter 2), and anyone else who wants to explore the capabilities and applications of AM technologies. The resulting testbed exemplifies the cyber-enabled manufacturing research concept.

A technical view of the testbed centers is shown in Figure 9-1. AM machines are augmented with sensors and control systems. With these systems, process models can be built, along with process-structure-property relationships. Composable simulation models become feasible. These are integrated into CAD/E/M systems and design frameworks. The entire system – including design, analysis, and manufacturing software, machines, and manufacturing processes – becomes available to participating researchers wherever they happen to be.

Several operating modes were explored, at different parts of the trade-off space between centralization and distribution. It is likely that 3-5 main sites should be constructed, with each site focusing on a collection of similar technologies and processes. For long-term sustainability,
funds need to be found for facility construction, equipment purchase, operations and maintenance, materials, administration, and some travel. Initial estimates are for $10-20M in equipment and facility funds would be needed for initial development of testbed center sites, and approximately $1M per site needed in operating funds annually (does not include research funds). Some of the initial investments could be reduced by selecting sites where a concentration of equipment and expertise already exists. Fees for access to the testbed resources could help cover costs.
Appendix I
Roadmap for Additive Manufacturing Workshop Participants
Washington, D.C., March 30-31, 2009

UNIVERSITY
Jack Beuth, Carnegie Mellon University
Dave Bourell, University of Texas at Austin
Bert Bras, Georgia Institute of Technology
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Denis Cormier, North Carolina State University
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David Rosen, Georgia Institute of Technology
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Ryan Wicker, University of Texas at El Paso
Hong-Chao Zhang, Texas Tech University

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Rex Brown, Honeywell
Andy Christensen, Medical Modeling LLC
Kent Firestone, Solid Concepts
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Ken Johnson, Solidica
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Greg Morris, Morris Technologies
Tom Mueller, Express Pattern
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Jim Williams, Paramount Industries
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Khershed Cooper, ONR
Shaw Feng, NIST
David Forrest, NSWC-IMM
Joycelyn Harrison, NSF
George Hazelrigg, NSF
Kevin Jurrens, NIST
Christine Kelley, NIH
Kevin Lyons, NIST
Dave Stieren, NIST-MEP
Karen Taminger, NASA Langley
Jay Tiley, AFRL
Ralph Wachter, ONR
Appendix II

Two-Page White Papers Relating to Participant Perspectives
On the Future Challenges and Opportunities in Additive Manufacturing
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<td>Jim Williams</td>
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<td>Terry Wohlers</td>
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Within the next 10-15 years additive manufacturing should become an integral component of available manufacturing processes for metallic parts, now represented primarily by forging, casting and machining. Implementation of additive manufacturing deposition technologies can influence three areas – fabrication cost, reduction in schedule and component performance. However, for additive manufacturing to be implemented into the manufacturing flow path, the advantages of the additive processes must be compelling in order to offset the associated development and characterization costs.

Additive manufacturing can help reduce the high buy-to-fly ratios common to forged and machined aerospace components and structures. These high buy-to-fly ratios are reflected in large costs associated with material loss and time consumed during machining. Additive manufacturing can also dramatically shorten the development cycle time for new components by circumventing the fabrication of new tooling. And finally, the deposition technologies offer the ability to tailor the strength of component features by selectively placing alloy compositions as needed.

Many of the components of an additive manufacturing system for industrial applications have already been developed. However, these technologies are often stand alone processes that need to be integrated to produce a seamless manufacturing flow path. We see the need for a modular, integrated manufacturing cell or system that will include deposition, machining, heat treatment and inspection operations for full additive manufacture to finish machined part capability. Such a manufacturing cell would address the fabrication of part families to avoid suboptimization to single components. A change to another part family may require no more than the addition of another machining module. Such a modular manufacturing cell could significantly increase work flow and lower the cost of component fabrication. The modular approach to a manufacturing cell will also help prevent contamination in the deposition unit by the machining operations.

There currently are a number of developed deposition technologies, i.e. electron beam wire and laser powder deposition, that have demonstrated the ability to deposit high quality material with mechanical properties between that of the cast and wrought forms of the alloys, often moving into the wrought property range. These machines operate at various degrees of automation. For the most part, there has been little development of integrated deposition/manufacturing systems for industrial scale fabrication of components.

The deposition system probably requires the most enhancements to bring it up to production level fabrication. There are a number of ongoing activities today addressing some of these needs. It is important that the deposition unit operate with a minimum of operator intervention, much like current state-of-the-art CNC machining systems; full CAD file to deposited part capability is a necessity. In addition, the deposition unit must have feedback/feed forward capability to control the melt pool size and temperature and maintain dimensional control of the deposited structure.
We need real time NDE capability of the deposit so that if microstructural imperfections are created, they can be identified and then removed immediately if required.

Much of what I have suggested above is evolutionary to current technologies, the primary exception being the modular approach to the additive manufacturing work cell. The individual module technologies are in place – it is a matter of time to assemble them together.
I see the future of Solid Freeform Fabrication (SFF) or Additive Manufacturing Processes as proceeding along three main branches. The first branch, which was very well-described in Dave Bourell’s white paper, is the widespread use of SFF processes as a means for desktop printing of 3-D shapes. I agree that the prototyping industry is clearly moving in this direction, with a number of prototyping processes that are technologically fairly simple and effective as potential platforms for widespread desktop use. Costs continue to go down for existing machines and low-cost desktop printing could be a reality within a decade – perhaps sooner.

The second main branch I see for these processes is their use as robust industrial manufacturing processes for high value-added products. Key industries of interest are the aerospace and biomedical (especially the customized implant) industries. We are currently collaborating with aerospace industry consultants and subcontractors who are developing additive manufacturing methods for component manufacturing and repair applications. Their interest is in wire-feed electron beam-based processes due to better consistency of the fraction of beam power transferred to the substrate, and due to their increased flexibility in beam control compared to laser-based processes. Our collaborators on this work include: Nate Klingbeil of Wright State University, Keystone Synergistic Enterprises (Port St. Lucie, FL), Acceleron, Inc. (East Granby, CT), Karen Taminger of NASA-Langley and Pratt & Whitney.

Our modeling research addresses the two main factors of interest to industry: part quality and cost. These two factors are strongly coupled. With respect to part quality, main concerns are the ability to accurately fabricate complicated 3-D shapes with a minimum number of experiments (learning how to fabricate new geometries must occur quickly), and the ability to control microstructure throughout fabricated features. The ability to rapidly create new part geometries is also clearly a cost issue. With respect to cost factors, a key metric is mass or volumetric build rate. Here our modeling research is attempting to guide our partners in how to switch from high volume deposition conditions (for max build rate) to low volume deposition conditions (for precision deposition) while maintaining geometric- and microstructure-related part quality metrics. My collaborators and I feel that the study of electron beam-based additive processes is a rich area of research and potential near-term application for the aerospace industry.

A final branch I see of importance for future research is the application of SFF concepts to the fabrication of microscale/nanoscale devices. There has been quite a bit of academic research in this area, though I have not seen as much interest from industry on this topic as I have for the first two branches (rapid prototyping and large-scale manufacturing applications). One of the things I would like to see in this workshop is whether there is significant evolving industrial pull for this topic. It is an area of nearly limitless study from an academic perspective.
I believe that one area of significant commercial advance in the next 10-15 years will be the creation of a widespread consumer market for low-cost, mass produced 3D printers. We can learn from the history and evolution of 2D printers that are ubiquitous in homes and offices around the world. My version of this reality begins with the advent of affordable personal computers in the workplace in the mid-1980s. (Does anyone remember the Mac Plus?!) The second necessary component was inexpensive, easy-to-use word processing applications which allowed the computer to mimic a typewriter. Access to personal word processing created the need to print out hard copies, and thus the demand for low-cost, office 2D printers developed. Over a period of a few years, personal computers transitioned from the workplace to the home in low-cost versions, which created a parallel market for low-cost printers. A critical key was the advent of widely available, relatively low-cost word processing software applications.

We now have a widely developed and, thanks to the internet, a widely integrated system of extremely low-cost computers. As a civilization, we are overall quite computer literate at virtually all points on the globe. [I wonder sometimes on a country-by-country basis what is the average distance between a person and a computer?!] We have a technology in place for tabletop manufacturing in three dimensions at the mass marketed consumer level. When I look inside a $200 multifunction machine (printer/copier/fax), I convince myself that its technological complexity is comparable or exceeds that of a hypothetical 3D printer. We already have at least one working concept of a low-cost 3D prototype printer in the FAB@HOME printer (http://fabathome.org), and there are reports and rumors of companies developing some form of low-cost, consumer 3D printer. I have even heard that select name brand copy centers may be installing 3D fabricators soon.

So we have the technology, the computer hardware base, highly integrated communication and a computer-savvy society. What’s the hold-up presently preventing an avalanche of low-cost 3D printers flooding the marketplace? It is the lack of demand by large numbers of users. I believe that the main obstacle is low-cost, easy-to-use, intuitive 3D software applications. This may not necessarily be a research issue, but perhaps it is. Like the 2D word processing applications of yesteryear and today, this 3D software needs to be simple enough for non-technical users to learn quickly, versatile enough to unleash the creative energies of individuals and cheap enough to be mass produced and marketed. Once persons can create an object, the demand for a 3D printer will be created analogous to the 2D printer example. A secondary obstacle is the dearth of “cool” 3D objects available free and on-line. Analogous to “clip art” or downloadable sound freeware, accessible libraries of 3D objects coupled to a 3D printer will enable individuals to exercise their creative bent and satisfy demand. Finally, a significant aspect of low-cost 3D printers will be low-cost print media/consumables. I know there is a business aspect to pricing, but the cost of consumables must be within the ability of individuals to pay.
There is an element of bootstrapping associated with the development of a 3D consumer technology. That is, object creation will feed interest in object printing which will spur creativity, new applications and demand. I feel it is coming, and that the widespread availability of a 3D part generation capability will foster uncounted new uses of the technology.
Rapid manufacturing has the potential to make an impact on the production of goods at least as large as that of Henry Ford’s assembly line. Whereas Ford’s assembly line allowed copies of a single good to be produced in a very efficient, linear manner, RM will allow a customized version of a product to be manufactured quickly and efficiently, when it is needed by the end customer. In the next 10 to 15 years, I envision that RM machines building fully functional parts and assemblies, both mechanical and electrical, will be commonplace.

RM will continue to become less expensive, and better. As with most technologies, quality goes up, and cost goes down as time goes on. Software will be developed that allows more people to produce better solids models much more intuitively. RM equipment will decrease in cost, size and complexity. We will soon find these machines in homes and retail businesses. Service bureaus will find it more and more difficult to maintain a competitive advantage in this environment.

Technically, resolutions will increase to the point where layers or build lines are largely invisible. Accurate color will be commonplace, as will the ability to build parts and assemblies in multiple materials, simultaneously. This will give way to RM parts that contain working electronics right from the machine.

In many parts of the world, outside of the United States, automobile manufacturers offer individual programs that allow a customer to specify many different colors, textures and options for their automobile. The resulting product is truly unique to that customer, their needs and desires. Leveraging the advantages of RM, many companies will be able to offer personally customized products quickly, efficiently and cost effectively. Whether it’s a bicycle frame built of nano particles with custom tube lengths and geometry, or a set of custom silverware for a special event, ease of customization will become more popular as the quality of RM parts rivals current manufactured goods, and little or no post processing is necessary.

RM will also be tasked to build objects on a much smaller, and a much larger scale than is possible today. For example, micro medical devices and electronics, or entire automobiles and buildings.

Currently, RM technologies rely on a layered building approach where a computer model is virtually sliced into many very thin layers, and then those layers are each manufactured individually, one on top of the other. A new building method may be employed such that an object is built from the inside out. Perhaps this would be called cloud building. A point would be identified at the nano level within the model, and the RM machine would then begin building from that point, outward. Not quite random, this method may better allow for the use of multiple materials in a single model, such as a cellular phone where plastics and metals are used.

With the ability to create circuitry, electrical components can be created that are fully sealed, and truly “plug and play”. Traditionally, it has been important to be able to open a broken device, evaluate the problem, and fix that problem. In the future, RM electrical components and devices will be built within their cases, as one unit. The advantages will include longevity and durability. However, without the ability to fix a unit, we may find issue with waste when they do fail.

On a larger scale, entire buildings could be constructed by RM. From walls, windows, plumbing and electrical would all be built simultaneously. Interim steps to a completely RM’d building might focus on the structure of the building itself, where physical allowances are made for easy installation of windows, doors, wires and pipes. The RM machine itself may look more like a strange type of crane than what we are accustomed to. Large rail structures would comprise the fast and slow axis’, and a gantry along the fast axis would contain the actual building head, as well as connections to raw material sources. The machine would be assembled on site, and then removed once it’s portion of a project was completed. I see this as being particularly beneficial in low income areas, and even in space programs.
Imagine a moon base being built using a large RM machine with raw materials from the moon. Instead of building and packing structures on earth to be launched via space vehicle to the moon, and then built by the astronauts, a single RM machine can be delivered. It will be able to build many structures more quickly, and less costly, than sending each one on their own rocket. We may need to send some consumeables, but I believe that scientists could find a way to make a cement of the sand and dust on the lunar surface.

Generally, post processing will have to be eliminated or at least greatly reduced. 3D printing requires depowdering and infiltration. FDM requires the removal of support material. When a machine is finished building a part, that part should be ready for use. Additional processing will slow the adoption of RM technology, particularly for lower price target markets.

Improved color and transparency will help make RM mainstream. The only full color technology at the moment is Zcorp’s 3D printing, however, resolution and accuracy are often unpredictable. FDM has the ability to make parts of single different colors, but the selection is quite limited, and the entire part must be of that one color. SLA has the ability to shade portions of a model in a contrasting color. Regardless, none of the available color technologies are “consumer ready”.

One final idea of RM is for food. Using raw materials such as animal protein, plant protein and flavor bases, some foods may be satisfactorily replicated. Specifically, I see the best application of such a process in space missions where physical space is extremely limited. Having one machine and some basic raw consumeables to “cook” most foods would certainly be space efficient. The only question though…would it be as good as current astronaut food?

I see three general categories for the capabilities of RM.

Consumer
- 3D printers in the home.
- Mainstream 3D solid modeling software. Likely with an entirely new user interface. For example, instead of a mouse, the user wears gloves to virtually mold a 3D sculpture.
- Internet sites that offer 3D solids for sale and/or download.

Business
- RM of complicated end parts.
- Electrical circuits integrated into parts.
- “TRM” or Total Rapid Manufacturing.
- High speed capabilities.

Government
- Mobile RM devices suitable for battlefield and space.
- Used to build replacement parts for all types of equipment on the battlefield, from small electronic devices to heavy equipment parts.
ROADMAP FOR ADDITIVE MANUFACTURING WORKSHOP WHITE PAPER (2 PAGE MAX)

Please check off (☑) the appropriate topics for this paper:

☒ Industry Targets ☒ Technology Goals and Barriers ☐ Design and Analysis
☒ Processes and Machines ☒ Materials/Materials Processing ☐ Energy/Sustainability
☒ Nano- and Biotechnology

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There appears to be three avenues that rapid manufacturing seems to be branching out into in the upcoming years. All three of these need further development and support by research institutes, manufacturing, customers and standards groups.

The first leg is the “everyone has one at home” for the lower end plastic type quick build type parts that are inexpensive and easy to build. This could be from the kids designing their favorite cartoon hero to the new entrepreneur designing his first new invention and printing it out for a concept model for limited fit form function testing. For this to work the cost needs to come down both for the machine and supplies. The machine will need to be low maintenance and be a single push of a button just like printers of today, push the print button and grab the part.

The second is for the manufacturing community that is in need of a quick way of building home products that are low to medium quantities that can compete with the injection molding industry and don’t require the stringent requirement of say aerospace products. The machines required to perform this type of operation would be medium to low cost, repeatable, and hold part tolerances. For this to happen machine cost of operation will need to be lowered for the cost of parts to be competitive. With the advancements in high speed machining molds are being made much faster reducing the cost of the mold and in turn lowering the threshold for the cost break point for rapid manufactured parts off of a SFF machine vs. a molded part.

The third is the high end market. This market is for the advanced materials such as metals, ceramics, high temperature plastics that hold close tolerances and meet manufactures specifications. These specifications can include part tolerances, material properties surface roughness and density requirements. With the machines of today’s ability to build such complex parts this is a great way to move into the rapid manufacturing arena without competing with traditional methods and high speed machining. To reach this goal, standards need to be developed for both machines and materials. With the ability to change the material properties with processing parameters and machine performance this is no simple task. The needs for these standards are required so that engineers and designers are able to design product with the enhanced material properties. This all being said equipment vendors need to make the process repeatable and get it out of the lab environment and to the end users.
Over the last twenty years since the initial development of the 1st Stereolithography machine, rapid prototyping based on solid freeform fabrication (SFF) has become a common practice in product development. The most significant benefit of SFF is that it is a direct manufacturing process that can fabricate parts directly from computer-aided design (CAD) models without part-specific tooling or fixtures. In the next 10-15 years, I believe more novel applications will be developed by innovatively utilizing the benefits provided by such type of disruptive manufacturing technology.

The new applications can be developed based on the time and cost benefits provided by the additive manufacturing technologies, most likely in mass customization or personalized manufacturing for small quantity productions, such as the Invisalign developed by the Align Technology. The new applications can also come from better design performances enabled by the additive manufacturing technologies, such as the unusual lamps developed by the Freedom of Creation. Compared to the traditional manufacturing processes, the additive manufacturing technologies have the revolutionary capability of fabricating truly complex 3-dimensional shapes cost-effectively in macro- and meso-scale levels (feature size > 0.1 mm). With suitable design tools, I believe such revolutionary capability will provide product designers with tremendous freedoms to come up with new designs that are unimaginable before.

Although more design freedoms is generally welcome in product design, the SFF’s unlimited geometric capabilities may be so dramatic that the designers do not know what to do with them initially. Currently there is limited knowledge regarding the use of complex shapes to achieve improved performance such as heterogeneous material properties and multi-functionality in a product design. In addition, much more complex geometries in design pose significant challenges in modeling, analyzing, synthesizing, and optimizing the shapes to meet the specified requirements. Therefore, the benefits of using such capabilities for better design performance are still mainly untapped. To change such situations, new design for additive manufacturing methods and related CAD tools need to be developed. Many fundamental research issues such as topology configuration, shape modeling, and design optimization need to be addressed. Based on such research results, I believe novel CAD tools will be developed and widely available even for normal people who are not CAD expert. In addition, various product design software systems specifically developed for customized products can be quickly made based on more widely available open source codes. In addition to proper design tools, it is also important to educate future and current-practicing engineers with the capabilities of additive manufacturing technologies. Over the years, based on the efforts of providing better design tools, more widely available SFF system, and related educations, I believe a significant amount of novel applications will be developed by normal people who are innovative in their own fields.

The additive manufacturing technologies have only 20-years development. In comparison, most traditional manufacturing processes have hundreds of years of development. Therefore, it is also
important to continue the process, material and machine development of these technologies especially for direct manufacturing applications. The additive manufacturing technologies were originally developed for rapid prototyping (RP) purpose. Some early adoptions of SFF in direct product manufacturing include aerospace and medical applications such as air ducts in Boeing’s F/A-18 fighter jet and Siemens’s hearing aid shells respectively. Direct manufacturing applications require much better accuracy and surface finish, shorter building time and higher degree of manufacturing automation. Therefore, significant advances in material, process and machine developments are essential. For well-accepted SFF processes such as Stereolithography apparatus (SLA) and selective laser sintering (SLS), advanced computational techniques in process planning are especially important for the next 15 years. As shown in CNC industry over the last 10 years, the greatest technological gain in CNC has been with the machine controller software that intelligently anticipates the geometry changes. Similarly, for more mature processes such as SLA and SLS, I expect the greatest technological gain will be achieved with the machine controllers based on more complex and intelligent process planning algorithms and more widely available computing resources. Such improvements are critical for a wider adoption of direct digital manufacturing in various applications.

To achieve more widely available SFF systems for the general public, I expect more novel additive manufacturing technologies will be developed based on new off-the-shelf technologies such as digital micro-mirror device, inkjet printing and LED over the next 10 years. Driven by other applications, such technologies are relatively inexpensive even with quite amazing R&D efforts. Developing novel SFF processes based on such off-the-shelf technologies will definitely demonstrate significant cost and time benefits. I expect machine cost will also go down significantly after many important existing patents expired in the next 10 years. With the goal of developing inexpensive machine, maintenance, and building materials, such additive manufacturing technologies will become commodity accessible by every one for rather wide applications.
This white paper represents a summary of many discussions with many people over what we would like to see happen in the industry over the next 10-15 years. It is not necessarily a prediction of what will happen. Other than the cost issue, the prevailing sentiment is that existing technology for prototyping purposes is relatively mature and capable. The overwhelming majority of interest for the future lies with freeform fabrication of production parts (i.e. additive manufacturing). Many of the underlined objectives represent sheer guesses as to what the 10-15 year target values for a particular property should be. These are just starting points for discussion.

Additive Manufacturing of Polymeric Materials

- **Material Properties** - While polymer-based additive processes continue to improve in terms of material properties, there is still considerable room for improvement. In some processes, the deposited material is porous. In some cases, parts suffer thermal distortion for certain types of geometries such as long narrow flat pieces. Some materials have properties that degrade substantially over time. In terms of additive manufacturing of functional parts, injection molding is the competition. The 10-15 year objective would be to have materials whose properties meet or exceed what one would typically see in a particular injection molded thermoplastic material (ABS, HDPE, PP, etc).

- **Color** - At the present moment, it is possible to produce short run injection mold tooling on very short notice. In order for polymer-based additive manufacturing systems to have a distinct advantage over injection molding with bridge tooling, they should be capable of fabricating components in any desired color, including multiple colors within a part. If it were possible to "print" functional plastic parts in any number of color combinations, then that would open up all kinds of opportunities.

- **Speed** - While the speed of print-based systems has increased dramatically in recent years, builds of just moderate size are still often measured in hours. The 10-15 year objective would be for systems with large scale parallel deposition heads that can produce moderate sized parts in just a few minutes rather than hours.

- **Reliability** - As the number of parallel deposition heads increases in order to improve build speed, the potential for a machine to go down with a print failure increases exponentially. Deposition heads must be engineered to have mean time between failure of at least several months.

- **Cost** - Machine prices have been dropping rapidly in recent years, however, the price of consumables is several orders of magnitude higher than that of injection molding thermoplastics. For several systems, the price of resin ($/kg) is considerably higher than the price of powdered titanium used in direct-metal processes, and this is despite the fact that titanium is in relatively short supply! Resin prices will have to come down to at most one order of magnitude higher than commodity injection molding polymers. One would hope that prices will drop as the volume of machines shipped increase.
Additive Manufacturing of Metals

- **Build Size** - This is among the most significant limitations of currently available technologies. Aerospace is one of the largest potential users due to the fact that the number of parts needed in a given year might be in the tens or hundreds. However, very few aerospace parts are small enough to be produced in commercially available laser or e-beam systems. Based on discussions with aerospace companies, an absolute bare minimum build volume would be something on the order of 600mm x 600mm x 600mm. It would be preferable for a system to have one axis at least 1,200 mm long.

- **Deposition rate** - In order for metal additive processes to make economic sense, true deposition rate must be increased dramatically. By true deposition rate, I mean that time needed for intermediate stress relief, preheating, and post-processing cooling must be included. A goal would be to produce a large part whose dimensions match the minimum listed above in less than 8 hours (a guess - just intended to start discussion).

- **Surface finish** - Most metal additive processes produce parts with a textured surface. Much of the appeal of additive manufacturing stems from the ability to produce complex geometric shapes that would be difficult to produce via other means. The complex geometries often involve surfaces that are inaccessible for finish machining. Depending on the loading requirements of the part, rough surfaces may or may not be acceptable. The ideal part will come out of the machine at net shape rather than near net shape (e.g. finish machining is not necessary).

- **Thermal Stresses/Distortion** - Distortion associated with thermal stresses are one of several reasons why it is difficult to fabricate large metal parts. This issue must be overcome either by in-situ stress relief or via solid state processes that don't produce such large thermal stresses.

- **Availability and Safety of Feedstock** - Feedstock in powder, wire, or ribbon form is often difficult to obtain in the same alloy as the forged or cast target material. Feedstock in powder form is particularly expensive, and there are substantial safety hazards associated with powdered metals that must be addressed.

- **Equipment Cost** - The cost of equipment is extremely high, although this is probably a lower priority than the other technical issues. The parts and materials produced via these processes tend to be high dollar value. Additive processes are not likely to compete with casting or machining of commodity metals in the near future except for extremely complex geometries.

Miscellaneous

- **Multi-Material Systems** - Growing interest in smart materials will increase the need for polymer based systems in which metal traces such as electrical conductors can be printed. Systems that enable the user to embed sensors, actuators, etc are also of interest. There has been much research along these lines, but things such as support structure and powder/liquid spreaders make it difficult if not impossible to pause commercially available machines and to insert devices without the device or the deposition equipment being damaged.

- **Composites** - Composites are being increasingly specified in automotive, aerospace, and other areas due to their extremely high strength-to-weight performance. Additive systems to produce continuously reinforced composites are not available. Additive systems to produce discontinuously reinforced composites are available in limited form, although these composites don't really compete with the continuously reinforced composites used in automotive or aerospace.
In additive manufacturing, material is selectively deposited or bonded to create parts of near arbitrary geometry. Generally, the minimum feature of an additive manufacturing process consists of many smaller elements (powder particles, polymer molecules, crystals). Since orientation is not critical, the material’s position along must be controlled.

I believe one important direction of future work will be to create processes that use functional block additive manufacturing in which the fundamental additive feature is the smallest possible building block with the necessary functionality. While this could be a single monomer, the functional block could also be much larger. Larger functional blocks could have embedded functionality to dramatically increase the capabilities of parts produced by additive manufacturing. For example, they could include sensors or actuators fabricated using traditional approaches. As these building blocks could be at size scales from centimeter to nanometer, a range of manufacturing technologies will be applicable.

The use of more fundamental building blocks will permit the manufacture of parts with a greater range of material and device performance capabilities. Already the incorporation of two materials (typically structure and support) dramatically increases the range of structures possible with many additive manufacturing processes. These capabilities would permit the fabrication of more systems with unique performance characteristics not achievable by other manufacturing processes. For example, a medical implant could incorporate load and other sensors connected to electronics for monitoring their results. Each implant could be custom manufactured with biological agents or even the recipient’s own live cells to aid in implant acceptance.

Functional block additive manufacturing would also address a key need in micro/nano fabrication for improved ability to integrate components produced from different processes or incompatible materials into functional systems. These limits have long constrained the fabrication of complex microscale systems. The additive manufacturing approach could provide a potential solution to this integration challenge. Current work on printed electronics and solar cells already moves in this direction.

The key to success of this approach is the ability to manipulate diverse components at the required size scales. Macroscale manipulation techniques are well-developed. However, at the micro/nano scale, significant advances are still required. While many relevant techniques have been developed, they have been used in relatively simple applications—often with limited numbers of components. Applications to additive manufacturing at industrial scales would require additional process characterization and development. Potentially relevant methods include robots, digital microfluidics, directed self assembly, and optical tweezers. Research is required in techniques to manipulate individual components at sufficient speeds and resolutions to incorporate them into reliable manufacturing processes.
Due to the functional anisotropy of most basic building blocks, control over component orientation must receive increased attention. Some promising orientation control methods have been demonstrated in self-assembled systems. For example, DNA has been used to selectively bind desired objects with controlled orientation. However, other mechanisms will be required for many materials and processing conditions.

New developments in software for designing and representing these more complex structures and would be required. The design challenge may be particularly important. As the complexity of the design increases beyond the capability of the human designer to comprehend all the interactions, computer-aided design and modeling tools become increasingly critical.
My vision is for the Rapid Manufacturing (RM) market to greatly expand over the next 10–15 years. To accomplish this, RM must become more accepted as a viable alternative to traditional manufacturing processes. I think in order for this to happen, robust design data must be made available to the end customer, machines must continue to become more “manufacturing capable”, and we must make the appropriate materials available to the market place.

One area of opportunity for research would be to establish rigorous mechanical data for existing RM materials. Most of the commercially available materials in today’s marketplace come with general mechanical properties listed on the product data sheet. These values are typically derived using virgin material and only include best-case orientation data. Some material providers are starting to include Z-axis data on their datasheet, which is helpful for the end customer to understand that there is a difference in mechanical strength based on part orientation. However, this is only the tip of the iceberg. In order for mechanical data to be considered robust enough to use for design, it must include at least:

- Data derived from recycled material in addition to virgin material
- Comprehensive mechanical testing from all areas of the recommended build volume
- Testing from a worst-case build orientation
- Testing using a range of process parameters
- Reporting a more comprehensive set of mechanical data

It is often said that this responsibility lies in the hands of the company that intends to sell into the RM market. While this is true, if machine and material providers were to commission this type of work to an experienced research organization, the resulting data should help to accelerate acceptance of Rapid Manufacturing materials and processes.

A second area of opportunity is improving existing machines to make them more “manufacturing capable”. This could include more closed-loop feedback controls, more stable components, or anything that improves reliability and repeatability of the equipment. Some of the machine manufacturers are working on this, but typically only on their new products. If the only way to gain technological advancements is by purchasing new equipment, adoption will be slow. One of the main barriers into Rapid Manufacturing is part cost to the end customer. We must continue to improve existing machines to keep piece part prices at a competitive level.

A final area of research opportunity is in the development of materials that address specific needs of the RM market. These don’t necessarily have to be completely new material systems. In the last few years, several new filled SLS and SLA material systems have been successfully introduced that addressed specific needs such as higher use temperature, increased impact resistance, and flammability resistance. The challenge seems to be in understanding what the
market requires and working towards addressing those needs. Research and development of met
cals and high-temperature thermoplastics are important, but simply looking at new additives to exi
existing material systems can open up new market opportunities.

Research and development activities over the next 10 –15 years need to be focused on speeding up the adop
tion curve of these technologies into more traditional manufacturing environments. In order to achi
wider acceptance, I think it is time to focus more on the development end of the spectrum.
Background on Molecular Manufacturing

The term “nanotechnology” embodies a wide range of techniques and products. Often it involves the use of nanoparticles, which may have functionalized surfaces to interface with biological systems, bond with matrix materials, or catalyze reactions. Here we address a radically different, less mature, but more promising branch of nanotechnology known as “Molecular Manufacturing” (aka “Productive Nanosystems”). This is the original concept for nanotechnology proposed by Drexler in 1981, and is much more relevant to the field of additive manufacturing than nanoparticle technology.

Molecular manufacturing is an emerging technology based on assemblers able to build systems to complex atomic specification under programmable control. This means that molecular machines in the form of robotic arms and assembly lines would position molecules and transfer atoms to additively build structures and devices that are atomically precise. A wide range of high performance products will be possible, from complex composite materials to supercomputers. One important product would be more molecular machine systems: building macroscopic atomically exact products requires massive parallelization of assembly lines so we will need a lot of them. Molecular manufacturing is the only serious proposal for a technology that could realistically produce large atomically precise objects.

The feasibility of molecular manufacturing is proven by living systems. Proteins are made using positional assembly by a machine called a ribosome which exists in every living cell in the human body. The ribosome grabs different transfer RNA molecules out of solution and transfers amino acids onto a growing polypeptide to produce atomically exact structures. This is done according to a programmed instruction set which the ribosome reads from a numerical control tape (messenger RNA).

Despite this existence proof, molecular manufacturing has been highly controversial and was long-dismissed as either not possible outside of living systems, or incapable of making a broad range of non-biological products. In 1999, Ho and Lee (Cornell U.) flattened these criticisms by using a scanning tunneling microscope to chemically bind an individual iron atom to an individual carbon monoxide molecule in vacuum. This was the birth of human-controlled molecular manufacturing, and has since been repeated by other groups with different materials. Recently this technique led to DARPA’s initiative for tip-based directed assembly using scanning probe tools (DARPA BAA07-59); Zyvex was awarded a contract from this announcement. In another important advance, Prof. Alex Zettl (U.C. Berkeley) and his group built a molecular motor based on carbon nanotubes, which could serve to power other molecular machines.

Issues for this Workshop

What roles will nanotechnology play in the development of the additive manufacturing field?

Molecular manufacturing is additive manufacturing at its most basic level, building up structures and devices using individual atoms and molecules that result in atomically precise products. In
every respect, it is the endpoint of additive manufacturing. However the time horizon is 10-25 years, depending on the level of funding and on the quality and focus of our efforts. We must balance near-term goals of more conventional additive manufacturing process with this longer term, high payoff end goal.

In the near term, tip-based manufacturing can provide the ability to make small devices, on the order of hundreds to thousands of atoms that could be useful in nanoelectronics (molecular switches, circuits, and sensor devices) and in physics research of nanoscale-unique phenomena.

Where are the opportunities for additive manufacturing in the bioengineering, medical device, and healthcare areas and what research is needed to realize these opportunities?

The International Technology Roadmap for Productive Nanosystems has identified Energy and Medicine as the two most attractive targets for high impact advances.

What research efforts are of critical importance for the additive manufacturing field over the next 10-12 years?

Needed research in molecular manufacturing has been outlined in greater detail in the International Technology Roadmap for Productive Nanosystems. Along the critical path to develop molecular manufacturing, we need:

- Better tools to build structures atom by atom. This includes:
  - more accurate positioning devices for tip-based manufacturing
  - a wider range of tip tools
  - a library of molecular feedstock that can be used to transfer different kinds of atoms to a growing workpiece

- Designs for useful near-term structures and devices that can realistically be synthesized using tip-based manufacturing

- Self-assembly and synthetic methods to produce structures and devices that complement and interface with devices produced by tip-based synthesis. Prof. Chris Schafmeister’s (Temple U.) rigid bis-peptide ladders are one example.

- Better computational tools for both product design and modeling of the molecular manufacturing process (Nanorex has provided a significant advance with Nanoengineer).

- Significant funding for both industry and academia to develop tools and techniques. Because the time horizon for development is beyond the 5-year benchmark typical for industry investment and venture capital targets, a sustained government-supported initiative is essential. This includes incentives and matching funds for industry investment, grants and scholarships to build a talent pool in universities, and capital for critical infrastructure in government laboratories and universities.
Rather than present a specific list of where I think we’ll be in 10-15 years, I thought that a
cognitive ramble would be more suitable; the main reason is that, as in most futurology
exercises, the “future” presented generally reflects the issues of today – and so the actual future is
clearly very difficult to predict. If, for example, we’d taken Marshall Burns’ book as gospel when
it was written in the early 90’s, we’d be living in a Utopian society, “fabbing” our way forward
with materials pumped into our houses as feedstock; last time I looked, my house was devoid of
such a system…..

I should state clearly that this comment is in no way meant to be disrespectful to the early
forecasters and I think that some grandstanding is generally required in order to move technology
forwards - however, as I think that as we are now (probably…..) genuinely on the cusp of seeing
additive manufacturing becoming a manufacturing reality, then a dose of realism is required to
ensure that the research we undertake is of real relevance to the future.

Therefore, though probably dull, I think the key to getting these technologies adopted as
manufacturing systems is the drive towards Standards; this is unless of course we want to be
simply printing off gaming characters for the foreseeable future. Without robust standards that are
widely adopted by vendors and manufactures alike, then we will be no further on in 10 years.
However, we are beginning to see the start of this with the new ASTM F42 initiative and so I
believe that that the AM research community should fully support this in order to give their
subject area more credence for the future.

However, speaking on a more general level, it is clear that issues that will certainly be / continue
to be of importance in the coming decade or so will include (no doubt, amongst significant
others):

- Ageing population – especially in a western context
- Population expansion – especially in a non-western context
- The environment – promoting a more “green” method of living / production of
  components
- Health of the citizen (or probably more accurately, the un-health of the citizen…)
- Security
- Transportation

I believe that, uniquely, additive manufacturing is able to positively affect all of these areas and
thus there will be a rich seam of research (and pots of research money…..) to pursue.

I think that metals will be of increasing importance, but I also think that polymer systems will
continue to yield research potential – one of the mistakes that I observe at the moment is that
many research organizations are going hell-for-leather for metals research when there is still significant work to be undertaken with polymers.

I also think that it would be a mistake to investigate simply the materials and processes without taking wider consideration of the design and implementation aspects also; it is in these two areas that ultimately provide the biggest benefits of taking an additive manufacturing approach and will provide the business drivers for adopting AM. There is also considerable research to be undertaken in these two fields.

I think that we will digress from working predominantly at the macro level (where most work is currently) with opportunities to work at the mega scale down to the micro and nano levels – without taking and AM approach, how are all these (speculated) nano robots / machines going to be assembled?

I do not, however, believe that AM will become a panacea and that, despite significant potential, it will simply fit into a portfolio (though for some businesses / products, it will be the only viable approach – indeed, I think that many new businesses will emerge that are predicated on taking an AM approach). One of the bigger challenges will be integrating AM components within conventionally manufactured items – it is unlikely that all of a vehicle (for example) will be manufactured additively and so, regardless of how reconfigurable and flexible an AM supply chain may be, the AM component will still have to sit somewhere within a conventional businesss configuration.

With this in mind, although I think that at some time in the future we will move to a stage where we have home-based systems, I’m not convinced that this will happen within 10 years; any home-systems will produce parts that lack the structural integrity required for manufactured goods. I do however, think that we will have a more distributed manufacturing reality with hub-based AM systems – potentially even on the high street.
Among various applications enabled by additive manufacturing, I believe that its main biomedical application in 15 years will be the creation of a viable, controllable bioprinting technology.

Bioprinting has yielded revolutionary advances in tissue engineering and regenerative medicine with great potential for use in the manufacture of arbitrary cell patterning as well as heterogeneous two or three-dimensional (2D or 3D) living constructs and organs. Such artificial constructs are envisioned to be useful for drug screening, chemical toxicity testing, and evaluation of the health and safety of nanomaterials. Integrated with a better understanding of multicellular self-assembly and tissue maturation, bioprinting-based organ printing provides a promising solution to the organ donor shortage.

While some major challenges in bioprinting are biological (i.e. cell source selection, vascularization and maintenance of printed constructs, and accelerated tissue maturation), the scale-up of manufacturing processes to produce viable, uniform multicellular spheroids for use in bioprinting is necessary to make bioprinting technically and commercially feasible. Printing of multicellular spheroids instead of single cells is preferred in practical bioprinting because tissue or organ constructs are usually printed either in forms of cell aggregates/spheroids or directly using pre-designed cell aggregates/spheroids. Using multicellular spheroids results in faster printing due to the dramatic reduction of printing cycles, better cell survival from the social effect and maximally high cell density, and the opportunity to use pre-designed cell aggregates, even in the form of hollow spheres. The effective fabrication of multicellular spheroids is the first step towards successful bioprinting, and the following barriers in multicellular spheroid fabrication must be carefully addressed:

1. Viability (percentage of living cells) and functionality: The fabricated spheroid must maintain certain percentage of viability and functionality. Cell death due to process-induced cell injury is common in jet-based cell direct-write processes;

2. Size and its distribution: Different tissue or organ constructs have their own anatomical structures and require different cellular spheroid sizes. Furthermore, uniform cell size distribution is needed for effective cellular spheroid fusion to form a functional construct; and

3. Scale-up production: Billions of cells will be deposited to form a biological construct in bioprinting. Any commercial fabrication process must be scaled up for future practical applications.
**Roadmap for Additive Manufacturing Workshop White Paper (2 Page Max)**

Please check off (☑) the appropriate topics for this paper:

- Industry Targets
- Technology Goals and Barriers
- Design and Analysis
- Processes and Machines
- Materials/Materials Processing
- Energy/Sustainability
- Nano- and Biotechnology

Institution: University of Kentucky

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Significant progress has been made during the last two decades on developing new and innovative design methodologies and advanced manufacturing techniques in additive manufacturing (AM), which offers a viable, functionally feasible and technologically superior alternative to subtractive manufacturing, particularly for the manufacture of products with complex features from traditionally difficult-to-process materials. Despite this major technological advancement in materials processing and manufacturing technologies, very little effort has been made in developing sustainability principles and applications/practices to enable environmentally benign, economically more advantageous and societal benefit-driven AM methodologies. Elimination of coolants/lubricants and metal chips and debris from the AM processes, such as machining and grinding, may in general be viewed as positive environmental impact. However, recent studies at MIT and elsewhere show that currently achievable energy efficiency (power consumption) in a range of AM processes is much lower than in the traditional manufacturing processes.

Next generation AM processes must fully demonstrate the use of sustainability principles including energy efficiency, and the following major sustainability targets/goals:

- Reduced manufacturing costs, material and energy use, industrial waste, toxic and hazardous materials and adverse environmental effects;
- Improved personnel health, safety and security in additive manufacturing processes and the use of products from AM; and
- Demonstrated repairability, reusability, recoverability, recycleability and disposability of products produced from AM.

To achieve one or more of the above sustainability goals, a total life-cycle analysis and a comprehensive sustainability evaluation of each AM process must be made. Analysis of all four stages of product sustainability (pre-manufacturing, manufacturing, use and post-use) would be necessary to reach these goals. Also, product design and manufacture in the 21st century will require a greater integration of life-cycle data, sustainable product/process designs and their implementation in the manufacture of innovative engineered products. End-of-life products from additive manufacturing must be recovered, reused and remanufactured. Redesigned next generation products are expected to utilize most of, if not all, materials from the first life, thus making a “near-perpetual” material flow in AM to enable “near-zero” wastes and minimized adverse environmental effects.

To achieve this, the major research challenges posed for the next 10-15 years are:

- Conducting fundamental studies towards developing sustainable materials for use in AM;
- Increasing the science base for sustainability principles applied to product design for AM processes;
- Predictive modeling, simulation and control for product and process sustainability in AM; and
- Developing multi life-cycle models, including economic evaluation of sustainable additive manufacturing processes.
**On-Site Building Construction Automation Using SFF**

**Introduction:** The excerpt below is from the document on the Grand Challenges recently specified by the National Academy of Engineering:

"...dramatic progress may be possible only by developing entirely new construction methods. Most of the basic methods of manual construction have been around for centuries — even millennia. Advances in computer science and robotics should make more automation possible in construction, for instance, greatly speeding up construction times and lowering costs."

The need for advancing construction technologies has thus been realized and emphasized. Significant progress has been made, especially in the last two centuries, in manufacturing technologies and for most products present day manufacturing technologies automatically produce complicated parts with high degree of accuracy and other quality metrics. In contrast, over the last several centuries there has been little change in the methods of construction. The basic manual methods of placement and assembly have continued to dominate in this industry and the most widespread advances have only been in some material handling systems such as construction elevators and cranes but even these are only used in large projects. Automated single-function construction equipment has been developed for certain operations but these are used only in infrastructure construction and by large companies. On-site building construction automation is rare, and automation in this domain has occurred primarily in secondary components such as windows, and in rare instances for in-factory production of prefab structures.

This apparent resistance to innovation and change in construction industry is not altogether surprising. The industry is highly fragmented and is dominated by small-to-mid-sized companies. The fragmented nature of the industry is primarily due to its use of primitive and simple tools. The low cost and the low degree of sophistication of such tools allow any small company to engage in construction activities. This situation stifles advances and innovation in production practices. Companies face fierce competition to survive because they lack economically viable alternatives, and building code compliance allows little room for experimentation or innovation in construction technologies. Other reasons for lack of advancement in this respect are: a) unsuitability of the available automated fabrication and assembly technologies for large scale products b) unsuitability of conventional manufacturing processes for construction materials, c) uncontrollable environment of construction (rain, wind, debris, dust, etc.) which is hostile to automated machinery, d) conventional design practices that are not suitable for automation, e) significantly smaller product batch sizes as compared with other industries, e) high investment and maintenance cost of automated equipment, f) high cost of specialized operators and maintenance crew for automated equipment.

It is important to note that while most manufactured products can be imported or outsourced, construction must remain largely indigenous. Furthermore, construction is the largest sector of the US economy (over one trillion per year). Thus, a concentrated effort is most important to develop and implement automation in construction.

It should be noted that the available automated technologies commonly apply to construction of infrastructure (roads, bridges, tunnels, etc.). Unfortunately there has not been much practical advancement in automation of building construction. Material handling cranes and elevators remain as the prime equipment only at large building construction sites where numerous operations are performed by manual labor. Small building construction is done by often primitive and always simple tools.

Major attempts at building construction automation were made in the 80s and 90s by large Japanese construction companies. Integrated automatic systems composed of numerous robots and other automation components were developed and performance of such systems in construction of steel and reinforced concrete high rises was demonstrated. The endeavor reduced labor cost and injuries but because of the system complexity and the variety of sophisticated machinery the overall operating cost was very prohibitive to the point that the benefits of automation were outweighed by the related costs. Consequently, the complicated automation systems are now used sporadically as demonstration cases and as means of promoting the companies that developed them.
SFF as a Promising Future Construction Automation Paradigm: From the evolution of manufacturing technologies and the success of automation in this domain some valuable lessons may be learned. There has been significant advancement in automation of subtractive processes in manufacturing but such processes are not suitable for building construction because buildings have a huge volume of void compared to the solid material volume that constitutes them. Therefore, additive processes are most suitable for building construction. Up until two decades ago there has been no automation for additive fabrication in manufacturing. Additive fabrication has generally depended on existence of molds in the cavity of which molten plastic, metal, ceramic, etc. is injected or poured. Solid Free Form (SFF) fabrication is a new breed of additive fabrication technologies with which complex objects may be constructed without the need for molds. It is interesting to note, however, that while the manufacturing industry has only recently discovered layered fabrication, the construction industry has been effectively using this method in a manual mode for several millennia. A logical expectation is therefore the success of future application of variations of the SFF approach to layered construction of building structures. One significant advantage of layered fabrication is that the portion of the object that has not yet been built is not on the way and hence numerous activities such as automated plumbing, automated electrical network installation, automated tiling, etc. may be integrated with such a fabrication paradigm. The SFF paradigm in construction could also allow seamless integration of a large number of engineering techniques including various aspects of design, materials and processing, robotics, metrology and inspection, and planning and control.

Crucial Future Actions: Because of the many benefits of automated construction and its potential impact on the US economy and global environment, serious attention should be paid to this matter by the related researchers and technology innovators, government entities, equipment companies, construction companies, designers and owners. Government should create programs to support research to advance SFF-based construction automation technologies at universities and research organizations. The regulatory processes for qualification and approval of promising technologies should be improved so as to minimize the related barriers against new technologies. Construction equipment manufacturers as technology providers should increase their internal R&D on development and testing of SFF-based automated technologies and should directly fund or provide matching fund to the related ongoing projects at universities and research institutes. Designers and owners should be made aware of the advantages of the new automated construction methods. Construction companies and equipment manufacturers should be the primary sponsors of the related awareness programs. Designers should incorporate design features that allow the use of candidate automation technologies. Demonstration projects are essential for increasing the awareness within the industry. Such projects should be sponsored by all stakeholders.

The figure below demonstrates the construction application of a candidate SFF technology called Contour Crafting (www.ContourCrafting.org)
An Additive Manufacturing (AM) process enables producing three-dimensional physical parts of arbitrary shapes, with the use of service materials to generate functionalities required for target applications. Because AM is inherently capable of making parts of any desired geometry and material complexity, one great future promise of this process is to produce parts with graded composite materials to generate new functionalities that are not possible or too costly using conventional processes. Potential applications include, for example, nozzle throat inserts for a hypersonic spacecraft propulsion system and bone grafts with varying material composition, cellular structure and porosity.

One of the most unique types of composites is FGMs (Functionally Graded Materials), which have two or more materials graded into one structure. An FGM structure can provide varying material properties within the build structure as designed. Also, the gradient structure allows minimization of thermal stresses at critical locations and elimination of cracks which often result from large stress discontinuity at the interface between two materials. Moreover, a ceramic-metal FGM structure provides higher thermal shock resistance than a monolithic ceramic structure, and allows the structure to be readily attached to the underlying metal substructure as is often required in a real-world application.

Among the various kinds of freeform fabrication processes, those using nozzles to extrude pastes or ejecting droplets are probably most versatile for fabricating FGM parts because they can easily accommodate multiple nozzles for deposition of multiple materials. In terms of materials, composite parts made of metals and ceramics (including metal-metal composite, ceramic-ceramic composite, and metal-ceramic composite) are suitable for industrial applications requiring structural integrity because metals and ceramics have higher mechanical strength and thermal resistance than polymers. In biomedical applications, a bone graft may have its scaffold fabricated from biopolymers or bioceramics together with the deposition of biofactors and even living cells during the fabrication process.

In order to achieve new functionalities and higher performance in additive manufacturing with FGMs, there are challenging issues in design, material and process that need to be addressed through fundamental research. These research issues are listed below in terms of a set of questions:

- What should the dimensions of CAD parts be in order to achieve near-netshaped dimensions after bulk sintering of the fabricated green parts?
- How to represent and design the internal architectures of bone materials for various bone types (long, short, flat and irregular)?
- How to design the grading of multiple materials to achieve desired microstructures and physical properties after bulk sintering of the fabricated green parts?
• What is the compatibility requirement between two materials, which differ in their density, melting point, thermal conductivity, thermal expansion coefficient, elastic modulus, etc., in order for them to be used in freeform fabrication of FGMs?
• How does the surface chemistry of powders of various materials affect their ability to be produced into extrudable pastes with consistent rheological properties?
• How to perform in-situ mixing of different materials to achieve uniform mixing in making pastes with varying ratios of materials as desired?
• How to fabricate FGMs to minimize stress concentration and prevent cracks from occurring after bulk sintering?
• Does liquid phase migration exist during the process of extruding colloidal pastes and, if so, how is it related to process parameters?
• What modeling and control strategy is effective for feedback control of the nonlinear process of freeform fabrication of FGMs?
• How can we achieve controlled porosity, including a possibility of full or near-full density, after bulk sintering of the fabricated green part?
• How to distribute the deposition of biofactors during the process of fabricating a 3D bone scaffold to create a favorable environment for living cells?
• How to perform mathematical modeling and analysis to predict the process characteristics and the part’s physical properties in freeform fabrication of FGMs?
In SLS and other processes, the development of materials and process are tight together like Siamese twins.

In conventional manufacturing, we take QA assured material according to tight specifications and merely change its shape during manufacturing (cutting, forging, casting, etc.). The material modifications like surface integrity, HEZ, annealing, internal tensions, etc., are controllable and mostly surface related; the core remains unchanged or similar to the original state (even that can create failures).

In ALM, we are simultaneously “making the materials” voxel by voxel in the entire volume, layer wise and shaping it. Both the consolidation process and geometrical shaping have influence and uncertainties often too large deviations for a controlled process.

Looking at the whole as a system, clearly we need more materials—it is an issue (e.g., high-performance materials), but this isn’t the key issue any more.

Key issue number one is consistency. In other words, we need one overall good system. This can be achieved by controlling all inputs, including the local geometry, raw material, energy delivered, transformations, heating, and cooling, all in a multi-hierarchical, sophisticated CAC Complete Adaptive Controller system.

It starts with tightly controlled input material properties, precise controlled repeatable consolidation or layering conditions, parameter steadiness, quality, a time-dependent control system ending in narrowband material and geometry product quality.

Key issue number two is taking advantage of “making the materials” in the geometrical shaping evolving the ideas of online alloying, online blending, online. The multimaterial is an inherent advantage that no other process can deliver. It is unique for ALM. If we can govern this consistently by means of the CAC (Complete Adaptive Controller system), we have gained a new dimension in manufacturing, actually design, raw materials, and manufacturing unite in one great opportunity.

Once having achieved this, we get confidence in the ALM, repeatability and consistency, new never before creative options for new applications.

Just think how the CNC technology, adaptive controls, fuzzy logic, learning systems have improved the accuracy, repeatability, and quality of conventional manufacturing during the last 25 years.

Orselina, Switzerland, March 25, 2009
Energy
The United States consumes 25% of all the oil produced in the world, but controls only 3% of the world's oil reserves. As a result of this imbalance, we have become heavily reliant on foreign oil. Reducing our dependence on oil is not only the fastest and cheapest path to energy security, it is also the best way to keep our planet healthy. Renewable energy seems to be the best solution as it is also sustainable. The key issue to widely use renewable energy is the cost. Fuel cells are considered our ultimate “green” energy source, and the key issues in fuel cells are also cost and durability. Today, the most widely deployed fuel cells cost about $4,500 per kilowatt; by contrast, a diesel generator costs $800 to $1,500 per kilowatt, and a natural gas turbine can cost $400 per kilowatt or even less. Therefore there are a lot of opportunities in additive manufacturing to contribute in the area of energy, such as material design to enable lower manufacturing cost, and to facilitate mass production.

In order to drastically reduce the cost of energy, mass production of new energy facilities such as fuel cells, will be required. Additive manufacturing technologies will be able to help in developing high-speed forming, stamping, and molding of components for renewable energy. Additive manufacturing will permit the design to be modified with a minimum of production line changes. However, there are other technical challenges that will need to be addressed at the same time. Additive manufacturing is also an enabling technology for integrated and collaborative product and process development. As a cost issue, a renewable energy system needs to rely on an integrated and collaborative process, and additive manufacturing can further be developed to help in the system integration process to reduce overall cost. An additive process can accelerate the search procedure to explore these multi-functional requirements by exploring new materials, processes, and other related issues.

Sustainability
There are several sustainability issues that need to be addressed. One of the critical issues is that additive manufacturing can greatly contribute is the reuse or remanufacturing of the parts or products we already have. If a part or product can be repaired and reused for its initial product function, not only will the material waste and amount of landfill be reduced, but also energy and matter consumption during manufacture will be reduced because existing components are utilized. In addition, the utilization of existing components reduces the costs associated with producing or acquiring new components. Therefore, a more dramatic reduction in environmental impact can be made by product reuse in which the geometrical form of the product is retained and the product is reused for the same purpose as during its original life-cycle, or for secondary purposes. Many of today’s current repair procedures like closing and filling cracks through mechanical pressure or welding, rebuilding worn surfaces using metal spraying and welding, etc., do not lend themselves to automated operations. Manual operations such as Tungsten inert gas (TIG) welding add several variables to the repair process that adversely affect the quality and cost
of the finished product. As additive manufacturing can add material and recover the functionality, it is an excellent way to help sustain the environment.

Manufacturing companies use high pressure die casting or stamping processes to produce large amounts of parts. Due to high temperatures and high pressure fabrication processing over time, die components are frequently worn out and cracked, and thus require repair or replacement. There are existing welding-based repair processes in the shop, but the capability of these processes is limited and the durability of the repaired die is not predictable. The additive manufacturing process will also need to be reliable, timely and cost effective in order to justify the repair.

An automated remanufacturing process will be able to offer excellent repair quality and part consistency. Since a remanufacturing system often involves material additive and material removal processes, the study of how to effectively integrate and automate the hybrid process for remanufacturing will substantially provide a positive impact to the environment.
Where will additive manufacturing technologies be in 10-15 years

Interoperability

In 10-15 years, Freeform Manufacturing (FM) will use advanced product representations that support FM equipment manufacturers and users in applying FM technologies to a broader set of problems. The product representation will have complete acceptance by the FM community as the standard will meet companies existing demands (and past applications like single slice format) while accommodating future needs. The new format has dramatically improved existing data transfer capabilities from computer-aided design and engineering (CAD/CAE) systems to Freeform Manufacturing (FM) systems allowing for the complete and unambiguous 3-D exchange of information between appropriate engineering and manufacturing applications. The product representation enables products to be described completely throughout the life cycle of a product including design, process planning and production, and ultimately, disposal. This description also includes sustainable manufacturing indicators and metrics which support engineering decisions throughout all product lifecycle phases.

Integrated processes

In 10-15 years Freeform Manufacturing (FM) systems will have become integrated (physical/informational) with other machining systems, enhancing the overall capability and versatility of production manufacturing systems. Seamless transition between the manufacturing system’s various tools (additive/subtractive/metrology) is supported through advanced planning applications that determine optimal plans while considering all aspects that impact sustainable product production such as product function, material selection/deposition, resource allocation, optimal path planning (at layer and adjacent layers), accuracy, tolerance allocation, surface finish, and time to complete the operations.

Design process – Incomplete product definition

In 15 years, it will be commonplace to design a component whose functionality can be achieved by manufacturing the component utilizing one of a number of capable processes. A number of Freeform Manufacturing (FM) systems will provide the designer with the ability to specify how material is deposited at the surface and through out the part (i.e., internal structures that provide unique functional requirements such as shrinkage in specific directions when heated). Key features with demanding tolerances are designed to meet engineering specifications while non-critical features are loosely-defined so that the “process” can allocate dimensions to best address
the mandatory feature requirements. The same finished part, manufactured using different processes, may look physically different (non-critical features), yet conform to the engineering specifications necessary to achieve the required part functionality.

**Exploit uniqueness of FM systems**

Product designers will be able to exploit the uniqueness of the Freeform Manufacturing (FM) systems to meet ever demanding product requirements that:

- require improved selection of engineering materials
- have functional features that can not be manufactured at reasonable costs or manufactured at all
- are comprised of heterogeneous materials
- require mechanical/electrical properties to vary through-out a single part.
- have internal structures that provide unique functional requirements such as shrinkage in specific directions when heated, surface features on walls of internal channels, etc.

**Materials**

In 10-15 years, Freeform Manufacturing systems will be supported by a number of engineering materials. The material delivery systems will allow the designer/manufacturing engineer to precisely place material/s to create embedded structures or enable designer materials. Engineers must be able to create accurate models for analysis. Reliability will be a key objective.

**How might research enlighten and/or accelerate progress towards achieving this end?**

Research that addresses the above topics is key to making progress in this field. There has to be a recognizable “pull” from industry (customers) that serves as a rallying point for government and universities to commit their time and resources. Appropriate standards and best practices need to be identified and plans defined to “quickly” serve as basis for old and new Freeform Manufacturing systems. For engineers to accept these new processes, they need to have confidence that the parts being manufactured meet expected material conditions and properties. This will require that “as-defined” manufactured parts can be modeled and analyzed. Certification of FM processes will also be essential if parts are manufactured for direct implementation into a product or system.
A roadmap for the future has two components. One is nut & bolt and processing issues similar to Moore's Law for the Semiconductor Industry. The other is more transformational issues, such as new products or new science. In my December 2000 Journal of Metals paper, my crystal ball was forecasting three major transformational areas for additive manufacturing.

1) **Designed Materials.**

   This is a group of materials fabricated via additive manufacturing technology such as closed loop Direct Metal Deposition (DMD) which has properties not generally observed in Mother Nature. For example, metals with negative co-efficient of thermal expansion. Technological feasibility was already demonstrated. Barrier for mass market penetration is commercial availability of multi-material CAD and homogenization design for design optimization of the structure for a specific property.

2) **Remote Manufacturing.**

   The concept in remote manufacturing is the ability to communicate with a DMD machine and fabricate the part from a remote location. This is similar to the concept of a "3-D fax", but for part fabrication, one needs zero-defect CAD compressed 90% or more for rapid data transfer. Data security is also an important challenge if it is transmitted via wireless communication. Again, a concept has been demonstrated, but for mass penetration availability of zero defect data compression and secure transmission is still a technological challenge.

3) **Integrated Design and Manufacturing**

   The major technological barrier is the complete integration of homogenization design with heterogeneous CAD and closed loop additive manufacturing. Again, proof of the concept is already demonstrated, but an efficient commercial software with the capability of easy integration with hardware that is needed for increased acceptance in the market place. On the other hand, if it is successful, customers will have a product with desired performance instead of facing the limitation generally observed by the traditional materials selection approach. I strongly believe that when the above mentioned technological barriers are overcome, we may witness a major shift in engineering practice where components with desired performance can be ordered “any place at anytime”.

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1 J. Mazumder, A Crystal Ball View of Direct Metal Deposition, *Journal of Metals*, Dec, 2000, p. 28-29. 73
However, nut & bolt issues are equally important for commercial viability and mass acceptance. Some of the issues are:

1) **Deposition rate**: Higher deposition rate is a must for making it a commercially palatable process. Presently, about 6 in³/hr/kW is the limit - similar to electronics industries, our goal should be to double the deposition rate every 2 years.

2) **Powder catchment** ideally should be 99% or more, whereas presently, it is around 20 - 70% based on the design of the 3-D structure.

3) **Online diagnostics and feedback control** are a must for robust quality production. Some of the important issues include (a) repeatable deposition geometry, (b) defects such as porosity, voids, microcracks, (c) composition control, (d) residual stress evolution and (e) distortion.

4) **Surface Finish**: However, near net shape is the product from additive manufacturing may be presently possible, but it still needs some post-processing to bring it to mirror (um) finish. A system which can achieve mirror finish will widen the market for molds, etc.

5) **Control of internal geometry**: **Conformal cooling for energy conservation and lead time reduction**. Additive manufacturing can offer many a functionality for a designed product. For example, in the pixel by pixel manufacturing of a product, using additive manufacturing, one can create a cooling line in a mold which conforms to the shape of the product that the tool will be making. A recent study with a global company revealed that a particular set of 5 tools can save the company 23 billion BTU/year. Additive manufacturing can be effectively used for conservation of energy during manufacturing leading to a significant reduction of the carbon footprint. Manufacturing is responsible for 33% of the world's carbon footprint. The scope is enormous.

6) **Patient specific biomedical products**: Synthesis of a CT scan with additive manufacturing for rapid prototyping biomedical products such as prosthesis, scaffolds for regenerative treatments, etc. This will enable accelerated recovery of wounded people, and products can be patient specific. Recent work at Michigan demonstrates patient specific bone by inserting the genes harvested from the bone marrow into the scaffold. Within 6 weeks, scaffold was covered with bones grown from the genes. With recent freedom of research in stem cells, who knows where we can go. I can foresee additive manufacturing systems in the field hospitals or emergency rooms where quick prosthesis or scaffold can be generated for speedy regeneration limiting human agony and medical expenses.

In summary, additive manufacturing is an enabling technology which can impact the entire spectrum of the global economy as long as we make an effort to overcome the specific scientific and technological barriers for the applications demanded by society.
I believe one area of significant growth in the next 10–15 years for additive manufacturing would be in the area of multi-functional property-tailored structures, where the material composition, microstructures, the cellular structures, part boundary surfaces are varied to simultaneously meet multiple functional requirements. Example parts include functional gradient materials, cellular solids, and tissue scaffolds.

The fundamental challenges to the realization of such multi-functional property-tailored structures are the following.

- **On the manufacturing side:** the *fabrication efficiency* remains the major challenge for the broad adoption of additive manufacturing.
- **On the materials side:** the material property depends on heavily on the process and analytical or *quantitative relationship* for describing generally the process and resulting property remains difficult.
- **On the design side:** Even though computer software for representing material gradient distribution and cellular solids have been under research for a while, *design methodology* that can fully utilize the geometry and material flexibility in the multifunctional parts has yet to be developed.
This paper is primarily focused on additive manufacture for sustainability

I believe that one area that will significantly drive the adoption of Additive Manufacturing (AM) over the next 10-15 years will be its use as a sustainable technology alternative to traditional manufacturing processes, supply chains and product design.

Current products are designed for manufacture and in many cases are sub-optimal. They use excessive material as they are designed for processes such as machining and molding. Moreover, they are made in geographically disparate locations, often dictated by the location of tooling in low labor cost economies.

There are however a number of clear (potential) benefits to the adoption of AM for production part manufacture, which could be driven by the sustainability agenda. These include:

1) The more efficient use of raw materials in powder/liquid form by displacing machining from solid billet stock
2) The displacing of energy inefficient manufacturing processes such as casting and CNC machining, with the eradication of cutting fluids and chips
3) The ability to eliminate fixed asset tooling, allowing for manufacture at any geographic location, such as next to the customer, reducing transportation within the supply chain and subsequent carbon emissions
4) Lighter weight parts, which when used in transport products such as aircraft increase fuel efficiency and reduce carbon emissions
5) The ability to manufacture optimized designs that are in themselves more efficient than conventional manufactured products, such as conformal cooling and heating channel, gas flow paths and ducting used in HVAC systems

However, at present there are a number of barriers to the sustainable utilization of AM, albeit these barriers do represent research opportunity. There is clearly a need for more robust process and materials property data, which will only be valid if it is collated and disseminated against an agreed set of standards. Such data (including materials properties and machine capability data) can then be embedded into Knowledge Based Engineering systems. Only then can it be cascaded down to the engineering user community and used to design the next generation of sustainable products.
However, this then brings us to the limitation of current design software tools. Assuming we understand the properties of a given AM material and the capabilities and constraints of the AM process, we do not have the design tools to maximize the flexibility of the manufacturing processes itself. Most common CAD tools are designed for parts made using either subtractive machining, molding or casting. They are not designed for AM where we can construct parts with features such as complex internal geometry, internal micro-lattice structures, organic structures or variable metallurgical properties.

Assuming we develop the materials and systems knowledge of AM and have the CAD tools at our disposal to produce optimized, light weight efficient parts, we also need to consider the efficiency of current AM machine tools and the pre-processing, processing and post processing of these systems.

We must therefore look at AM waste streams, such as support structure in metallic AM parts and non-recyclable materials in polymeric RM. We must also address the design of the machines to ensure that they are as efficient as possible, both in terms of material utilization and wastage, but also thermal energy management and post processing.

If we are to maximize the potential economic and environmental benefits of a distributed AM supply chain (Grid-RM), then we need to consider how data flows within the AM supply chain and how it is managed. We will need to consider how digital information (such as material and machine process data) can be embedded into parts to allow for traceability. We will also need to know how to track both digital data and physical assets on a global basis and how to tie parts to data over many years of product life cycle.

Finally, we need to get a better understanding of product life cycle and disposal. How will AM parts be recycled or disposed of and how long will they last.

We need to develop a holistic view of RM over product life cycle, as described below.

![Image of material flow through the product life cycle]

**In 15-years** perhaps the adoption of wide scale AM will not be as a result of solely displacing expensive and unnecessary tooling, or the ability to manufacture cost effective personalized products. Perhaps adoption will be driven by legislation for cleaner greener products, both in their production but also their usage phase. Perhaps adoption will be driven by the consumer’s desire for cleaner greener products. Or, perhaps adoption will be driven by a global shortage of natural resources making efficient AM the only viable production process for many parts.

**Keywords** – Resource efficiency, low carbon manufacturing, environment, additive, alternative, legislation, consumer
Design for manufacturing (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize costs. However, the improvement of rapid prototyping, or Additive Manufacturing (AM), technologies provides an opportunity to re-think DFM to take advantage of the unique capabilities of these technologies. Several companies are now using AM technologies for production manufacturing. For example, Siemens, Phonak, Widex, and the other hearing aid manufacturers use selective laser sintering (SLS) and stereolithography (SL) machines to produce hearing aid shells, Align Technology uses stereolithography to fabricate molds for producing clear braces (“aligners”), and Boeing and its suppliers use SLS to produce ducts and similar parts for F-18 fighter jets. In the first three cases, AM machines enable one-off, custom manufacturing of 10’s to 100’s of thousands of parts. In the last case, AM technology enables low volume manufacturing and, at least as importantly, piece part reductions to greatly simplify product assembly. More generally, the unique capabilities of AM technologies enable new opportunities for customization, improvements in product performance, multi-functionality, and lower overall manufacturing costs. These unique capabilities include:

- **Shape complexity:** it is possible to build virtually any shape, lot sizes of one are practical, customized geometries are achieved readily, and shape optimization is enabled.
- **Material complexity:** material can be processed one point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients.
- **Hierarchical complexity:** hierarchical multi-scale structures can be designed and fabricated from the microstructure through geometric mesostructure (sizes in the millimeter range) to the part-scale macrostructure.
- **Functional complexity:** with many AM technologies, it is possible to embed components (e.g., hardware, sensors, actuators), fabricate working kinematic joints, and deposit conductive materials, enabling the manufacturing of functional devices right “out of the vat.”

New CAD and DFM methods are needed in order to take advantage of these capabilities. In the hearing aid and aligner cases, new CAD systems had to be developed to enable efficient shape modeling and part design. During a U.S. government sponsored study of European researcher groups, many researchers said that they foresaw the lack of capable CAD tools as a serious impediment for their research and for the utilization of AM technologies for production manufacturing applications. However, if suitable CAD and DFM methods and tools can be developed, designers can design devices with significantly improved performance that fully utilize material, and with efficient manufacturing processes. With the shape, material, hierarchical, and functional complexity capabilities, DFM can move from an emphasis on cost minimization to a focus on achieving heretofore unrealizable capabilities. Hence, a new definition of DFM can be proposed. DFM for Additive Manufacturing (DFAM) is the:
**DFAM**: Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives.

In order to achieve this new concept of DFAM and enable wide ranges of new applications, new approaches, methods, and tools are needed. For structural components, AM technologies enable designers to put material only where it is needed for a specific application. Achieving high stiffness or strength and minimal weight are typical objectives. Multifunctional requirements are also common, such as structural strength and vibration absorption. The area of compliant mechanisms shares the same motivation, where the local compliance of the structure enables the mechanism to perform specified motions. The requirements that we propose include the capability to:

- Define and explore large, complex design spaces.
- Represent and design with hundreds of thousands of shape elements, enabling large complex design problems as well as designed material mesostructures.
- Represent complex material compositions and ensure that they are physically meaningful.
- Determine mechanical properties from material compositions and mesostructures across length scales; ensure that these properties can be communicated among CAD/CAE/CAM tools seamlessly.
- Design and simulate complex devices with embedded actuators and sensors, as well as electronic circuits fabricated through direct-write processes.
- Generate fabrication/assembly process plans for such devices.

Related to the promise of DFAM capabilities is the need for standards. Design engineers should have confidence in the mechanical properties predicted from a complex combination of materials or a complex array of structural elements. They should have confidence in process planning methods to generate plans that are feasible and that guarantee performance of manufactured devices. These will not be possible without standard methods for representing and reasoning with complex material distributions and geometric constructions. It must be possible to qualify materials and manufacturing processes; standards are needed for material testing methods, as well as for reporting process performances.

To take advantage of the unique capabilities of AM processes, many advances are needed in design, CAD, CAE, and CAM technologies and tools.
For sustained growth in rapid manufacturing and solid freeform fabrication (SFF), I believe that SFF-specific design methods, computational tools, and databases are needed for assisting the designers of functional, rapidly manufactured products. While some of my observations are derived from my participation in the SFF research community, many are also obtained from my experiences with teaching a Solid Freeform Fabrication course for graduates and advanced undergraduates at UT Austin. As I guide students through their SFF design projects, I observe many of the challenges they face, and I believe that these challenges closely parallel those of industry-based designers who wish to utilize SFF but may have limited experience with the technology.

The first challenge faced by many designers is the difficulty of generating design concepts and product architectures that properly leverage the manufacturing freedom of SFF. Most designers seem to be fixated on the traditional paradigm of design for manufacturing. This paradigm includes a number of formal and informal rules for assembly, machining, injection molding, etc., and it is manifested in the conventionally fabricated products that most designers reverse engineer, study, and redesign. It is difficult for designers to envision all of the possibilities offered by SFF, and there are few products in the marketplace that embody those possibilities and serve as analogies. Concept generation and ideation tools are needed to help designers overcome this mental barrier. For example, to encourage my students to leverage the manufacturing freedom of SFF, I have created a set of idea generators in the form of reference cards with examples of products that cannot be fabricated any other way. Categories include part consolidation with pictures of the ductwork in the F/18, complex mesostructures with examples of molds with conformal cooling channels and materials with spatially tailored stiffness, external customization with personally tailored shoes and clothing and other examples such as complex wiring harnesses, and production and assembly aids. Better tools are needed for concept and architectural design for SFF.

Another challenge faced by many designers is the difficulty of gathering comprehensive material property information. This information is needed for embodying designs, including the process of finite element analysis. When material datasheets are provided by vendors, they often include only a limited set of properties, and only point values are provided for those properties. Experienced SFF users and researchers know that these values are grossly insufficient because even properly tuned machines output materials with some statistical variation in material properties, and even more importantly, these properties are direction-dependent for many SFF technologies. Some of this information is available in the research literature (for certain machine-material combinations). However, designers need centralized databases of material properties, quantified with appropriate statistics, and organized by machine/technology and build direction.
Sophisticated designers also face a host of computer-aided engineering challenges for SFF applications. For example, topology optimization techniques are available for customizing the mesostructure of SFF products to achieve spatially tailored stiffness, heat transfer characteristics, acoustic properties, mass reduction, and other features. However, most contemporary topology optimization techniques are appropriate primarily for linear elasticity (and nonlinear elasticity in advanced algorithms) and its analogs in the thermal and electromechanical domains. Extensions are needed for other problem domains. Also, with the exception of some very simple topology optimization capabilities that have been incorporated into software packages such as ANSYS, user-friendly software packages are needed for making these tools available to the average designer (who does not hold a PhD in engineering mechanics). Other computer-aided engineering challenges include the difficulty of generating error-free .stl files from many popular CAD packages and the need for libraries of complex features (e.g., cellular structures) that could be easily modified and inserted into CAD files, thereby limiting the painstaking solid modeling required for many complex structures.
ROADMAP FOR ADDITIVE MANUFACTURING WORKSHOP WHITE PAPER (2 PAGE MAX)

Please check off (☑) the appropriate topics for this paper:

☐ Industry Targets  ☑ Technology Goals and Barriers  ☐ Design and Analysis  
☑ Processes and Machines  ☑ Materials/Materials Processing  ☐ Energy/Sustainability  
☐ Nano- and Biotechnology

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As we enter the next 10 to 15 years in aerospace, additive manufacturing could play an important role in the fabrication of many lightweight low cost components. The reality is, additive manufacturing accounts for a small percentage of the detailed parts used in aircraft manufacturing today. There are many reasons contributing to this such as, the lack of design guidelines, design/material allowable data, standards and flight data that are preventing the transition of this technology into the aerospace industry on any sizable scale.

In the past 2 years though, continuing needs in producing lower cost and lighter weight aircraft components, has turned the engineering and manufacturing communities towards this growing technology. With the advancement of new stronger materials, larger build capacity, the ability to fabricate complex shaped parts and the development of more consistent manufacturing process ability, additive manufacturing is finally finding its way onto military and civilian aircraft. Another reason for growing interest is due to the flexibility of engineering tools that allow designers the ability to produce designs, transfer the data to a machine and fabricate a net shaped part without the need for high cost tooling. Potential considerable benefits from this technology to the aerospace community have been calculated showing large savings. The ability to fabricate complex geometries in one piece that usually take two and three manufacturing processes to complete, has also excited the design community. Manufacturing groups who can now receive net shaped parts with reduced lead times (days/weeks vs. months) will see reduced installation costs and increased fabrication cycles.

Still, the need for further advancement is needed. Higher temperature more structural materials, conductive materials for static dissipation requirements, equipment that can fabricate parts with “specialty layered technology” (gradient material capability that interfaces gradient designed CAD models (like TNO’s CAD software) with the machines such as Optomec and POM, so that gradient materials can be designed and built seamlessly), and engineering tools to allow design groups greater flexibility in choosing the process/materials to meet their needs will help transition additive manufacturing sooner then later. More flexible material choices that meet the requirements of the aerospace industry are just some of the engineering demands. Even the ability to fabricate parts that meet low observable signature requirements have been discussed as with newer military aircraft the demand for stealthy parts in lieu of heavy coatings is of growing interest.

A large concern within a few of the aerospace communities, and with their customers, is with the industrial base readiness. Equipment that can process at higher temperatures to meet future aerospace requirements has not been produced in the quantities needed to meet production rates. No US producer of equipment is at this time even considering designing and or producing equipment with higher temperature capabilities. The equipment that has been designed and built, for high temp applications, has been from Europe and at great cost to the small business while
other older equipment is simply modified to meet the needs. The higher cost of these new materials and now high equipment costs could make this technology potentially cost prohibitive from transitioning to the aerospace market.

So what's the next move? Aerospace manufactures usually have three key thoughts in mind; cost, weight and schedule. Cost of producing additive manufactured parts will be the major key factor along with the creation of necessary data on materials and processes. Can parts be fabricated at or below the cost of current manufactured parts? Indications so far say yes but, only on simple parts that can be built in large quantities. Complex part fabrication still needs to be analyzed. Industry Design Guidelines may help in determining cost though simplified designs. Equipment that can consistently produce components that meet engineering requirements will also need to be produced and at affordable costs. Weight is already showing benefits in some cases but, the need for stronger even lighter materials are ever increasing especially when designing vertical lift aircraft as has been seen with the new Joint Strike Fighter. Other areas of consideration might be hybrid machines that can interface between building parts and inserting electronic hardware for things like a micro spacecraft. Example: Using a cold process like Solidica's Ultrasonic Consolidation (http://www.solidica.com) combined with Optomec's Aerosol Jet system to create printed circuit boards layer by layer (http://www.optomec.com/).

The question remains, is additive manufacturing technology progressing fast enough to keep up with the advancement of aerospace technology interests/needs, possibly? I believe we can eventually get there with materials that will meet engineering requirements but it will all depend on if the industry can afford it. Some materials are reaching the $200.00/lb mark and may be unaffordable. New high temperature equipment is rumored to cost some $1.2M. Modified equipment is less expensive but, what's the guarantee it will maintain its ability to produce continuously without extensive service or downtime.

We have just recently seen programs funded to address some to these issues dealing with aerospace needs. Further programs will be needed if we are to fully support the development and transition prospects of this technology and feel the potential considerable benefits.
In 15 years, additive manufacturing will be a ubiquitous set of technologies, existing alongside today’s “traditional” technologies in large factories, regional assembly centers, and local 3D printing shops. Through additive manufacturing, it will become technically feasible, economically viable, and commercially beneficial to locally produce goods that are person-specific, location-specific, and/or event-specific. Thus, just as Web 2.0 enables dynamic creation of millions of pieces of highly individualized digital content, additive manufacturing will enable dynamic creation of millions of highly individual goods.

Additive manufacturing will likely help reverse the trends of increasingly centralized production at locations of lowest labor and/or greatest natural resources. This centralized production has directly contributed to increased urbanization; outsourcing of jobs by multi-national corporations; rising shipping traffic; and increasing fuel consumption to distribute products after production. Each of these trends can begin to be reversed by the increased utilization of AM.

In industrial factories, AM will be deployed alongside other manufacturing processes: utilized primarily to build geometrically complex, multi-material, integrated, embedded and/or customer-specific products. In many cases these will supplant existing methods of product creation for many product types (including up to 10’s of thousands of parts per year of some types of products). AM will remain a higher-cost alternative than mass-production processes (such as injection molding) for simple-shaped, single-material products made in the hundreds of thousands or millions. Nonetheless, AM production in industrial factories is already utilized in the manufacture of airplane components, for instance.

In regional assembly centers, AM will be utilized to distribute production (and thus reduce shipping costs) to nearer their point of consumption. Certain types of components (memory chips, etc.) will require factories with high infrastructure costs. For these components, they will still be centrally produced and then shipped to regional assembly centers where the portions of assembled products which do not require massive factories are made. AM will be utilized (along with other production & assembly equipment) to regionally produce an increasing number and overall fraction of components for these complex, assembled goods. This regional assembly will reduce overall shipping costs; enable region-specific features to be more easily integrated; aid in lean and JIT implementation; and enable companies to demonstrate that they are “made in the U.S.A.” rather than made internationally. This type of regional assembly is the next evolution of the car industry (which already assembles regionally – Toyota & Honda have assembly centers in the US, for instance, and US companies assemble cars worldwide for regional consumers).

A new, thriving type of digitally-enabled physical-product entrepreneurship (digiproneurship) will emerge. Opportunities for entrepreneurship will exist in at least 3 areas: 1.) Creation of software tools to enable digiproneurship; 2.) franchising local 3D printing centers to be utilized by digiproneurs; and 3.) creating and selling unique digital designs that can be converted into 3D
objects at 3D printing centers or on a home 3D printer. Software tools for digiproneurship include: interfaces that enable non-experts to make meaningful design modifications; B2B tools which enable design digiproneurs to collaborate with 3D printing centers to deliver goods to end-users; web portals for digiproneurship social networks; and more.

This vision requires widely-distributed availability of 3D printing centers worldwide; lower-cost machines and materials; a wider selection of validated materials with robust material properties; a much greater awareness of these processes by the general public; standards which enable customers to order goods and know that they will be exactly the same wherever and whenever they order them from; and government policy which does not favor existing forms of employment and product creation, but instead encourages innovation and new forms of wealth creation.

Focused research and development is needed in the following areas to bring about this vision:

Processes & Machines
- Greater process repeatability, including feedback and feedforward control.
- Process parameter standards and process calibration standards that enable widely distributed machines to produce products in an identical manner regardless of location, age of machine, or operator.

Materials
- Better understanding of materials behavior during AM. (For instance, develop a basic understanding of how materials respond when thermally processed at rapid heating and cooling rates – such as during laser processing – rather than using existing models that are accurate for slower, batch processing such as molding, casting, etc.)
- Formulate and modify existing materials to work better than existing materials in AM processes
- Investigate “process ➔ microstructure ➔ property” relationships for all AM processes
- Come to understand microstructural evolution in the various processes

Software
- Software-tools to better enable design for AM. In particular, allowing ordinary consumers to make meaningful modifications to parts that conform to some standards or expert-designed constraints (can come about from combining product-specific parametric shape grammars with computational semantics and intuitive user interfaces)

Business development
- Formulation of econometrics that enable potential investors in AM to know what type of business model, production arrangements, etc., will be most profitable for them.
- Incentivize the creation of local and regional 3D printing and AM centers.
- Create digital tools that enable direct B2B (business-to-business) and/or B2C (business-to-consumer) marketing by entrepreneurs.

Education
- Workforce training for unemployed or underemployed entrepreneurial-minded inventors; designers and engineers in industry; artistic individuals; architects; etc.
- Undergraduate Education – add AM to courses throughout engr. and business education
- Graduate Education – improve upper-level knowledge by starting upper-division and graduate-level courses with in-depth analysis that enable engineers to improve the technologies.
Additive Manufacturing Applications in Aerospace Components

Current approaches for fabricating functional metal hardware for aerospace components include forging, casting, and extruding. Material properties and part complexity generally dictate which process is selected. However, these often result in starting with a block of material and machining down to the final part (Figure 1). This leads to significant lead time in ordering large billets of material, long spindle times in machining, and significant material waste in the production of machining chips. Layer-additive technologies can be considered “green manufacturing” in that the amount of energy and material used to develop a final part are considerably less with additive manufacturing as compared to conventional approaches. Layer additive technologies also offer significant reduction in lead time, cost, and waste (in the form of few machining chips and less “toxic waste” from the cutting fluids).

The first use of large scale metal deposition for aerospace components will occur in non-critical components as a direct replacement of a conventional component. The deposited material will be used to reduce the amount of material machined away by addition of features (bosses, flanges, ribs, and other asperities) onto a simplified perform. Direct replacement of existing parts will be using existing materials, thus the material properties of deposited material onto forging/casting must match or exceed specifications for that part. This application will require equivalent chemistry, properties, and no voids. The driving force for the change from conventional to deposited materials is significant reduction in cost and lead time.
As deposited material becomes certified for use in flight hardware, certifying organizations and aircraft designers will become more familiar and more comfortable with additive manufacturing. Gradually, over the next 5-10 years, it can be expected that designers will begin exploring additional uses of metal deposition to build entire parts with additive manufacturing. This will also facilitate designing parts that are not fabricable using traditional methods, taking advantage of the flexibility and complexity of additive manufacturing. This step will require improvements in fabrication process control of the chemistry, properties, and geometry as compared to present day products. The primary driving factor will still be reduction in cost and lead time.

In the far term, designs will eventually progress to solid-freeform-fabrication-enabled concepts. New alloys will be developed that are specifically designed for additive manufacturing processes. New structures will also be designed that take advantage of the ability to locally-tailor complex shapes, microstructures and chemistries through functional gradients. Additive manufacturing also enables embedded multifunctionality and larger-scale component fabrication (unitized structures). The driving force for these developments will go beyond environmentally friendly, rapid, and lower cost and be driven more by performance enhancements and reduction in weight.
I believe “high-end” applications focused on Direct Digital Manufacturing (DDM) will make significant advancements in the next 10-15 years, and the three application/focus areas I think will experience profound growth in using additive fabrication (AF) technologies include (1) metals-based AF, (2) integrated additive manufacturing, and (3) regenerative medicine (tissue engineering).

In the area of metals-based AF, we have all seen significant focus on and advancement in metals technologies over the past decade. Perhaps the most significant impact on our industry from these technologies has been the gaining interest of metallurgical engineers in these technologies (This has certainly had an impact on me). I believe metallurgists are and will continue to provide valuable insight into advancing these technologies (and most importantly characterizing their microstructure) so that we can use appropriate technologies in DDM applications (which I also see profoundly growing over the next 10-15 years with metals technologies leading the way). Although I see these technologies being used across the spectrum, the particular applications I see as being the most significant include medical implants and aerospace/space applications.

The second area that I see as being an important growth area for AF is in integrated manufacturing using AF technologies. As we all recognize, there are enumerable possible benefits derived from building parts using AF technologies. However, we have all experienced the inability of a certain technology to fabricate just exactly what we are trying to build. Although many technologies are not easily accessible to integrating with other technologies, many technologies do operate in uncontrolled or “minimally” controlled environments. I believe many of these systems can produce “more functional” and “multiple material” parts by integrating them with other additive and/or subtractive technologies. As an example, my group along with Brent Stucker’s group at Utah State developed a flexible and mobile fused deposition modeling (FDM) manufacturing system that can deposit material on virtually any surface. This new machine has been integrated with an ultrasonic consolidation (UC) machine and used to dispense support material for UC fabrication as well as a potting material for embedded electronics so that the combined processes can produce fully functional integrated electronic systems. The development of integrated technologies for fabricating 3D electronic systems is a focus of my group, and I believe represents another significant opportunity for growth of our industry. It is interesting that a “printable/flexible electronics” industry already exists (in the ~$10B range), and this industry has by and large emerged from the electronics fabrication industry -- I believe both industries can benefit from cross-fertilization (especially since some industry estimates in “printable electronics” include revenues in excess of $100B and possibly up to $300B by 2025!).

Finally, the use of AF technologies in the field of regenerative medicine or tissue engineering (TE) has grown rapidly in the last five years. Most AF technologies have been explored in
varying degrees for fabricating biocompatible three-dimensional (3D) implantable structures with a number of successes reported for many technologies. Although challenges remain in controlling the spatial, mechanical, temporal, and biochemical architectures of implantable scaffolds, AF provides the manufacturing platform for solving these challenges, and I believe we will see enormous growth over the next 10-15 years in using AF for directly fabricating tissue engineered scaffolds in medicine. This is because regeneration typically requires multiple materials (i.e., regenerative environments typically require variations in mechanical and biochemical architectures), and as the science and medicine are advanced so that we better understand the necessary conditions for regeneration, AF will be positioned to provide the necessary solutions.
As a product developer, inventor of AM applications, developer of LS material solutions, service bureau and manufacturer with a history of customers and industries (toys, personal care products, medical, health care, military, aerospace, energy, industrial products, home-building, housewares, foundry, etc) there is clearly no boundaries in the near term or future except what we don’t know. AM applications we see today present clear and convincing arguments that we have barely scratched the surface across the entire application opportunity spectrum.

A closer examination of past and present AM beneficiaries would boldly point to some form of prototype application. A very small percent would be end products or production tools that facilitate production quantities. e.g. Align Technology. For the AM industry to realize its rightful place as an industrial process along side traditional processes much more investment and research needs to happen. The reality is prototypes and patterns that support other duplication processes, as a growth application category, are unlikely to realize more than incremental growth. With the shrinking of America’s industrial base (pre and post our current recession) the growth will be offset by the amount equal to the transfer by foreign export of our manufacturing and the effects of inflation. This is of course unless we invest to not just marginalize the loss, but make a quantum gain on it. In my opinion given the current state of (or lack of): material choices, materials science research, breakthrough AM processing technologies, industry standards, AM application and design ingenuity offer unparallel discovery opportunities.

The bright side is that there is evidence of growing interest in AM to manufacture end products. Examples that are well publicized and historically significant included SLA and SLS processes starting with Siemans/Phonak’s hearing aid JV effort and Invisalign. To date defense, aerospace, healthcare and a growing underground of custom-personalized (collectables and fashion jewelry) consumer products seem to be the major benefactors of AM end products. The visible thread is they are all custom applications and representative of low-volume mass-customization.

Do these examples represent growth opportunities or establish the high water mark? Paramount’s experience is that there is no limit unless we do nothing to advance the materials and process. Government, small and large businesses as well as public and private institutional stakeholders must invest to fill all the gaps. The gaps are plentiful and offer boundless opportunities for discovery and investment. Recently the AFRL has come to the forefront by investing R&D funding into laser sintered high-temperature materials research through the SBIR/STTR program. There is reported congressional earmarks managed by ONR for similar material R&D efforts. Point is the US Government is investing in AM materials and process R&D. DOD prime contractors are selecting non-structural system parts to be manufactured using AM. The potential for savings on one DOD system alone is estimated in excess of $100MM over the system’s manufacturing life. There is a growing number of production tooling jigs and fixtures making their way to the production floor.
In a closer examination one needs to look at the opportunities as a complex matrix of drivers each sharing in the success bubble.

Materials/Materials Science… Of the three dominant AM processes (SLA, SLS, FDM) AM has two principle polymer chemistries that make up today’s manufactured end products. Photo-polymers and laser sintered powders. An exception is the collectable market that uses Z-Corp’s starch based materials. Photo-polymers and LS powders are marginally successful. They are limited by their material’s science or by their respective equipment technology. e.g. LS produces a part that is not fully dense and produces an inadequate dimensional representation of the 3D CAD model. However, the LS process offers the best hope today of manufacturing a reliable and environmentally stable part. The short coming is the processing science is limited to crystalline materials. Because LS material developers start with injection molding (IM) and the abundance of IM materials are amorphous LS growth will be incremental. To date LS is limited to nylons (polyamides). This issue begs for a breakthrough material’s science. SLA is capable of manufacturing very accurate parts but its limiter is epoxy based photo-cure resin systems which are not environmentally stable amongst other short comings. FDM offers injection molding grade materials that at first glance would appear to offer a viable end product best-solution. The weak link with FDM is the Z layer is inherently weaker compared to SLA and SLS.

Breakthrough AM Process Technologies… The majority of new AM systems are all derivatives of existing photo-cure materials processing technologies. What is needed is a breakthrough processing technology that is not laser based. The breakthrough would coalesce sintering with amorphous engineered materials or create a new material chemistry based on sintering.

Application Ingenuity and Design Ingenuity… These two elements are not mutually exclusive. To continue to select DFM standards from non-additive manufacturing processes will not further the true benefits of AM. As an example injection molding DFM design standards were developed through years of trial and error based on the injection molding technology. AM practitioners need to create customer demand by example. What’s necessary is for the practitioner to get involved with a client’s product or system at the R&D phase. Inventing designs that enable AM as a feasible alternative. This may be unpaid work. Investing in your customer!

Lastly there’s the market place. To date industry and academia have been the direct users and beneficiaries of AM. Consumers are indirect beneficiaries. Their benefits are indirectly derived through the products they purchase or the medical and healthcare services they receive. For the consumer to become a direct beneficiary of AM they need a 3D printer next to their PC. There is an apparent opportunities at both ends of the market spectrum for direct benefits. Many AM equipment OEMs are attempting to fill the consumer gap with lower cost 3D printers. The $10,000 barrier has been barely broken. To drive this down to the masses we need a mass-produced product less than $1,000. To make the quantum leap we need RP for Kid’s. We need for AM what the Adam and the Commodore 64 did for the personal computer by introducing the computers for under $200-$700. This not so trivial milestone brought an affordable computer technology into the lives of children, their parents and our educational system.

In conclusion there is compelling evidence to support continued investment at all levels. The harsh reality is it’s far too expensive for the private sector to fund breakthrough process technologies and new materials chemistries. Government, research institutes and university intervention is necessary. Time is of the essence. The industry will continue to be marginalized as a prototyping process unless something is done. Manufacturing opportunities will not wait until AM comes along. AM needs to step up -- on cost and technical benefits.
I’ve chose to comment briefly on each of the seven workshop topics.

**Industry Targets**: Some of the possibly less obvious industries that will drive the market over the next decade include the military, dentistry, jewelry, entertainment products (e.g., video games), collectables, home accessories, and toys. Many of the parts produced by additive manufacturing (AM) will go into or become custom, semi-custom, and limited edition products. New types of businesses will unleash new types of products, some unthinkable, that before were impractical due to cost, risk, or manufacturability. Some companies will use AM technology to bridge the gap between a finished design and production tooling.

**Technology Goals and Barriers**: AM systems of the future will be designed and manufactured using quality standards, such as those applied to today’s CNC machining industry. Until this occurs, companies will limit their use of AM technology for production applications. Work was launched in January 2009 by ASTM International Committee F42 on Additive Manufacturing Technologies, an effort that has been missing for years.

**Design and Analysis**: In 10-15 years, schools will offer courses and programs that include instruction on how to design for direct digital manufacturing. In the meantime, some innovative organizations will develop methods of product design that take advantage of AM processes and materials.

**Processes and Machines**: Raster processing of layers is faster than vector-driven approaches, but processing an entire layer at once is faster than raster. Two whole layer AM processes have been commercialized and two others are in the works. This type of processing is not only faster, but it may offer improvements in accuracy, surface finish, simplicity, and machine reliability.

**Materials/Materials Processing**: As the market expands, organizations will be motivated to develop and commercialize materials for new applications, including niche areas, some of which are big. As consumption grows further, and as competition increases, the current high prices of AM materials will decline. This must occur if the industry hopes for a large number of companies to embrace AM technology for production applications.

**Energy/Sustainability**: It is believed that some AM processes reduce material consumption, part weight, and hazardous materials, compared to using conventional methods of manufacturing to produce similar parts. Few studies have provided hard evidence, but this will change over the next decade. Future studies will likely support the notion that AM for manufacturing can significantly reduce energy consumption and carbon emissions.

**Nano- and Biotechnology**: Already, nanotechnology has altered hundreds of everyday products. In 10-15 years, few products and industries will not be effected by it in some way. Meanwhile, many universities and research institutes are exploring ways in which AM can be applied to medical implant design and manufacturing, tissue engineering, and regenerative medicine. Two companies in Italy have used AM to manufacture 10,000 metal hip implants, 2,000 of which have been implanted into human beings.