Additive Manufacturing Overview

For

The United States Marine Corps

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Abstract

The purpose of this paper is threefold: (1) to provide a brief overview of the 3D printing industry, the technology, the applications and the materials; (2) to convey the rapid and accelerating pace of the growth of the industry and (3) to outline the potential benefits to the Marine Corps.

3D Printing, also called Additive Manufacturing (A/M) is not new. The technology was invented over 30 years ago. However, now technological advancement is accelerating. Originally thought of as simply an application for Rapid Prototyping, it is now a viable option for a myriad of applications including aerospace, automotive, medicine, construction, science, and art. This paper offers a brief primer to the history, current state, and possible future growth of 3D printing. It includes a short history of the technology, a review of the most common processes and materials, a look at some of the most critical challenges to implementation and a discussion of the future of 3D printing.

Finally a description of the potential benefits to the Marine Corps that can be gained by implementation of 3D printing technologies is presented. The technology offers many potential benefits to the military. The most immediate is the possibility of more efficient logistics.

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Acronyms

A/M	Additive Manufacturing
AAV	Assault Amphibious Vehicle
AM	Additive Manufacturing
AMF	Additive Manufacturing Format (ASTM standard file format)
ASTM	American Society for Testing and Materials (formerly)
BCA	Business Case Analysis
CAD	Computer Aided Design
CEO	Chief Executive Officer
CLI	Coalition Logistics Interoperability
CNC	Computer Numeric Control
ConOps	Concept of Operations
DARPA	Defense Advanced Projects Research Agency
DIY	Do It Yourself
DMS/MS	Diminishing Manufacturing Sources/Material Shortages
DoD	Department of Defense
ExLog	Expeditionary Logistics Wargame
GCSS-MC	Global Combat Support System - Marine Corps
GE	General Electric
IP	Intellectual Property
IPR	Instant Parts Replacement
ISO	International Standards Organization
ITAR	International Traffic in Arms Regulation
LAV	Light Armored Vehicle
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacture
MAGTF	Marine Air Ground Task Force
MCB	Marine Corps Base
MEU	Marine Expeditionary Unit
MLT	MAGTF Logistics Tool
NASA	National Aeronautics and Space Administration
NCMS	National Center for Manufacturing Sciences
NLI	Naval Logistics Integration
ONR	Office of Naval Research
Optempo	Operational Tempo
R&D	Research and Development
REF	Rapid Equipping Force
RepRap	Replicating Rapid Prototyping
S&R	Sense and Respond
S&T	Science and Technology
STL	Stereo Lithography
TRL:	Technology Readiness Level

Introduction

In 1983, Chuck Hull serendipitously stumbled on what he later called "Stereolithography" to usher in the opening of the 3D printing revolution. Three years later he established 3D Systems, the father of all Additive Manufacturing companies. He also developed the STL file format, still commonly used to define a three dimensional object for printing.

Although Additive Manufacturing or 3D Printing was first demonstrated over 30 years ago, until recently its development largely took place in the shadows. High cost, limited capabilities, technical challenges, poor quality, and widespread misconceptions all contributed to the lack of attention. However, in the past few years, progress has accelerated dramatically. Most projections indicate that expansion of the technology will continue exponentially. New applications are being discovered or revealed every week.

As with most emerging technologies, there has been a cycle of over optimism and grand expectations. This is often followed by a period of disappointment when progress takes a bit longer than the optimists had hoped. As Bill Gates is reported to have said: "*We always overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten.*" (Hornick, 2014) This phenomenon is expressed by the information technology research and advisory company Gartner, Inc. in their "Hype Cycle for Emerging Technologies." (Figure 1)

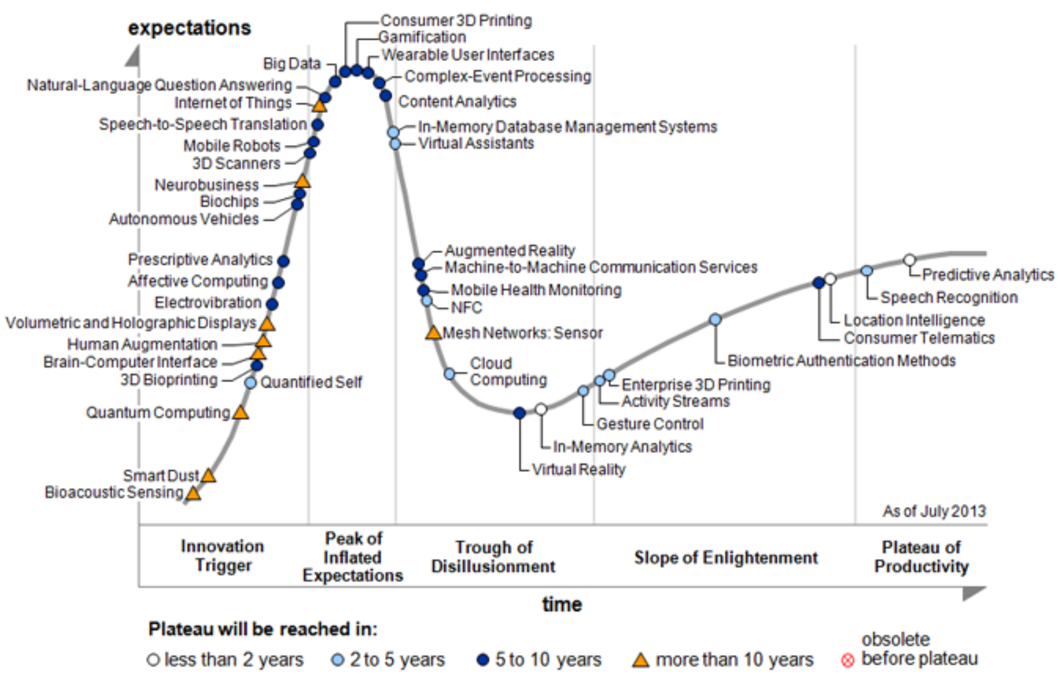

Figure 1 Gartner Hype Cycle for Emerging Technologies, 2013 (Gartner, Inc., 2013)

A case might be made that the most recent enthusiasm for 3D printing went mainstream in 2011 when a favorable article appeared in *The Economist* (The Economist, 2011). This was followed by a series of articles in respected publications such as *Forbes* (Hart, 2012) , *The Harvard Business Review* (D'Aveni, 2013) and others.

At the same time the “RepRap” (replicating rapid prototyping) project initiated by Dr. Adrian Bower at the University of Bath, in 2005 (Winnan, 2012) was gaining momentum. This began the personal 3D printing movement that fueled the “Maker” movement.

Potential benefits of 3D printing now go far beyond speedy prototyping. Replacement of hard to get or obsolete items can be made possible in less time and at lower cost. Previously impossible complex geometries are now possible. Dramatic weight saving is often the norm.

Additive Manufacturing Overview

<u>What is It?</u>

Q. Is it called Additive Manufacturing or 3D Printing?

A. Yes.

The terms are usually used interchangeably. There are some authorities who try to separate them, sometimes reserving 3D for the home printers and A/M for industrial uses. However even though the ASTM standard directs the term Additive Manufacturing, there is no mutual agreement. Most practitioners use whichever term seems most convenient at the moment. In this paper they will both be used without distinction.

Definition – ASTM Standard F2792-12A defines A/M as “A process of joining materials to make objects from 3D model data, usually layer upon layer as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication.” (ASTM, 2012)

> *“AM is used to build physical models, prototypes, patterns, tooling components, and production parts in plastic, metal, ceramic, glass and composite materials”.*
>
> *“Additive manufacturing is a tool that streamlines and expedites the product development process.”* (Wohlers, 2014)

Uses & Benefits

Rapid Prototyping – The original industrial use for A/M. Using 3D printing technology, prototypes can be made quickly and designs adjusted in hours or days instead of weeks or months. This brings products to market faster at lower cost and higher quality.

Cost Saving or "Buy to fly." How much material must be obtained to produce a finished item? Compared to "Subtractive Manufacturing" the cost savings in greatly reduced material waste can be dramatic. In the traditional method, material is removed from a billet of material in a lathe, Computer Numeric Control (CNC) machine or other tool to form the shape of the item. Often as much as 90% of the original material is lost to scrap. When a material such as Titanium is used, this waste is the major cost driver. When Additive Manufacturing techniques are used, waste is minimal; usually less than 5%, making exotic materials far more economical.

Mass Customization – Using A/M technology, it is possible to make each item uniquely fitted to its application. Dentures, Dental Implants and Invisalign® Braces are all examples of this. The SOLS Company makes precisely fitted orthotics by 3D scanning the user's foot and then printing a uniquely customized insert. The cost is no greater than that of "off-the-shelf" orthotic inserts.

"One-off" or Short Production Runs – Unlike traditional manufacturing methods that require expensive and time consuming tooling setup, A/M goes straight from CAD drawing to the printer with only a software interface. The per-item cost of one is no more than for one thousand. Economy of scale is less important. The converse of this is that for large production runs of identical items, traditional methods usually remain the best choice.

Complexity is Free – Permitting much greater freedom of design. 3D Printing makes possible nearly anything a designer might imagine. Designs that would not be possible using traditional methods are no more difficult in 3D that simple ones.

Stronger/Lighter – Because of the elimination of design constraints, it is possible to manufacture much stronger items weighing less than their traditionally made counterparts. And because of the near elimination of waste, it is possible to make them at reasonable cost.

The Art of the Possible Today

Invisalign braces, support brackets on the Juno spacecraft, many parts on the Boeing 787, and critical parts of the newest General Electric jet engines are just a sampling of the production components that are now 3D printed.

Elon Musk's SpaceX just announced that they would use a 3D printed combustion chamber on the new "SuperDraco" rocket engine to be used on their "Dragon" manned space craft. (Szondy, 2014) An unmanned cargo version of the Dragon is already in use under contract to NASA to resupply the International Space Station.

> *"Through 3D printing, robust and high-performing engine parts can be created at a fraction of the cost and time of traditional manufacturing methods," said Elon Musk, Chief Designer and CEO. "SpaceX is pushing the boundaries of what additive manufacturing can do in the 21st century, ultimately making our vehicles more efficient, reliable and robust than ever before."* (SpaceX, 2014)

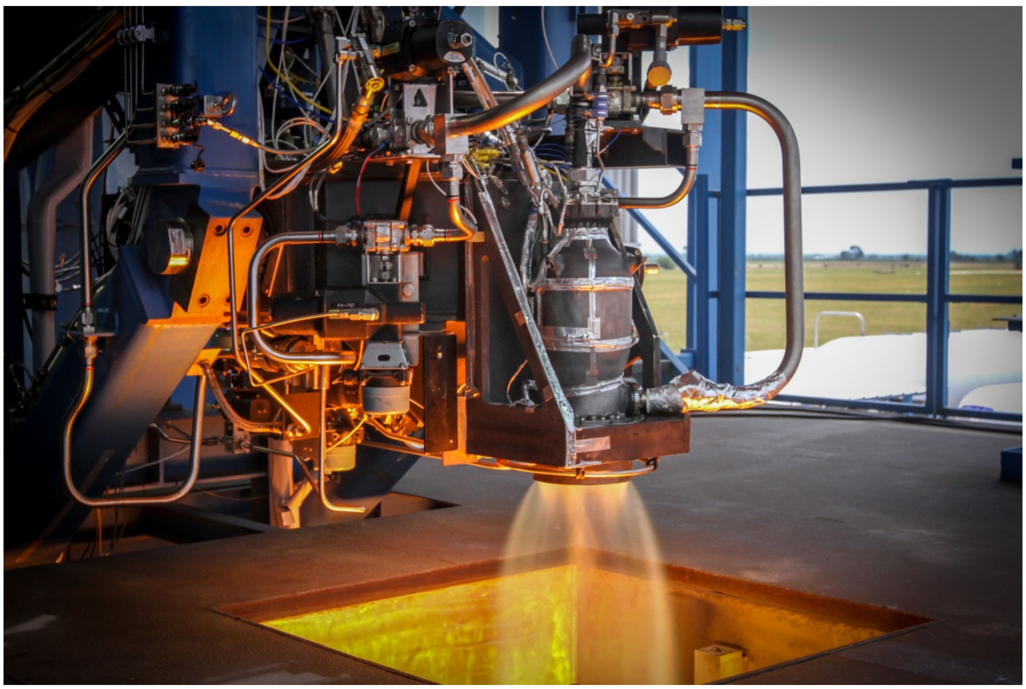

Figure 2 SpaceX SuperDraco Rocket Thruster (SpaceX, 2014)

Solid Concepts, a 3D Printing service agency, has printed a complete .45 Caliber M1911 pistol (see figure 3) and fired over 2,000 rounds through it as a demonstration of the art of the possible. Materials are Stainless Steel and Inconel 625 (a nickel-chromium alloy). The only parts not printed are the springs. In answer to demand, one hundred copies of the gun will be offered for sale to the public for $11,900 each. (Solid Concepts, 2013)

Figure 3 Working 3D Printed .45 Cal M1911 Pistol (Solid Concepts Blog, 2013)

Industrial vs Hobby (and the increasingly blurred line between them)

Early Industrial Use

Additive Manufacturing has been used for many years in industry. As can be seen in figure 4 in the following section on industry growth, sales began to pick up in the mid 1990's. Early use was primarily as a means of rapid prototyping. The benefits of this were easily discerned by those early adopters. However, the technology was still fairly primitive and the price was high. The cost-benefit proposition was only positive in specific high value situations such as prototyping of new designs of costly machinery. During that period, the only materials widely used were polymers.

As the ability to print in metals became possible and the variety of materials grew, industry use expanded. At the same time printer prices began to come down; still too expensive for home or hobby use, but well within the budgets of the manufacturing industry.

Home Printers

Once again, referencing the section below on growth, in figure 5, significant sales of so called home printers began around 2008 as the first relatively low cost printers became available. This growth was fueled by the rise of the "Maker" movement, open source software, and Do It Yourself (DIY) and RepRap printers.

The Makers are a group of tinkers and inventors, working in their garages and basements to solve problems of their own choosing with technology. For the most part, they are motivated by the sheer joy of the activity, rather than the hope of profit. They could be compared with early computer makers like Wozniak, Hewlett, Packard and others. One might even be reminded of the early days of the automobile or aviation development.

One difference is that this is a true "Movement." The Makers gather regularly at "Maker Faires" around the country to show their work and see what others are doing. The sharing of ideas and inspirations creates a dynamic environment in which new concepts and approaches bubble up. As Hod Lipson put it, *Ubiquity is what enables new technologies to stir up revolution.* (Lipson, 2013)

The blurring of the lines between industrial and home 3D Printing can already be seen. It is caused by a combination of the ideas sparked by the "revolution" mentioned by Lipson and reduction in cost of increasingly capable 3D printers. At Michigan Technological University, a team led by Associate Professor Joshua Pearce is developing an inexpensive "home" 3D metal printer. They have made the plans available freely to the public. According to Pearce, "I anticipate rapid progress when the maker community gets their hands on it. Within a month, somebody will make one that's better than ours." (Goodrich, 2013)

Small "Mom and Pop" type businesses are springing up all over the country, each with a unique business idea based on 3D printing with a low end printer. The SOLS Company mentioned previously uses inexpensive, "home" type printers to make the custom orthotics that they sell.

Additive Manufacturing Industry Growth

The Wohlers Report is published annually. It is a comprehensive study covering all aspects of 3D printing, including its history, applications, processes, materials, and manufacturers. It includes developments in research and development, investment, as well as collaborative activities in government, academia, and industry.

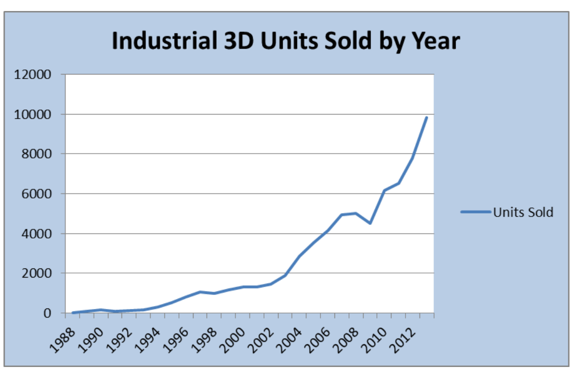

Figure 4 Growth of Industrial 3D Industry (Castle Island Co., 2014)

According to the 2014 Wohlers Report the value of the A/M market including all products and services grew nearly 35% in 2013 to $3.07 billion. Annual growth in the three previous years was estimated to be between 25% and 30%. (Wohlers, 2014)

Figure 4 shows the units sales growth of industrial printers over the past twenty five years.

The past few years have seen the rise of the "personal" 3D printer. Generally speaking systems that sell for $5,000 or less are considered "personal". However, that distinction is becoming less clear as capabilities of these printers increases and prices come down. Figure 5 indicates the burgeoning growth of low cost "personal" 3D printers in the past six years.

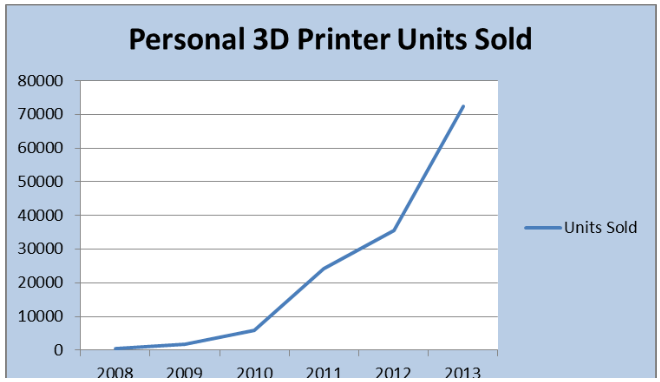

Figure 5 Growth of Personal 3D Printer Sales (Castle Island Co., 2014)

Challenges, Issues, Concerns

Additive Manufacturing technology is advancing very quickly. Every week articles are published describing new applications or new materials. As with any such technology, there are still issues to address and challenges to overcome. The following are a few of them.

Intellectual Property (IP) – There is no doubt that IP issues will be an obstacle to early adoption of A/M. According to John Hornick, an attorney specializing in this field, there will be a period of time when industry will defend their IP vigorously. He believes that in a few industries such as aerospace, IP will probably remain important. However, he believes that:

> *"As democratization of design and manufacturing increases away from control, IP will become increasingly irrelevant."* (Hornick, 2014)

Many in the industry believe that the issues will be overcome with creative solutions in a manner similar to the approach of the music industry. IP owners will sell data as well as or instead of physical items.

Security – According to Albert Davis, Director, S&T Division, Office of Intelligence and Counterintelligence, DOE, speaking at the Oak Ridge National Labs Additive Manufacturing Summit, there are several national security issues associated with 3D printing to consider. Central to these concerns is the fact that the majority of 3D printing companies are not headquartered in the United States. This raises a host of potential threats and issues. In addition to possible espionage and sabotage, International Traffic in Arms Regulations (ITAR) issues must be considered.

Certification of the finished part – It is important to recognize that many 3D printed items are superior to their conventionally manufactured counterparts. They are very often lighter, stronger and more durable. In order to gain this advantage parts must be designed for 3D printing and more importantly, there must be a method of certifying that quality is in keeping with requirements.

If each printed item must be individually certified much of the advantage of speed and reduced cost would be negated. The answer to this, according to a number of A/M practitioners, is to certify the material and the process. Some 3D printer manufacturers are incorporating a closed loop process monitoring system that is able to identify faults in the print process. However, to date none have offered the ability to detect faults in real time and report them in an understandable format. This will almost certainly be accomplished in the near future.

Software – Although Carl Bass, CEO at Autodesk disputed this at the Inside 3D Printing conference in New York in April 2014, most laymen are challenged by the design and printing software. According to many sources, the problem is that computers think in two dimensions (2D). Even 3D Computer Aided Design (CAD) is a 2D representation of a 3D object. The solution may very well be similar to the design table used by Tony Stark in the movie, "Iron Man." In any case, this is an issue that will be overcome sooner rather than later according to most knowledgeable people. Many are working on it.

Standards – The industry is just maturing to the point that it has recognized the need for standardization in file formats, terminology, data structure, etc. The root of this issue is the nature of the growth the industry experienced over the past thirty years. Each new organization followed its own path and developed its own practices, standards, language, software, and methods. The reasons and the challenges are very similar to those encountered in the effort to achieve data interoperability among joint and coalition forces.

Training – The population of those proficient with this technology is small. Within the military, smaller still. This will need to be addressed as the technology is implemented. That, however, is not unusual. The military is constantly embracing and learning new technologies. That will be the easiest obstacle to overcome.

Resistance to Change - This is always the most difficult hurdle to overcome in any large organization. The best approach is small steps and convincing demonstrations presenting the capabilities to decision makers and action officers.

Addressing the Challenges

It should not be inferred that these issues are not being addressed. As early as 1994 the Department of Energy described a roadmap addressing some of these issues entitled "En Route to the Future: A Roadmap from Rapid Prototyping to Advanced Rapid Manufacturing." That document identified three areas of concern: (Bourell D. , 2013)

1. Rapid Prototyping/Solid Freeform Fabrication/Additive Processes
2. Product Design and Visualization
3. High Speed Machining

In 1998 NCMS published *The Roadmap to Manufacturing: 1998 Industrial roadmap for the Rapid Prototyping Industry.* Figure 6 illustrates the future as viewed from that year. It may be noted that the key long term goals were (and remain) Direct manufacturing and Design verification.

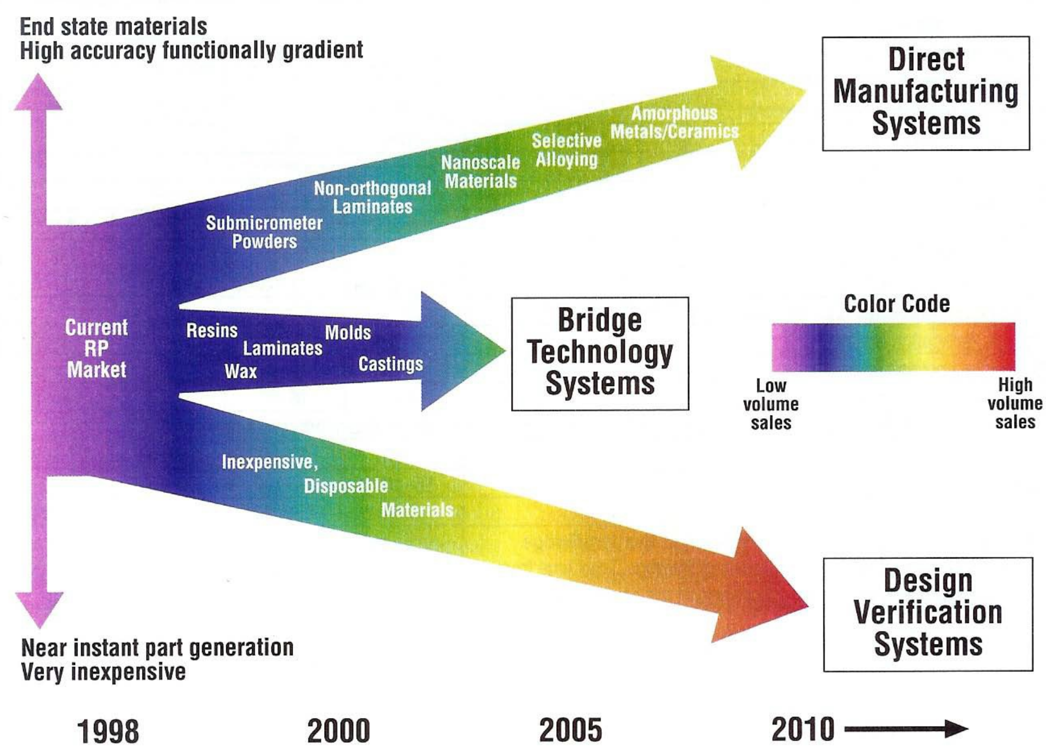

Figure 6 1998 Industrial Roadmap (National Center for Manufacturing Sciences, 1998)

In March, 2009 the Roadmap for Additive Manufacturing Workshop was held in Alexandria, Virginia with the objective of developing a way forward for the ensuing 10-12 years. The detailed results of that meeting are contained in *Roadmap for Additive Manufacturing; Identifying the Future of Freeform Processing* published by the University of Texas at Austin. That workshop examined eight focus areas deemed essential for the progress of the technology. (Bourell L. R., 2009)

- Design
- Process Modeling and Control
- Materials, Processes and Machines
- Biomedical Applications
- Energy and Sustainability Applications
- Education
- Development and Community
- National Test Bed Center

Examination of those individual topic areas revealed several common themes: (Wohlers, 2014)

- Consistency, Repeatability
- Process Standards
- Closed Loop Feedback Control
- Predictive Analysis and Modeling
- Material Property Data Generation
- Exploitation of Unique Features of A/M
- Design Rules/Tools
- In-build Considerations (Inspections, Sensors)
- Education

The Future

Hod Lipson asks the question: "*What would you make if you had a machine that could make anything?*" He answers with: "*In the not-so-different future, people will 3D print living tissue, nutritionally calibrated food and ready-made fully assembled electronic components.*" (Lipson, 2013) In fact these predictions, made less than a year ago, are already coming to pass. At the "Inside 3D Printing" conference in New York in April 2014, Google announced their intention to 3D print a cell phone, circuits and all. Organova is printing living liver tissue for medical testing, and printed food has made an appearance. The technology is moving so fast and the implications so wide that none of us can accurately imagine the future.

One assessment of what the future holds for additive manufacturing may be derived from both patents issued and patents applied for. The following chart (figure 7) illustrates the accelerating nature of technological developments in this field. According to Castle Island Co. these patents have been issued in over 66 different technology areas. A short list includes subjects as diverse as rocket engine parts, petroleum drilling components, personalized jewelry, artificial bone implants, counterfeit prevention, superconductor composites, orthodonture, gun components and a vast myriad of other applications.

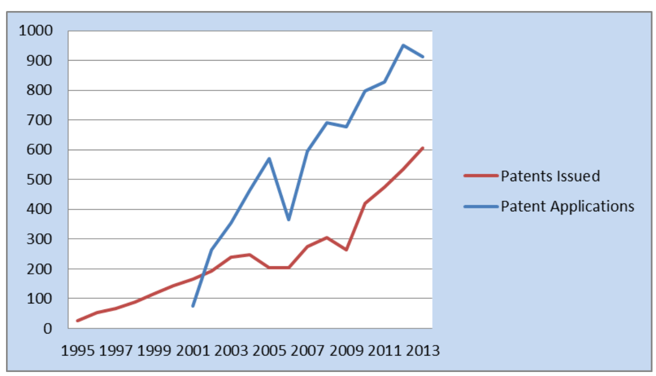

Figure 7 Growth of Patents and Patent Applications (Castle Island Co., 2014)

A/M Process

Printing Process Categories

There are many different A/M machines and methods. In an attempt to bring order and clarify the additive manufacturing universe, ASTM International, Committee F42 published the *Standard Terminology for Additive Manufacturing Technologies* which is derived from ISO 10303-1. The chart in figure 8 lists the broad process categories used in additive manufacturing.

ASTM Additive Manufacturing Process Categories

Category	Short Description
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as they are deposited
Material extrusion	Material is selectivey dispensed through a nozzle or orifice
Material jetting	Droplets of build material are selectively deposited
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed
Sheet lamination	Sheets of material are bonded to form an object
Vat photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization

Figure 8 A/M Process Categories (ASTM, 2012)

In an even simpler process classification Hod Lipson divides the printer world into two families (Lipson, 2013):

1. Printers that squirt, squeeze or spray
2. Printers that fuse, bind or glue.

Printing Processes

Stereo Lithography, the original 3D printing process invented in 1983 had much in common with similar breakthrough discoveries throughout history. The applications and benefits were not immediately evident. However in the past few years there has been an explosion of discoveries and new inventions. Figure 9 lists a few of the most prominent processes available now.

Principal 3D Printing Processes

Material	Process	Short	ASTM Category	Patent Holder	Comment
Plastics	Stereo Lithography	SLA	Vat Photo-polymerization		Original process invented by Chuck Hull
	Selective Laser Sintering	SLS	Powder Bed Fusion		Plastic or metal
	Photopolymer Jetting		Material Jetting		Similar to inkjet printing
	Indirect Process				Injection molding
Metals	Deposition Metal Laser Sintering	DMLS	Powder Bed Fusion		
	Direct Metal Printing		Material Jetting		Multi Step process
	Ultrasonic Additive Manufacturing	UAM	Sheet Lamination	Fabrisonic LLC	
	Electron Beam Melting	EBM	Powder Bed Fusion	Arcam	
	Laser Engineered Net Shaping	LENS	Directed energy deposition	Optomec	Developed with help of NCMS collaboration
	Selective Laser Melting		Powder Bed Fusion	SLM Solutions	
	Direct Metal Deposition		Direted Energy Deposition	DM3D	
	Digital Part Materialization		Binder Jetting	ExOne	
	Direct Metal Sintering		Powder Bed Fusion	3D Systems	
	Direct Metal Laser Sintering		Powder Bed Fusion	EOS	

Figure 9 Principal Printing Processes (Wohlers, 2014)

Common Materials

As is true of the section of 3D printing processes, new materials used in Additive Manufacturing are being added every week. The following section lists a few of the most interesting.

Plastics:

Some Common Plastic Materials		
Abreviation	**Material Name**	**Description**
PLA	Polylactic Acid	Common choice; biodegradable; there are several varieties
PLA Soft	Soft/Flesible Ploylactive Acid	Rubbery and flexible
	Laywood D3	Recycled wood and PLA binder
	Laybrick	Rough finish texture similar to sandstone
ABS	Acrylonitrile Butadiene Styrene	The plastic used in Lego bricks
HIPS	High Impact Polystyrene	May be used for final parts, better and cheaper than PVA
	Nylon	Strong/Flexible; difficult to use due to shrinkage, warping
PET	Polyethylene Terephthalate	Crystal Clear
PCL	Polycaprolactone	"MakerBot Flexible Filament" AKA Instamorph & Polymorph

Figure 10 Common Plastic Materials (France, 2013)

Metals – Theoretically any metal material that can be welded can be 3D printed. This is a short list intended to convey the range of possibilities

- Stainless Steel
- Tool Steel
- Cobalt Chromium Alloys
- Inconel
- Titanium
- Aluminum Alloys

Others

- Ceramic
- Sand
- Glass
- Wood

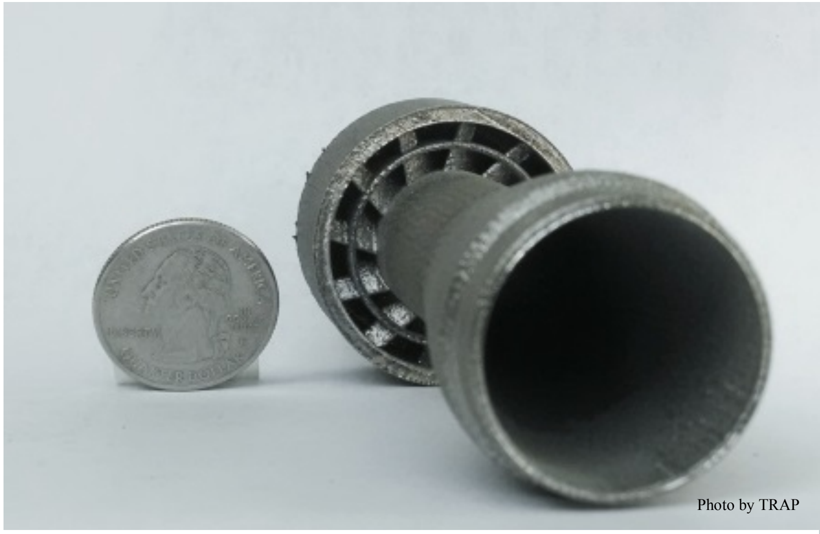

Figure 11 SLM Solutions 3D Printed Metal Gas Turbine Nozzle

Produce the Data

Model

The steps required to complete the process of producing a 3D print are (1) Model (or Capture), (2) Translate to a printer file format (STL or AMF), (3) Slice and (4) Print. There are many 3D modeling file formats and software applications and packages to aid in Computer Aided Design. A short list of relevant 3D file formats includes .off, .ply, .3ds, .obj, .x3d, .u3d and vrml. Principal companies providing design or modeling software include AutoDesk, Adobe, Spaceclaim, Netfabb, Materialise and many others. Detailed analysis of this complex and fast changing subject is beyond the scope of this paper.

Generally speaking the 3D modeling program must generate an .STL file in order to print. A program called a slicer divides the .STL model into thin slices that can be laid down or selected from a vat or powder bed one layer at a time.

Late development – in a move that promises to improve integration of modeling and printing software Autodesk published the announcement below during the writing of this paper..

> (14 May 2014) –"*Today, Autodesk is announcing two contributions to help make things better. First is an open software platform for 3D printing called Spark, which will make it more reliable yet simpler to print 3D models, and easier to control how that model is actually printed. Second, we will be introducing our own 3D printer that will serve as a reference implementation for Spark.*" (Bass, 2014)

3D Scanning or Capture

An alternative to modeling an item is to scan a desired item. Most scanners output the data in the STL file format ready for printing.

The ASTM Standard F2792-12A definition of scanning is: "*A method of acquiring the shape and size of an object as a 3-dimensional representation by recording x, y, z coordinates on the object's surface and through software, the collection of points is converted into digital data.*" (ASTM, 2012)

3D scanning is sometimes called reality capture or design capture. At its core, 3D scanning is similar to traditional 2D scanning. An image is captured, translated into digital data and made usable for printing. There are a variety of technologies, each with its own strengths and weaknesses. A detailed discussion of this subject would fill a book by itself and is outside the scope of this paper. However, the capability is so exciting that a brief look just a few of the things made possible by 3D scanning seems useful.

Archeologists no longer dig up artifacts and bring them home in the manner of Indiana Jones. Nations now insist that items found in their countries must remain there. Now some scientists are 3D scanning their finds and sending the data to high end printers able to print good quality reproductions for study or display.

Figure 12 3D Printed Dinosaur (DrexelNow, 2012)

Paleontologists are using the same technique with fossils. At Drexel University in Philadelphia Dr. Kenneth Lacovara scans giant dinosaur bones in his lab. He then gives the digital files to Dr. James Tangorra, Assistant Professor in the College of Engineering to print scale models of the dinosaur bones. The focus of their work is to help understand the movements of extinct species. This same technology is being used to reproduce correctly sized replicas suitable for museum display at Philadelphia's Franklin Institute, (DrexelNow, 2012)

More mundane, but potentially of greater immediate use to the Marine Corps is the ability to scan a replacement part and send the print data to a printer close to the requirement. This could mean scanning the item Albany, Georgia, sending the data where needed, and printing the item at a forward base or aboard a Navy ship at sea anywhere in the world. Or it might simply be used to make an additional copy of a needed part locally.

Printer Manufacturers

The Wohlers Report lists 66 printer manufacturers. Figure 13 lists only a few of the largest.

Major Printer Manufacturers (Short List)

3D Systems	Arcam	Materialise
Stratasys	Renishaw	Optomec
ExOne	EOS	SLM Solutions
Voxeljet	mCOR	DM3D

Figure 13 Major Printer Manufacturers

Additive Manufacturing and the USMC

> *"The convergence of developing "disruptive" technologies and temporarily reduced optempo present a rare opportunity in time to make state-of-the-art changes in the way the military conducts logistics."* (NCMS, 2013)

The United States military is exploring 3D printing on several fronts. Both Army and Navy have incorporated 3D printing capability into certain repair facilities. The Navy uses Additive Manufacturing at its Fleet Repair Centers. They are taking the initial steps to study installation of 3D printers aboard ships at sea. The Army's Rapid Equipping Force (REF) has a forward deployed facility that includes additive manufacturing in concert with more traditional manufacturing and repair technologies. There is an array of research and development efforts addressing a myriad of topics from weapons effectiveness to energy conservation.

One key to full acceptance by the DoD will be a documentable means of certifying the quality of each printed part or component. According to Terry Wohlers, *"Qualification, validation, and verification of AM parts have increased as important research topics in recent years*. He also points out that *Standardization of processes, materials and design will facilitate progress. Currently ASTM and ISO are working jointly to fast track the standards that will encourage international cooperation and encourage greater acceptance of A/M."* (Wohlers, 2014)

Another developing theme in A/M Research and Development (R&D) is Logistics and Supply Chain Management. "*The effects of a disaggregated supply chain on the delivery of products and services and the location and nature of jobs association with those effects are examples that are becoming increasingly prevalent."* (Wohlers, 2014) This statement speaks forcefully to Marines. Distributed Operations, Seabasing and an Expeditionary model stretch the Marines' supply lines to the limit and often beyond. Manufacture and repair near the point of use hold the potential to reduce cost, improve asset availability, and increase combat effectiveness.

Problem

The Marine Corps is a "medium-weight" expeditionary force - light enough to move to trouble spots quickly, but heavy enough to accomplish the mission. With this requirement in mind, logistics must be as light and friction-free as possible, while always providing the support needed to conduct the necessary operation.

In addition, flexibility is paramount. A Marine Expeditionary Unit (MEU) is basically a heavily reinforced battalion deployed aboard Navy ships. During the course of a deployment which lasts six months or longer (much longer sometimes), the battalion and its supporting establishment, may be split to accomplish particular missions. Companies, even Platoons, may be sent many hundreds of miles from the main body for an unknown period of time in order to address a specific issue.

Inventory: It goes without saying that space available for storage of parts and supplies aboard ship is limited. The Marines bring with them the spare parts they think they are most likely to be needed and are most essential. This package of support is called a Class IX block. One experienced Marine who deployed many times claimed that the content of the IX block is actually decided by (1) what is available ashore before departure, and (2) what will fit. Whatever the decision process, unplanned mechanical failures are guaranteed to occur, and the needed repair parts will not always be available in the IX block.

Transportation: When a deployed Marine working in Supply is unable to acquire the needed item within the USMC IX Block, he or she must then “swivel chair” to the various Navy Supply systems which are unfamiliar. In many cases, this will result in significant delay and great cost, as the item must be flown in. In recent years the DoD has increased the use of high priced air express services such as FedEx, UPS and DHL to deliver high priority items to remote corners of the world. Delivering to ships at sea multiplies the complexity and cost.

Obsolescence: One more issue worth mentioning, is obsolescence. Many of the key Marine Corps assets are well beyond their originally expected service life. The Light Armored Vehicle (LAV) was fielded in the 1980’s and the Assault Amphibious Vehicle (AAV) was fielded in the 1970’s. Although these vehicles have been maintained and upgraded over the years, there are occasions when an item, no longer in the DoD stock fails and must be replaced. If that item is no longer being manufactured, the cost to restart a production line or to reverse engineer and manufacture a short run is extraordinarily high. It can sometimes take a year or more to acquire the necessary item.

Solutions

Inventory – Store files & raw materials; not parts. Store the CAD or other printable file for appropriate repair/replacement parts in the Logistics Data Warehouse (LDW) or the MLT or some other suitable database that is accessible to users.

This would require that the Marine Corps purchase tech data packages including CAD files with new acquisitions or upon loss of manufacturing sources. Although additional cost would be incurred and resistance from suppliers might be expected, the value of the data in terms of more efficient logistics would more than offset the price tag.

Transportation – Send electrons; not parts. Transportation costs can be a significant percentage of the price of logistical support. If only a small portion of these items could be supplied by sending the printer data electronically, cost we be reduced and significant time would be saved. The Navy has installed a 3D printer aboard the USS Essex. This experiment will enable the Navy to learn a great deal about 3D printing while afloat, as it works out the challenges.

Obsolescence – Reduced setup time and cost; no cost premium for a short manufacturing run. As mentioned above, Diminishing Manufacturing Sources/Material Shortages (DMS/MS) are a continuing issue, particularly in the aging vehicle fleets within the DoD. Many items can be easily printed "one-off" if the data is available or if a like item can be scanned. This approach would permit much quicker replacement at greatly reduced cost compared with reverse engineering and remanufacturing.

Recommended Way Forward

There is no longer any question regarding the value of 3D printing. It has survived the naysayers during its infancy just as previous disruptive technologies have. "I'll keep my horse." "Man was never meant to fly." Or the famous quote from the founder and CEO of Digital Equipment, Ken Olsen who said to the World Future Society in 1977, "*There is no reason for any individual to have a computer in his home.*" (Hornick, 2014)

Now the technology is in the early stages of going mainstream. But make no mistake, it is going there fast. Boeing, Airbus, Ford, GE, Pratt & Whitney are just a few of the large industrial firms using A/M every day. Small "start-ups" are finding innovative ways to leverage the unique capabilities. Forward looking government laboratories like Oak Ridge, Lawrence Livermore, NASA and DARPA are studying the technology. The Defense Department is approaching the subject from many angles. The Army uses a 3D printer in its Rapid Equipping Force. The Navy has installed 3D printers aboard at least one ship. Many new weapons systems coming on line in the near future will contain A/M components designed in to take advantage of their superior properties.

Dr. Khershed Cooper, Office of Naval Research (ONR) Program Officer writes:

> *"The benefits of AM to the Navy are plenty. The Navy and DoD are dealing with aging systems. Legacy systems are increasing in number and facing obsolescence. If a part breaks, we are faced with non-existent suppliers, unreliable foreign sources and unavailable drawings. In such a scenario it is possible to reverse engineer the damaged part and have a replacement produced by AM."* (Cooper, 2013)

Dr. Cooper goes on to advocate A/M as a means of mitigating excess inventory issues by stockpiling CAD files instead of parts. He sees the ability to remotely manufacture at the point of use as critical to Seabasing.

Additive Manufacturing is no longer a "science fair project." It is bringing unique value to many disparate endeavors. And the technology is exploding. Important new developments are announced weekly, sometimes daily. The possibilities are increasing exponentially. At this stage we cannot accurately judge all the uses to which it will be put. But we do know that it will be ubiquitous. Its potential impact on Marine Corps logistics will be enormous if used to its full capability. This will present a great opportunity as well as a daunting challenge.

A/M will provide applications that reduce costs, improve logistic responsiveness, facilitate Seabasing, and help enable Naval Logistics Integration. As the technology is incorporated into manufacturing and repair efforts, quality and durability will improve markedly. Service life will be extended and performance parameters will be increased.

In order to derive the greatest value from A/M as the technology matures, the Marine Corps must become involved in the guidance of this development, now. The Marine Corps is unlike the other services. Their requirements are often unique. The benefits of A/M promise to be even greater for the Marine Corps if development is properly managed.

In order to take advantage of this disruptive leap in technology, the Marine Corps must first conduct a detailed study of the current state of the industry particularly as it applies to the Marine Corps. This paper is merely an introduction written over a relatively short period of time. The industry is far more complex than the scope of this paper permits.

Once that study is complete, a mechanism must be established to continue to monitor industry development and assess its impact on the Marine Corps. This might be a small committee or an individual reporting to Headquarters, Marine Corps, Installation and Logistics. This is important because the rapid progress of the A/M industry will certainly take unpredictable turns as it moves forward, and the Marine Corps must be cognizant of these changes in order to take the maximum advantage of them.

Following that initial study, or in concert with it if possible, a Concept of Operations (ConOps) must be developed to define the ways in which A/M will be used. Also, a rigorous Business Case Analysis (BCA) must be conducted to demonstrate the overall value of the effort. Since it will be impossible to do everything at once, that ConOps should be prioritized based upon (1) the most immediate needs of the Marine Corps and (2) the Technology Readiness Level (TRL) of any specific A/M capability deemed useful. Because of the rapid progress of A/M technology, it should be understood that the ConOps and BCA will be living documents subject to frequent modifications and additions.

Finally, it must be understood the Additive Manufacturing / 3D Printing is the most disruptive technology since the assembly line. It promises the advent of a third Industrial Revolution. (The Economist, 2012) It is crucial that the Marine Corps participate.