AIR WAR COLLEGE

AIR UNIVERSITY

BUILDING A COMPETIVE EDGE

WITH

ADDITIVE MANUFACTURING

by

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And

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DISCLAIMER

Biographies

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Abstract

In a resource constrained environment, two major factors make it unlikely the United States will be properly equipped for its next war. First, the span of potential conflict ranges from counter-insurgency warfare to force-on-force confrontation with a technologically savvy peer competitor. It is impossible for the United States to optimize its force structure for every possible scenario. Second, the pace of technological change is accelerating. New and novel threat systems and technologies will proliferate faster than the United States can field systems to leverage and/or counter them. As a result, the United States military must be able to design, test, manufacture and field new weapons systems and technologies much faster than it can today. Resource constraints also drive a need for the Department of Defense to improve its ability to sustain its fielded systems and to cheaply and rapidly modify them to gain or maintain an advantage over its adversaries. Emerging manufacturing technologies like Additive Manufacturing can help the United States meet these challenges.

Additive Manufacturing is a term that describes a set of techniques used to convert a computer-generated design to a finished structure by assembling materials incrementally, one layer at a time. Additive Manufacturing techniques can be applied to a broad range of materials, including polymers (plastics), metals and organics. Additive Manufacturing allows users to build parts with virtually no waste of raw materials and without extensive machine set up. Consequently, Additive Manufacturing presents an opportunity to make radical changes to supply chain management, especially in the aerospace and defense industries. If the Department of Defense sufficiently embraces additive manufacturing, there is a potential to significantly reduce both the logistics footprint and the transportation requirements necessary to support deployed and home station operations. Equally important, Additive Manufacturing has the potential to dramatically improve rapid prototyping and Speed-to-Field for the military services. It can also help the Department of Defense reduce costs, eliminate waste and streamline its supply chain.

Equipping the Force for an Uncertain World

"There is the world that you would want, the world that you program to, and the world that actually happens…Every time we've tried to predict the world in the last century, we've been wrong."

Lieutenant General George J. Flynn
Director for Joint Force Development, The Joint Staff J-7
Address to the Air War College, 14 November 2012

In a resource constrained environment, it is unlikely the United States will be properly equipped for its next major conflict. The nation has a dismal record when it comes to predicting the nature of its next war. The country was poorly prepared for almost every one of its major military actions in the past century, to include World War I, World War II, Korea, Vietnam and, more recently, counter-insurgency operations in Iraq and Afghanistan. Operation DESERT STORM stands out as an exception to the rule, but even in that conflict, the United States was fortunate Saddam Hussein did not move aggressively against Saudi Arabia before the American military could move its forces into theater.

Predicting the nature of conflict over the next 20 years will be even more difficult. The span of potential action ranges from counter-insurgency warfare to force-on-force conflict with a technologically savvy peer-competitor, making it impossible for the United States to optimize its force structure to cover that full spectrum. Additionally, the rate of technological change is accelerating.[1] New and novel threat systems and technologies will proliferate faster than the United States can field systems to leverage and/or counter them.

Together, the uncertain nature of future conflict and the accelerating rate of technological change put the United States at significant risk of entering its next conflict poorly equipped for the fight at hand. It is possible, however, to mitigate this risk by developing the capability to rapidly design and produce new systems. Additive Manufacturing is a key emerging technology that could help the United States military maintain a competitive advantage by meeting the

Speed-to-Field dictates of the future. In addition, Additive Manufacturing can bolster the military's ability to efficiently sustain its fielded systems and, if necessary, modify them more quickly and more cheaply than possible with today's common practices. Additive Manufacturing can help the military reduce costs, eliminate waste and stream line its supply chain.

The Importance of Speed to Field

"The ability to learn faster than your competitors may be the only sustainable competitive advantage."

Arie De Geus
Corporate Planning Director, Royal Dutch Shell.[2]

During the Cold War, the United States had one enemy and could organize, train and equip its forces accordingly. The future will be different; there will likely be a broad range of potential competitors. In addition, the accelerating rate of technological change and the fusion of Genetics, Robotics and Nanotechnology[3] will drive rapid innovation and an ever-shifting landscape of threats. The ability to quickly field new systems (or modify existing ones) will likely be one of the major characteristics of a successful military. Furthermore, if the United States is able to demonstrate a robust rapid fielding capability, it could help preemptively deter enemies from developing new threats. Potential adversaries may decide that their competitive advantages would disappear too quickly to justify the cost of research and development for cutting edge systems. Regardless, the United States will not be able to predict the nature of its next conflict with enough accuracy to equip itself to guarantee success. Instead, the Department of Defense must develop the capability to field new equipment very rapidly, as the need becomes apparent.

There have been several studies inside and outside the Department of Defense focusing on the need to improve the department's ability to respond to urgent requirements. For instance, in the summer of 2008, the Defense Science Board prepared a report called “Capability Surprise” which focused on posturing the Department of Defense and its acquisition system to deal with the complexities of accelerating change and uncertainty. According to the Defense Science Board, today’s accelerating technology makes the threat environment increasingly dangerous as state and non-state actors have increasing capability to deliver strategic affects, either through the use of emerging technologies or the innovative application of current techniques. One of the aspects the board highlighted is that “rapid fielding of the same technology can create tremendous advantages to whoever fields the system first.”[4]

In the conclusion to its report, the Defense Science Board made five recommendations to the Department of Defense to help address surprise in the future. The recommendations addressed threat analysis, intelligence, management processes and the acquisition process. One of these recommendations was to streamline Rapid Fielding in order “to improve DoD capabilities for addressing priority surprise capability gaps and supporting urgent war fighter needs.”[5]

Additive Manufacturing is a capability that has the potential to directly address the requirements the Defense Science Board identified in its report. But it will not benefit America alone. Additive Manufacturing techniques will help a broad range of users (state and non-state) leverage new technology in relatively short periods of time with low barriers to entry. The nation or entity that can do this the fastest will have a competitive advantage.

In twentieth century conflicts, the United States enjoyed the advantage of being able to out-produce its enemies. America may not have that same edge in future conflicts with near-peer states. Even non-state actors may have significant capabilities to manufacture complex systems in low quantities. New technologies like Additive Manufacturing lower barriers to entry by reducing overhead investment required to create finished products.[6] In other words, the existence of the technology will be a double-edged sword. The United States must be prepared to leverage its advantages or risk significant disadvantage when competitors use Additive Manufacturing to their own benefit.

While Additive Manufacturing will be a potent tool to help improve Speed-to-Field, the advantages it offers in rapid prototyping, testing and production apply only to one small part of a much larger acquisition and logistics process. This paper will focus on the technology advantages Additive Manufacturing offers to the design, testing and fielding of new technology. It will also address some of the benefits Additive Manufacturing offers to sustaining, maintaining and modifying fielded systems. But any improvements in the aforementioned processes will need to be accompanied by parallel improvements in bureaucratic support systems that are beyond the scope of this paper.

Additive Manufacturing and How Can it Help the Department of Defense

"The revolution is not additive versus subtractive manufacturing; it is the ability to turn data into things and things into data."

Neil Gershenfeld, writing for Foreign Affairs[7]

Additive Manufacturing is a term that describes a set of techniques used to convert a computer-generated design to a finished structure by assembling materials incrementally, one layer at a time. Additive Manufacturing is a subset of a broader set of processes which all use computer modeling as their basis: Direct Digital Manufacturing (DDM).[8] In addition to Additive Manufacturing, Direct Digital Manufacturing covers two other processes: Subtractive Manufacturing and Hybrid Techniques.[9] Subtractive Manufacturing uses more traditional methods of removing materials from a mass to produce a part. Hybrid manufacturing combines elements of both of the above. This paper will focus exclusively on the promise of Additive

Manufacturing, but this focus is not intended to discount the value of other Direct Digital Manufacturing techniques.

Additive Manufacturing provides some unique advantages to designers and manufacturers. For instance, tooling costs are responsible for about 60 percent of the cost of building a new prototype.[10] But Additive Manufacturing allows prototypes to be constructed one layer at a time without retooling, so prototypes manufactured using this technology can be produced at greatly reduced cost. Such manufacturing also allows designers to explore the limits of design tolerance without fear of a lengthy and costly retooling process and enables designers to experiment with a broader range of prototypes.

Another major advantage is the elimination of waste.[11] For example, when working with metals, traditional techniques often require structures to be cut from much larger masses, leaving ample unused scrap. Figure 1 shows one of this paper's authors, Lt Col Earl Bennett, holding a C-5 End Fitting. The 30-pound part was cut from a 900-pound block of aluminum using Computer Numerical Control machines at the Warner Robins Air Logistics Complex. The process of manufacturing this part leaves 870 pounds of scrap aluminum shavings to be collected, processed to recapture cutting solvents, and compacted into soup can sized aluminum "pucks." Those pucks are then sold to a third party who conducts further reprocessing to convert the aluminum shavings back into usable materials. Time, energy, and fiscal resources are consumed at every step. Additive Manufacturing offers the potential for significant savings by eliminating or dramatically reducing scrap in this type of traditional manufacturing process. For example, researchers at the Georgia Institute of Technology developed an Additive Manufacturing process that enables industry to construct ceramic molds for complex metal parts using a 3D printing technique. The developers at Georgia Tech estimate the new technique could eliminate all of the traditional tooling requirements while simultaneously reducing cost 25 percent and reducing waste 90 percent.[12]

Figure 1: C-5 End Fitting and Machine Waste

In addition, Additive Manufacturing enables designers to build complex objects without additional cost. In essence, complexity is free. Aircraft structures are an excellent example. Maximizing strength and minimizing weight often requires intricate structures that are difficult, or even impossible, to construct using traditional manufacturing techniques, yet Additive Manufacturing can build these types of structures very easily.

A third advantage lies in the incredible flexibility it provides to the manufacturing process. Unlike traditional mass manufacturing, Additive Manufacturing enables users to construct a wide variety of objects, with significant variance in shape, without any retooling. Changing designs and shapes is simply a matter of changing the code in the Computer-Aided Design model. Additionally, this technologies can provide significant reductions in energy consumption. Industry advocates have reported the Department of Energy hopes to leverage the technology to cut the energy consumed by American manufacturing in half in the next decade.[13]

A more subtle advantage of Additive Manufacturing lies in its ability to help sustain legacy systems. For example, the United States Air Force operates a fleet of aircraft today that averages 22 years for fighters, 35 years for bombers, and 47 years for tankers.[14] Maintaining and operating this aging fleet of aircraft has been, and will continue to be, a significant challenge. Roughly half of the Air Force's $110.1 billion budget request for fiscal year 2013 is dedicated to weapons system support, operations and maintenance of current equipment.[15]

In the coming decades, all of the military services are likely to face continuing fiscal pressures in order to help balance the federal budget. For the Air Force, these budgetary pressures will preclude significant increases in funding for new acquisitions, forcing the service to operate its weapons systems well beyond their designed longevity. For example, the Air Force's last B-52H was produced in 1962.[16] At the time, the Air Force Chief of Staff, General Thomas White, anticipated the aircraft would have a service life of approximately eight years.[17] Yet the B-52H is still in service today, over fifty years later! Given this challenging environment, the Air Force and its sister services need to exploit new technologies in order to project power without bankrupting the nation. Additive Manufacturing can be leveraged to repair and sustain aging systems faster and cheaper than traditional processes.

Procuring spare parts for a system like the B-52, whose production line has long been closed, can be a daunting challenge. Spare parts simply are not available and must be reengineered. Additive Manufacturing tackles this reengineering challenge by using three dimensional scanners to "map" the desired part creating a design plan. This digital plan can then be transferred to an Additive Manufacturing machine to either produce the part directly or to produce a detailed model to expedite follow-on construction using traditional manufacturing techniques. Either technique offers significant reductions in both time and expense for an otherwise lengthy process.

Finally, Additive Manufacturing has the potential to significantly impact the industrial base. Since the end of the cold war, the number of American manufacturers who could build sophisticated systems like aircraft and ships has been shrinking. While Additive Manufacturing is unlikely to hold the key to turning a kitchen appliance factory into a shipyard, it may indeed return a great deal of flexibility to manufacturers in the United States. In World War II, American factories designed to make cars and other domestic products quickly retooled to produce planes, tanks and ships; the processes where similar enough to enable such a transition. Today, military equipment tends to be much more sophisticated and often requires specialized machinery. But, as industry adopts Additive Manufacturing processes, a broader range of domestic manufacturers may be able to shift their focus from domestic to military production when circumstances require.

In summary, Additive Manufacturing has the potential to reduce or eliminate re-tooling costs, enable rapid prototyping, help reengineer out-of-production parts and cut waste. It may also deliver significant energy savings, facilitate complex designs and significantly accelerate Speed-to-Field. All of these advantages help the United States military overcome resource constraints and gain significant competitive advantage against state and non-state competitors.

Current Status

There are several different types of Additive Manufacturing processes to include 3D printing and Additive Beam Techniques.[18] Most techniques are specific to certain classes of materials. For instance, Laser Engineered Net Shaping (LENS) is a process used to work with metals. Production-quality parts are fabricated one layer at a time by injecting metal powders into a laser beam. In contrast, Fused Deposition Modeling is a technique used to work with plastics or other materials with similar melting points, like Casting Wax (used to make molds) or

Elastomer (used to make flexible parts such as tubes). In Fused Deposition Modeling, materials are heated to a semi-liquid state and deposited, layer-by-layer, through a deposition head, much like a common ink-jet printer.

Example Additive Manufacturing Techniques[19]	
3D Printing	**Additive Beam**
Stereolithography (SLA)	Direct Metal Laser Sintering (DMLS)
3D Ink-Jet Printing	Direct Metal Deposition (DMD); (also known as Laser Engineered Nets Shaping (LENS)[20]
Fused Deposition Modeling (FDM)	Electron Beam Melting/Free Form Fabrication
	Selective Laser Sintering (SLS)

Figure 2: Example Additive Manufacturing Techniques

Although rapid prototyping is one of the great areas of promise for Additive Manufacturing, the technology is still underdeveloped in many ways. Some of the most promising techniques for working with metals also require significant pre- and post-manufacturing processing time like heat treating and polishing. These pre- and post-manufacturing requirements can account for as much as 80% of total production time.[21]

In 2011, the Air Force Research Laboratories (AFRL) completed an extensive technological review of Direct Digital Manufacturing techniques, including Additive Manufacturing. The review found advantages and disadvantages to several techniques. For example, 3D printing techniques were excellent for prototyping but generally did not produce products durable enough for field use.[22] Conversely, many additive beam processes capable of working with robust specialty metals were limited in the size of the parts they could produce, had slow deposition rates, and/or required significant post production machining to bring the parts into tolerance.[23] Another limitation of Additive Manufacturing is that, in most cases, traditional mass production manufacturing techniques are more economical for large quantities.[24]

Still, there is a lot of promise, even with current technology. Manufacturers are pushing the envelope on a daily basis. One area of investigation is printing circuitry. Companies are exploring ways to imbed electronics directly into to structures using 3D printers. One company, Optomec, partnered with an Unmanned Aerial Vehicle producer and a 3D printing company to design and produce a "smart wing" for a small drone.[25] This enabled the company to imbed sensors and other electronics directly into the frame of the aircraft. The company's concept is to generate the capability to produce small drones customized for their missions on demand.[26]

The ability to use Additive Manufacturing to imbed electronics into "printed" objects has the potential to greatly improve the design and flexibility of a myriad of systems, but producing microchips is still out of reach for current Additive Manufacturing technology.[27] Such a capability would be a major step towards moving Additive Manufacturing techniques from prototyping or parts production to manufacturing complex systems. Still, there are ample other novel applications for Additive Manufacturing outside of the industrial sector, including regenerative medicine.

The Biomedical Nanotechnology Laboratory at University of California San Diego recently demonstrated the capability to print synthetic, biocompatible blood vessels using a 3D printing technique called Dynamic Optical Projection Stereolithography (DOPsL).[28] This is just one of many explorations researchers are making in the applications of Additive Manufacturing into regenerative medical technologies. Other areas include "printing" skin and organs.[29]

Medical applications in development today demonstrate that Additive Manufacturing offers more than a possible means for getting new technologies and replacement parts to the battlefield; its potential to improve regenerative medicine will not only save lives and limbs, it will help return trained and experienced warriors to the battlefield by vastly improving the military's ability to treat wartime injuries.

In AFRL's 2011 assessment of Advanced Manufacturing Technologies, the study concluded:

> *"Overall, the additive manufacturing technologies are in an early stage of technical development and making a transition from prototyping to production. This transition is occurring in private industry through the design and testing of parts across many industries. There is a significant amount of continued development required for full qualification into critical applications. This transition will occur over the next ten years as the technical challenges continue to be solved."*[30]

Challenges

Additive manufacturing has ample potential, but there are still significant challenges to overcome before the technology can expand significantly beyond certain niche areas such as form-factor prototyping and low-rate production of very specialized parts. The first major challenge is material science. Manufacturers simply do not know enough about the properties of objects produced by using Additive Manufacturing machines to have the confidence to use them as structural parts. For example, in traditional manufacturing, metal structural parts are made by pouring, shaping or cutting. Additive manufacturing is radically different: parts produced on Additive Manufacturing machines are fused together one layer at a time in a process roughly analogous to assembling an object using 10,000 welds.[31] Manufactures need to understand what this process means in terms of the microstructure, residual stress and thermal effects.[32] More simply put, they need to know if an Additive Manufacturing part will be as good as a conventionally produced part, and if not, how it will vary.[33] Powders in particular are subject to exposure to oxygen and moisture. There need to be guidelines for storage, transportation and handling of raw materials. There needs to be established standards for processing them along with a good understanding of the end products of materials produced by such techniques. Right now, the limited material science research that has been done by private industry is largely guarded as proprietary information.[34] Industry insiders say to be truly viable, every material needs to have Design Allowable Data so that materials are fully characterized and parts can be designed accordingly.[35]

The second major challenge for Additive Manufacturing is in-process controls and part certification protocols. Many of the current commercial machines operate on fixed settings and are essentially "dumb."[36] The user feeds the program into the machine and it goes through the motions to build a part, layer by layer. Each new layer creates the opportunity to introduce a mistake, but there is no feedback mechanism in the process to identify flaws and either abort the build or correct errors in real time.[37] Simply jarring a machine once during manufacturing could theoretically ruin a part that took hours to build. In process controls could help detect and correct such flaws and are of even greater significance for users who are trying to print functional components rather than prototypes used simply for form factor.

Even if material science and in-process control issues can be solved, Additive Manufacturing still faces a major hurdle. In general, it is not as cost effective as traditional manufacturing methods for large-batch production.[38] Part of the reason lies in the limitations of present-day Additive Manufacturing machinery. Most use either single laser beams or single deposition heads to construct objects. The machinery is expensive and output is slow. To compete with traditional manufacturing, the ratio of productivity to capital cost must improve.[39]

Dr. Suman Das, Director of the Direct Digital Manufacturing Laboratory at the Georgia Institute of Technology, envisions the true benefits of additive manufacturing reaching fruition when parallel processes are developed and utilized. One possibility is a machine with multiple deposition heads laying down material simultaneously on a part in three dimensions to achieve almost the same rates of production possible with injection molding or metal castings without having to make the molds.[40] This will only add complexity to the process controls needed to produce defect-free parts.[41]

To address these issues, the United States government is engaged in a broader effort to bolster Additive Manufacturing technology. The Department of Defense, with the Air Force as the executive agent, is leading an effort to open a pilot manufacturing center focused on furthering Additive Manufacturing technology. The Department of Energy is the other principle financial contributor to the $45M effort.[42] Additional partners will include the National Aeronautics and Space Administration and the National Institute of Standards and Technology. The goal of the pilot facility is to "bring together large and small companies, academia, federal agencies and the states to accelerate innovation by investing in industrially-relevant manufacturing technologies."[43] The center is called the National Additive Manufacturing Innovation Institute (NAMII) with a mission is to "accelerate additive manufacturing technologies to the U.S. manufacturing sector and increase domestic manufacturing competitiveness" by fostering cooperation, innovation, information sharing, development, deployment and education in Additive Manufacturing technologies.[44] The institute will help the Department of Defense partner with academia and industry to expand the business case for Additive Manufacturing technologies, broaden the scope and address some of the challenges the technology faces.

The Defense Advanced Research Project Agency (DARPA) is also involved in this effort, supporting an Open Manufacturing Program looking for ways to insert new technology into industry by identifying problem areas; Additive Manufacturing is one of those areas.[45] They also partnered with Pennsylvania State University's Applied Research Lab to establish a

Manufacturing Demonstration Facility at the university. This facility is part of the National Additive Manufacturing Innovation Institute with a goal to make the facility a curator for process models and qualification schemes. The facility will store information, take new inputs from anyone who wants to contribute, and compare them to established processes, making the data available to industry. For now, the data is open only to U.S. industry and government, but that may broaden by necessity once the Defense Advanced Research Project Agency stops funding the project, requiring it to become self-sufficient.[46]

Service Implementation: An Air Force Example

Examining how Additive Manufacturing might be leveraged in the United States Air Force provides an excellent example of how it can benefit all of the military services. Given the Air Force's aging fleet of aircraft, Additive Manufacturing is a near perfect fit for the service as it struggles to continue operating aircraft approaching forty to fifty years in age. This approach can be used to produce replacement parts cheaply and quickly. In addition, the Air Force must still project power around the globe. Often this involves deploying packages of aircraft into austere environments several thousand miles from their bases in the United States. Traditionally, the Air Force has relied on a massive logistics machine to forecast spare parts and consumable requirements. These forecasts are used to build and tailor kits with every conceivable spare part which are then moved at considerable expense halfway around the world. But no forecast is ever perfect, and units often need parts that were not included or parts they did not need. When spares are not available, the backup plans involve either cannibalizing parts from another aircraft in theater or relying on extensive and expensive transportation networks to ship parts as fast as possible to the needed location. Conceivably, Additive Manufacturing could provide a partial solution to this dilemma.

In the next two decades, Additive Manufacturing technology should have advanced sufficiently to allow small deployable factories to move closer to the operating units. These factories could network into the Computer Aided Design (CAD)/Computer Aided Model (CAM) processes driven by the program offices and Air Logistics Complexes (ALCs) in the United States. They would be able to produce a significant number of replacement parts directly from the CAD data in theater. Instead of moving massive amounts of parts that are never used and running short of parts that were not envisioned to fail, factories would produce what is needed much closer to the point of use. These factories could also be placed on ships to allow them to easily move from theater to theater. Raw materials could be carried in sufficient quantities on the ships, obtained locally, or mined from waste streams in theater. Additionally, Additive Manufacturing cuts the amount of raw materials needed by up to 95 percent, slashing the amount of things required to move significantly. Not every aircraft part is a good candidate for this process, but even a 30 to 40 percent reduction in kit size would be a substantial savings.

Like any new technology, Additive Manufacturing is not without its risks or potential downfalls. For example, aircraft parts must be certified flight worthy by the appropriate engineering authority. Currently, these parts are controlled through the Department of Defense supply chain to ensure only serviceable, airworthy parts are installed on aircraft. A process would need to be developed to certify these manufactured parts before they can be installed on an aircraft. Fortunately, a process already exists at the ALCs to certify reverse engineered parts prior to placing them into service.[47] In this case, the ALCs produce the parts in accordance with approved engineering data on approved machines using approved materials. It would not be a large stretch to adopt a similar process for forward deployed factories. The factories would only use certified engineering data and manufacturing processes to produce parts. Additionally, they would require a small onsite engineering team to ensure proper materials are used and to ensure compliance with engineering specifications.

A second challenge to expanding Additive Manufacturing across the Air Force is access to raw materials. Obviously, any factory is useless without access to the materials needed to produce parts. Although this is a potential problem area, one of Additive Manufacturing's clear advantages is the significant reduction in the amount of material wasted in making components. Additionally, raw materials are often traded as commodities across the globe. Given this fact, it is not difficult to envision buying materials in a theater from local sources. This would not be viable for every required material, but would mitigate risk. Given the smaller amounts of materials needed to support additive manufacturing, the factories would also potentially be able to mine their own waste stream as well as the waste stream of deployed operations in order to access some raw materials. This has the added benefit of reducing the amount of material requiring disposal or retrograde shipment back to the United States. Finally, small amounts of critical materials such as rare earth minerals could be stored with the factory or resupplied by air or ship to ensure continued production.

Two final concerns with Additive Manufacturing are intellectual property rights and computer network access. It is not possible to manufacture parts without data. Either CAD data should already be on file for parts in a library or the part must be reverse engineered by scanning its dimensions into a file and manipulating the data. Either of these methods will generate risk either by total reliance on computer connectivity and security, or by potential legal issues with intellectual property rights. Although the reliance on computer networks will also be a vulnerability to additive manufacturing factories, this is the way of future warfare. Even today, military operations are reliant on network connectivity and security especially for intelligence sharing and command and control. In the future, this will increase and deployed factories will benefit from the same network the military must build and secure. Additionally, most Additive Manufacturing machine manufacturers currently limit their machines to only run proprietary materials. This business model is very similar to that used by ink jet printer manufactures who sell the machine for a reasonable price in order to hook a client for the long haul with the ink cartridges. This model can frustrate end users who are forced to hack and modify the machines once they buy them to run alternate materials if such materials are required to meet their unique manufacturing needs.[48]

Given the obvious potential advantages of Additive Manufacturing coupled with the Air Force's unique challenges of operating aging aircraft across the globe, what would be an ideal implementation across the Air Force? The ALCs are already embracing additive manufacturing, and this will most likely accelerate. However, implementing Additive Manufacturing in the field or at deployed locations is another story. Given the Air Force's current two level concept of maintenance, most heavy maintenance and component repair/fabrication occurs at the three ALCs or contract facilities. Spreading Additive Manufacturing across the Air Force outside the ALCs would require significant changes in how the Air Force operates.

The ALCs are very busy manufacturing and repairing structural parts, engines, avionics parts, and numerous other components to keep aging aircraft viable. For example, Warner Robins Air Logistics Center (WRALC), boasts a large machine shop with scores of metal and plastic fabrication machines ranging from drill presses and lathes to several giant Computer Numerical Control (CNC) machines that would fill a small three bedroom house. These machines run constantly producing parts that civilian industry is often not interested in making due to diminishing and irregular demand. The engineers and technicians at WRALC see incredible promise for the technology to reduce time and effort in producing prototypes and even components in the near future.[49] The largest obstacle to rapid implementation of Additive Manufacturing is the requirement to justify capital expenditure for the machines based on a lifetime cost of ownership. Additionally, government procurement regulations and annual budgeting processes may also contribute to a slower implementation of Additive Manufacturing at the ALCs. Regardless of these natural friction points, WRALC is pressing forward with using its new 3D printers to prototype several aircraft parts to check for fit prior to manufacturing the finished parts. As bureaucratic obstacles are pushed aside and the existing machines begin to show more uses and savings, the ALCs will benefit from increased capability allowing faster aircraft and component repairs at lower costs.

Although the ALCs have started to embrace Additive Manufacturing, implementation in the field and at deployed locations is another matter. Over the past 20 to 30 years, the Air Force has migrated to a two level concept of maintenance. In the past, Air Force field level units possessed a fairly robust back shop capability to repair and fabricate aircraft components on base.[50] In an effort to save money, most field units now perform only servicing and remove/replace bad components, which are sent to the ALCs for repair. Vast improvements in the transportation infrastructure have made this a viable concept. However, given the lower cost of entry and increasing age of Air Force aircraft, it may be time to revisit this concept. One of the most promising aspects of Additive Manufacturing is the ability to produce small lot sizes of parts without expensive and time consuming tooling and set up. As a result, one or two Additive Manufacturing machines might be able to compete with traditional machine shops and produce custom parts from CAD data increasing the amount of work in the field versus the depot while reducing the amount of resources spent on transportation. This effort would require significant coordination between engineers, system program offices and field units. Even if manufacture of some aircraft components could be distributed to the field, program offices would need to develop and maintain data packages as well as certify manufacturing processes.

Another concern is raw material certification and storage. Although there is significant work underway in this arena, there is a long way to go towards developing industry wide standards for materials designed for use with Additive Manufacturing. For example, the aerospace industry has developed standard alloys for use on machining centers that are accepted across the board and all material properties are well known. Until a similar system is fully developed for Additive Manufacturing, engineers will have to invest considerable effort testing and designing each new part built.[51]

Solutions to all these challenges are available so that in the future, it will be possible to forward position additive manufacturing shops in order to build replacement parts either at operating bases or deployed locations. By forward deploying mobile manufacturing centers, the Air Force may be able to significantly reduce the amount of parts and equipment stockpiled and shipped to forward operating locations. If Additive Manufacturing factories can be forward deployed closer to the operational units, it will be possible to significantly reduce the amount of items required to deploy and improve mission readiness rates.

Charting the Future of Additive Manufacturing

"Today, AM techniques are primarily suited for prototyping, small parts production, tooling, and small scale reverse engineering. But more mature technology will deliver new and vibrant capabilities."

The Economist, July 28th, 2012 [52]

"The military is a sizable potential market for parts made using additive manufacturing techniques, given that it has low-volume purchases, and it deals constantly with problems of obsolescence."

Richard A. McCormack

Manufacturing and Technology News, April 30, 2012[53]

No future is certain, but reviewing the current state of Additive Manufacturing technology and literature about its future trajectory makes it possible to project potential trends for the technology. None of these capabilities is guaranteed, but all seem well within the realm of reality.

The near future: 5-10 years

- In the commercial sector, there will be a focus on incorporating Additive Manufacturing techniques into aerospace applications, consumer products, medical implants, and distributed manufacturing.[54] The Department of Defense should parallel and leverage these efforts in order to lower costs and/or improve designs for aircraft, bolster care of wounded warriors and explore the possibilities of limited parts production at forward locations.
- There will be sufficient material understanding and process controls to begin limited manufacturing of structural parts using Additive Manufacturing techniques.[55] The Air Force, for example, can leverage these advances to improve the design and manufacturing of items like aircraft wing spars, engine turbine blades, and gun barrels.
- Technology should mature to the point that industry can produce hybrid manufacturing machines that leverage the capabilities of multiple Additive Manufacturing technologies in addition to subtractive manufacturing techniques.[56] These machines could be capable of producing complex parts made of multiple types of materials, to include large sections of aircraft or vehicles.
- There will be 3D printers capable of embedding circuitry and antennas into casings for electronic devices. Machines like these will enable designers to free up room in traditional form factors for even more advanced capabilities.[57] One potential application for this technology is to open space for additional sensor payloads in current Unmanned Aerial Vehicle designs.

On the horizon: 10-20 years

- It will be possible to print functional assemblies of multiple parts.[58] This will provide the Department of Defense, working with industry, vastly accelerated capabilities in rapid prototyping and short-notice production of small batch quantity machines.
- Decreasing costs will help popularize basic household Additive Manufacturing machines, primarily designed to work with plastics or other polymers. The world will enter an era of personalized Additive Manufacturing.[59]
- There may be programs and machines designed to "print food." [60] This technology could help reduce labor requirements at dining facilities in forward-deployed locations and, if sufficiently mature, may help improve moral for military members.
- The military should have, by this point, developed process controls and protocols sufficient to enable rapid production and quality certification of replacement parts for out-of-production systems. This will enable significant cost and time savings; it will also enable the military to extend the service life of a myriad of older systems.

Over the Horizon: greater than 20 years

- Additive Manufacturing will enable the production of very large and complex objects, to include complete systems or subsystems.
- Additive Manufacturing techniques will make it possible to produce replacement organs. This will enable the military services to retain service members who would have otherwise been forced to leave the military due to severe illness, disease or injury; more importantly, it will save lives.

Implications for the Department of Defense

The future capabilities outlined above are not a given. The Department of Defense must actively monitor the progress of this technology and partner with industry to help it advance in areas where a clear business case does not yet exist. To make these types of benefits a reality, the Department of Defense must continue to fund research efforts through mechanisms such as the National Additive Manufacturing Innovation Institute (NAMII) and the Open Manufacturing Program in order to advance Additive Manufacturing technology by:

- Advancing material science and building a database of Design Allowable Data Developing and refining Process Controls and Quality Certification Standards
- Shifting the "economy of scale" break-even point for Additive Manufacturing techniques further to the right by developing parallel processes (multiple beams or deposition heads)
- Encouraging engineers to design systems specifically to be manufactured using Additive Manufacturing techniques
- Purchasing CAD drawings and material specification for replacement parts when acquiring new systems

If successfully developed, these expanding technological capabilities have several major implications for defense acquisitions. First, it will be possible to design and produce complex prototypes at a much cheaper price. If the Department of Defense is successful in streamlining some of the major bureaucratic roadblocks in its acquisition process, the department will be able to leverage Additive Manufacturing technology to respond to new threats in a very rapid manner. Second, the military services will be able to design systems specifically so that they have the option to use Additive Manufacturing to "print" replacement parts. It will be feasible to structure supply chains such that it is possible to produce parts and equipment at forward locations using Additive Manufacturing technology. This sort of capability may not be required in a state-side/in garrison environment, but could be a huge force multiplier in forward-deployed locations, especially if supply lines are threatened. The Air Force, for example, would be able to reduce bulk on supply runs by bringing in raw materials for certain high-demand aircraft parts and "printing" spares on an as-needed basis. In the rear, the medical benefits of Additive Manufacturing will return wounded soldiers, sailors, airmen and marines to the battlefield much more quickly through the regenerative medical benefits of this growing technological field.

Conclusion

There is no guarantee what the international environment will look like in the next five years, let alone the next twenty. The world may see a resurgence of mercantilism, or new alliances may form to challenge the hegemony of the West. The potential range of possibilities is endless, but regardless of what the future holds, Additive Manufacturing promises capabilities that can deliver a competitive advantage in rapid prototyping, Speed-to-Field, distributed logistics, regenerative medicine and legacy sustainment. The Department of Defense must be actively engaged in developing this technology.

Additive Manufacturing appears to offer the opportunity to revolutionize manufacturing across the board. However, like any new technology it is important to separate the hype from the reality.[61] The amount of infrastructure devoted to traditional manufacturing techniques and supply chain management is colossal. This infrastructure has been built over the past century, and although there may be better ways of making things on the horizon, the current infrastructure has served industry and the Department of Defense well. Additionally, Additive Manufacturing may well require a near revolution in material sciences, engineering, and supply chain management to realize its full potential. Each of these fields already has a well-established culture, and shifting towards a revolutionary new way of making things will require significant effort and leadership. Admittedly, the United States will need to invest considerable effort and resources to establish accepted industry standards for materials and additive manufacturing processes. However, once these are established this technology holds considerable promise, and other nations are already leaning forward to embrace this capability.

Additive Manufacturing and the changes to designs it enables will allow engineers to reduce weight and build complex shapes that are not possible with current methods.

Additionally, the potential revolution in supply chain management that Additive Manufacturing may spark offers the promise of significantly reducing the amount of material required to support both home-station and deployed operations for all military services. The United States appears unwilling to cede its global influence to rising powers without a challenge, and maintaining this premier role in a changing world despite increasing fiscal constraints will be a significant challenge in the coming decades. Additive Manufacturing and the corresponding changes in supply chain management and deployed operations certainly offer promise to enable the Department of Defense to project power into contested environments. Combined with other emerging technologies, Additive Manufacturing appears to offer enough promise to justify increased DoD investment and potential changes to supply chain management over the coming years. This investment also appears to offer a creative means to achieve United States goals of continued global influence in a more contested environment with significant fiscal restraints on military spending.

Notes

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