AIR WAR COLLEGE

AIR UNIVERSITY

BUILDING A COMPETITIVE EDGE

WITH

ADDITIVE MANUFACTURING

by

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Biography

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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 (DoD) 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 has the potential to dramatically improve rapid prototyping and Speed-to-Field for all 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, J-7, Joint Staff
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, 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. It is impossible for the United States to optimize its force structure to cover the 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 unprepared for the fight at hand. It is possible, however, to mitigate this risk. Speed-to-Field with new, modified or replacement systems may be a major criteria for military success in the future. Additive Manufacturing is a key emerging technology that could help the United States military to 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 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 this sort of rapid fielding capability, it will 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 in the today's complex threat environment. 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 use of emerging technologies or innovative applications of current technologies. 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 acquisitions 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/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 smaller states or 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 re-tooling, so prototypes manufactured using this technology can be produced at greatly reduced cost. The lack of a requirement for tooling also allows designers to explore the limits of design tolerance without fear of a lengthy and costly retooling process. This also enables designers to experiment with a broader range of prototypes.

Another major advantage of Additive Manufacturing is the elimination of waste.[11] For example, when working with metals, more traditional techniques often require structures to be cut from much larger masses, leaving ample unused scrap. The 30-pound C-5 End fitting shown in Figure 1 was cut from a 900-pound block of aluminum using Computer Numerical Control machines at the Warner Robins Logistics Center. 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 funds 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 enabling industry to construct ceramic molds for complex metal parts using a 3D printing technique. They estimate the new technique could eliminate all of the traditional tooling requirements while simultaneously reducing cost 25 percent and reducing waste 90 percent.

Figure 1: C-5 End Fitting and Machine Waste

Another advantage is that 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 can require complex 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 Additive Manufacturing 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, Additive Manufacturing technologies may 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.[12]

Another advantage of Additive Manufacturing lies in its ability to help sustain legacy systems. Additive Manufacturing can be leveraged to repair aging systems much faster than traditional processes. For example, the Air Force's last B-52H was produced in 1962.[13] At the time, Air Force Chief of Staff General Thomas White anticipated the aircraft would have a service life of approximately eight years.[14] Yet the B-52H is still in service today, over fifty years later.

Procuring spare parts for a system like the B-52, whose production line has long been closed, can be a daunting challenge. Sometimes spare parts simply aren't available; instead, they have to be reengineered. Additive Manufacturing has the potential to cut significant time from the reengineering process. Engineers use a three dimensional scanner to "map" the desired part, creating a design plan which can 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 can cut significant time and expense in an otherwise lengthy processes.

A final advantage for Additive Manufacturing is its potential impact on the industrial base. Since the cold war, the number of 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 the industrial base in the United States. In World War II, the 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 transition. Today, military equipment tends to be much more sophisticated and to require specialized machinery, but as industry adopts Additive Manufacturing processes, one side benefit may be to restore flexibility to the industrial base. In the future, a broader range of domestic manufacturers may be able to shift focus their focus from domestic to military production if 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 could help the United States military overcome resource constraints to gain significant competitive advantage against state and non-state competitors.

The State of the Art

Additive techniques have shown promise as a means of fabrication with metals, polymers and organic materials. There are several different types of Additive Manufacturing processes. They include 3D printing and Additive Beam Techniques.[15]

Most Additive Manufacturing 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 contract, 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 like tubes). In Fused Deposition Modeling, materials are heated to a semi-liquid state and deposited, layer-by-layer, through a deposition head, much like domestic ink-jet printer.

Example Additive Manufacturing Techniques[16]	
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)[17]
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—heat treating and polishing, for example. These pre- and post-manufacturing requirements can account for as much as 80% of total production time.[18]

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.[19] 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.[20] Another limitation of Additive Manufacturing is that, in most cases, traditional mass production manufacturing techniques are more economical for large batch quantities.[21]

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 a Unmanned Aircraft System producer and a 3D printing company to design and produce a "smart wing" for a small drone.[22] 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.[23] 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.[24] Such a capability would be a major step towards moving Additive Manufacturing techniques from prototyping or parts production 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—but biocompatible—blood vessels using a 3D printing technique called Dynamic Optical Projection Stereolithography (DOPsL).[25] This is just one of many explorations researchers are making into the applications of Additive Manufacturing technologies into regenerative medical technologies. Other endeavors include "printing" skin and organs.[26]

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 experience experts 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."*[27]

Additive Manufacturing's 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 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. Manufactures need to understand what this process means in terms of the microstructure, residual stress and thermal effects. More simply put, manufactures need to know if an AM part will be as good as a conventionally produced part, and if not, how it will vary.[28] 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 need established standards for processing them along with a good understanding of the end products of materials produced by different Additive Manufacturing techniques. Right now, the limited material science research that has been done by private industry is largely guarded as proprietary information.[29] 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.[30]

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.”[31] 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. 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; they are of even greater significant for users that 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. Part of the reason is 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.[32] Future machines will need to be massively parallel with multiple beams or multiple deposition heads. This will only add complexity to the process controls needed to produce defect-free parts.[33]

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.[34] 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."[35] The center is called the National Additive Manufacturing Innovation Institute (NAMII). Its 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.[36]

The institute will help the Department of Defense partner with academia and industry to expand the business case for AM technologies, broaden the scope of Additive Manufacturing capabilities 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. 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. The goal is 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.

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 [37]

"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[38]

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.[39] 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.[40] 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 subtractive manufacturing techniques.[41] 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 designer to free up room in traditional form factors for even more advanced capabilities.[42] 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.[43] 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.[44]
- There may be programs and machines designed to "print food." [45] 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; when acquiring new systems, purchase CAD drawings and material specification for replacement parts

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 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 could 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.

Notes

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