Marine with Combat Logistics Battalion 31, 31st Marine Expeditionary Unit, prepares to print 3D model aboard USS *Wasp* while underway in Pacific Ocean, April 7, 2018 (U.S. Marine Corps/Bernadette Wildes)

Additive Manufacturing

Shaping the Sustainment Battlespace

By Michael Kidd, Angela Quinn, and Andres Munera

There is widespread interest and a level of euphoria surrounding the potential benefits of bringing additive manufacturing (also known as three-dimensional printing [3D printing]) to the military logistics tool kit. The technology has tremendous potential, with new uses being demonstrated weekly. In addition to mundane items such as novelty bottle openers, the Navy recently printed a carbon fiber submersible.[1] The Defense Logistics Agency is working with industry to print hard-to-source parts and is experimenting with printed food—and printed human organs are finding their way into the medical field.[2] It is important, however, to fully understand the enabling factors that will make the technology a useful part of the Department of Defense (DOD) supply chain and not simply an impressive application that ends up at best a fleeting initiative, and at worst an incredible drain on scarce resources and a public embarrassment.

Additive manufacturing and the ability to create single- or small-batch runs of parts should be managed carefully to ensure that this technology is deployed as a force multiplier versus a niche program with limited readiness impacts. Initial pilot programs are in place across several

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of the Services to provide feedback on how this equipment is working in the field. Specifically, the Army Breaching Tools, 3D printers on deployed aircraft carriers, and mobile radio solutions provide insight into the use of this technology, as they are already fielding additively manufactured resources.[3] While these programs have tapped into the innovative spirit of Servicemembers to solve unit-level problems, they have not yet provided enterprise solutions to sustain critical systems.

With an understanding of the potential positive results such as cost avoidance, reduced inventories, and time to deliver, as well as the challenges of implementation, acquisition and sustainment programs can transition DOD 3D printing capabilities into readiness multipliers. Additionally, updates to guidance are required to ensure officials are actively shrinking the supply chain through investments in additive manufacturing and just-in-time manufacturing as part of their overall acquisition strategy. Focusing on the manufacture of parts to increase systems sustainability, we examine costs and cost avoidance, supportability, and technical limitations in order to develop constructs for when to implement at various levels. The current DOD roadmap concentrates on technology development rather than enabling factors.[4] Therefore, this article identifies those factors that contribute to a methodical approach to additive manufacturing in support of DOD sustainment.

Industry Overview

Additive manufacturing uses several methods to produce exceptionally thin layers of material that are stacked on top of each other (added) and then fused together using a power source to create 3D items. Conversely, many traditional manufacturing methods like casting and forging are subtractive, removing excess material and creating waste in the production process.[5] Though still an emerging technology, 3D printing has several advantages over traditional methods of production. For instance, the micron-thin width of successive layers allows the creation of geometries not formerly possible.[6] Also, advances in material and bonding of layers create higher end quality-controlled products that include critical high-significance items such as aviation valves whose failure could have catastrophic consequences.

Significant technological advances in 3D printing have occurred over the past several years. In the decades before 3D printing, prototypes were designed using modeling techniques, or low production runs, which were expensive and time consuming. Today, with the use of computer-aided design (CAD) techniques, additive manufacturing is capable of producing prototypes, and even fully capable items, faster and at lower costs, allowing for rapid development of technologies. As the technology matures, there is a shift from merely a prototyping niche, morphing into low production runs, to large batch runs. Industry wide, 3D printers are now producing nearly one-third of items for end use.[7]

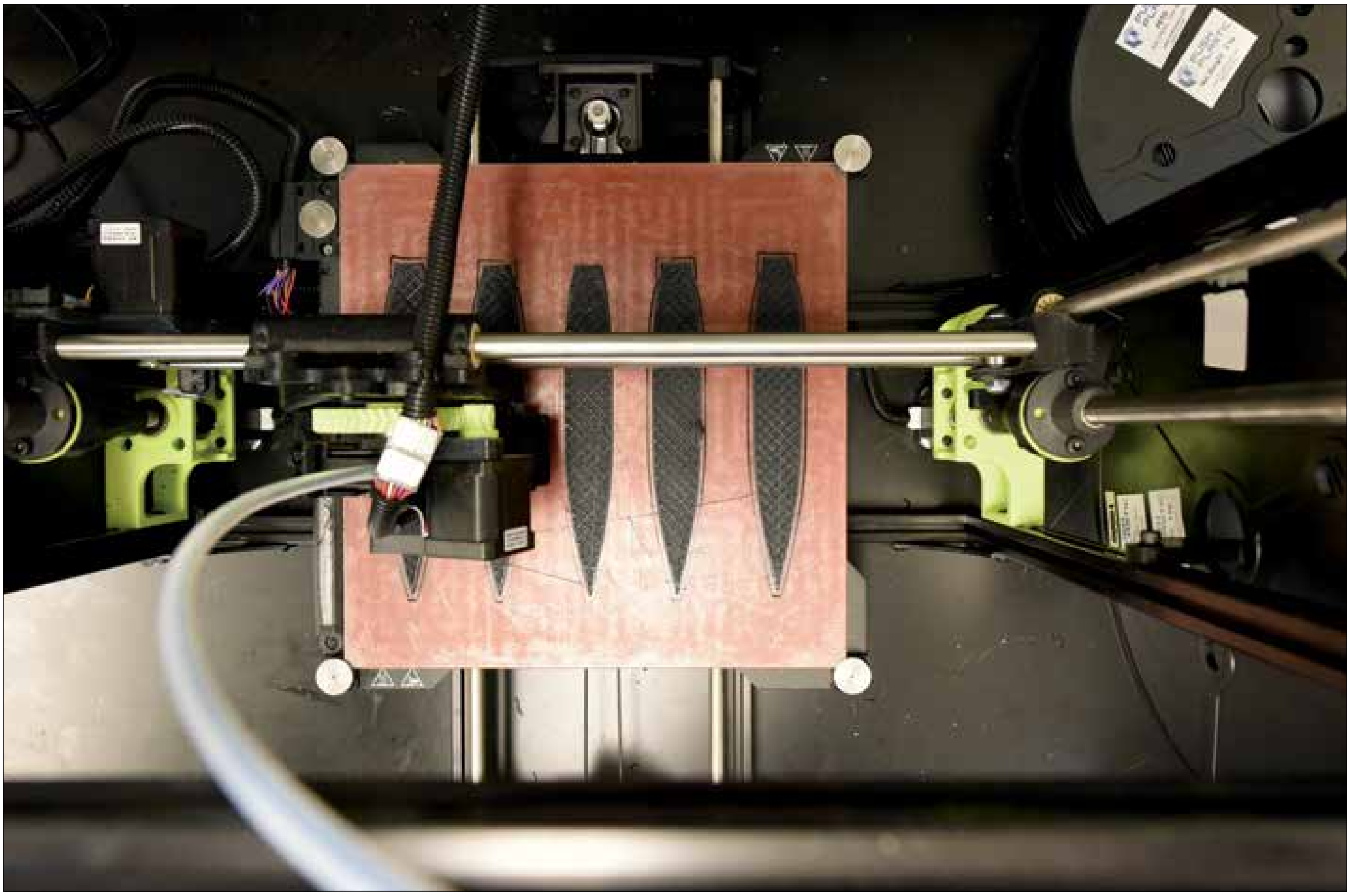
Still a nascent technology, 3D printing of parts on demand has not taken a foothold in terms of gross capacity, consisting of less than 1 percent of industrial production. However, looking at those dipping their toes into the technology across the commercial spectrum, the automotive, medical, and aerospace industries are early adopters, consisting of nearly 50 percent of commercial additive applications.[8] The medical field's engagement is still fairly close to prototyping, as they are taking advantage of the capability to create unique prosthetics and fitted medical devices such as hearing aids and orthodontia. Conversely, automotive manufacturers have been pushing the technology past its initial low run limitations. General Motors is producing larger components, including bumpers and spoilers, while firms such as EDAG Engineering and the BLM Group have moved additive manufacturing from a minor part of the supply chain to additively manufacturing close to entire concept cars.[9] Utilization on a handful of automotive assembly lines notwithstanding, the technology is still predominantly defined by its ability to produce goods without high-cost molds and castings, while setup costs are kept at a minimum, providing the flexibility to produce various components on a single machine.

Of particular interest to the military supply chain is the experience of aerospace corporations. Companies such as General Electric (GE) and Boeing have taken advantage of additive technologies to produce complex geometries that are difficult and expensive to manufacture under legacy technologies. GE Aviation is printing fuel nozzles, and the National Aeronautics and Space Administration is examining which rocket engine parts could be additively manufactured.[10] Currently, the manufacture of these parts involves low production runs that require significant investments in machine tools, which are thereafter underutilized. Furthermore, the quest for weight reduction has brought expensive materials into the manufacturing process. When titanium or other high-value materials are applied additively versus using subtractive manufacturing processes, which waste costly raw materials, companies can realize significant cost savings.[11]

Potential Benefits

Following 15 years of war, and the $5.6 trillion in treasure expended, there is more pressure than ever to find efficiencies, cut costs, and redefine the way business is conducted across DOD.[12] So pervasive is the pressure to reform business practices that Secretary of Defense James Mattis lists "bringing business reforms to DOD" as one of his top three priorities, along with strengthening partnerships and rebuilding warfighting readiness.[13] Three-dimensional printers offer the promise of creating items constrained only by imagination. The goal of producing parts on demand promises to eliminate time, costs, and infrastructure while contributing significantly to readiness levels.

Large production runs currently benefit from the speed and economies of scale of more traditional manufacturing methods, such as injection molding (which are able to distribute capital costs over high numbers of units).[14] As 3D printers develop, large batch runs will become more affordable. The maturing industry



LulzBot TAZ 6 prints small-scale ship model in Manufacturing, Knowledge, and Education Laboratory at Naval Surface Warfare Center, Carderock Division, Bethesda, Maryland, July 25, 2018 (U.S. Navy/Justin Hodge)

should provide opportunities to reduce supply chain labor and long-term sustainment costs. Collapsing the supply chain by producing parts on demand eliminates not only warehousing functions but also the process of creating and transporting the part and/or entire assembly.[15]

While supply chain savings will excite budgeteers and logisticians, the reduction in time to reliably deliver parts will produce significant improvements in equipment readiness. With advances in self-diagnostics, emerging failures can be detected prior to systems and equipment degrading, and systems can identify required parts as soon as failures appear. If parts can be produced locally, rather than waiting for nonstocked items to be ordered and delivered, maintainers can eliminate equipment down time.

In addition to the ability to deliver parts without warehousing, additive manufacture provides the ability to mitigate manufacturing obsolescence. Diminishing Manufacturing Sources/Material Shortages (DMS/MS) is a significant force degrader as the military continues to extend the service life of weapons systems far in excess of design parameters. Many production lines have shut down and companies have gone out of business due to the generally low demand signal for many parts supporting DOD systems.[16] As such, there is a struggle to field spare parts.[17] With excessive costs associated with restarting production lines or conducting reverse engineering, the Services are forced to cannibalize parts from degraded or even previously discarded equipment.

A significant challenge to production line retooling is the creation of dies and molds. Under traditional methods, fine silica-based sands are used to create molds for molten medal, and this requires skilled artisans and substantial investments in both production and storage costs. Retained CAD files now allow for the storage of these casting molds electronically. Printers can utilize globally available casting sand, currently in use at foundries worldwide, to recreate molds on demand, versus warehousing large numbers of molds or employing highly skilled individuals to recreate molds in the event of downstream requirements.[18] Such methods allow castings to be poured without high costs and long lead times. It is likely that initial large-scale fielding within DOD can have the most significant impact in mitigating DMS/MS cases.

Challenges

Although there are examples of high-quality airworthy valves being additively manufactured, concerns over quality control of printed parts remain.[19] Under the best circumstances, parts certification can be a lengthy and cumbersome process. Depending on the system, parts may be subject to review and testing from Service engineering authorities, original equipment manufacturers, non-DOD governmental or nongovernmental agencies, or combinations thereof.[20] These quality concerns are compounded when parts are manufactured at the end use location without the benefit of robust quality assurance resources. Furthermore, military application of 3D printing often takes place in austere environments that suffer from vibration pollution from aircraft engines, heavy vehicles, and even ocean movement on ships at sea. When producing precision parts with narrow tolerances, these environmental disruptions can negatively affect the production process and insert invisible flaws into finished products.[21]

Not only do locations face the quality risks associated with any production process, but there are also emerging cyber risks to be considered. Without robust cyber security covering technical files and even the printers themselves, internal flaws can be inserted into printed parts that are difficult to detect. These structural flaws have the ability to degrade weapons systems and create equipment and even personnel casualties.[22] Therefore, program managers must implement risk assessment and mitigation strategies to counter these quality and cyber vulnerabilities before fielding additive manufacturing, or additively manufactured parts.

Perhaps the most significant hurdle to unit-level implementation of on-demand additive parts production is the procurement and maintenance of intellectual property, which often originate from multiple sources with various levels of certification requirements.[23] Though Federal Acquisition Regulation (FAR) 27-406 directs the identification of data requirements upfront, DOD procured tens of thousands of weapons systems before the potential to produce spare parts locally was even a concept. Acquisition of data, postcontract award, entails significant costs and in some cases may not be possible, necessitating large investment in reverse engineering.[24]

Once data are procured, the cost and management may also limit how far down the supply chain 3D printers are deployed. Unit-level distribution provides the fastest production to the end-user timeline but produces other risks; maintaining changes to technical specifications and ensuring the information technology infrastructure to deliver CAD files to the production printers require a significant investment. As manufacturers' technical directives are issued, and parts specifications are altered, it is imperative that updates are pushed to the lowest level of production to reduce defective, or even dangerous, parts due to lax data management processes.

As the technology continues to mature and engineering and quality control concerns are rectified, the cost-benefit equation will shift toward additive manufacturing, especially for DMS/MS cases and low-demand items. Once the cost to field and maintain the technology and to procure the required raw material and data packages is less than the total costs of complete products, more products will transition to additive production. The cost to store and maintain inventories, and the difference in transportation that traditionally manufactured parts require due to the distance from the end user, offers opportunities for cost savings, too.

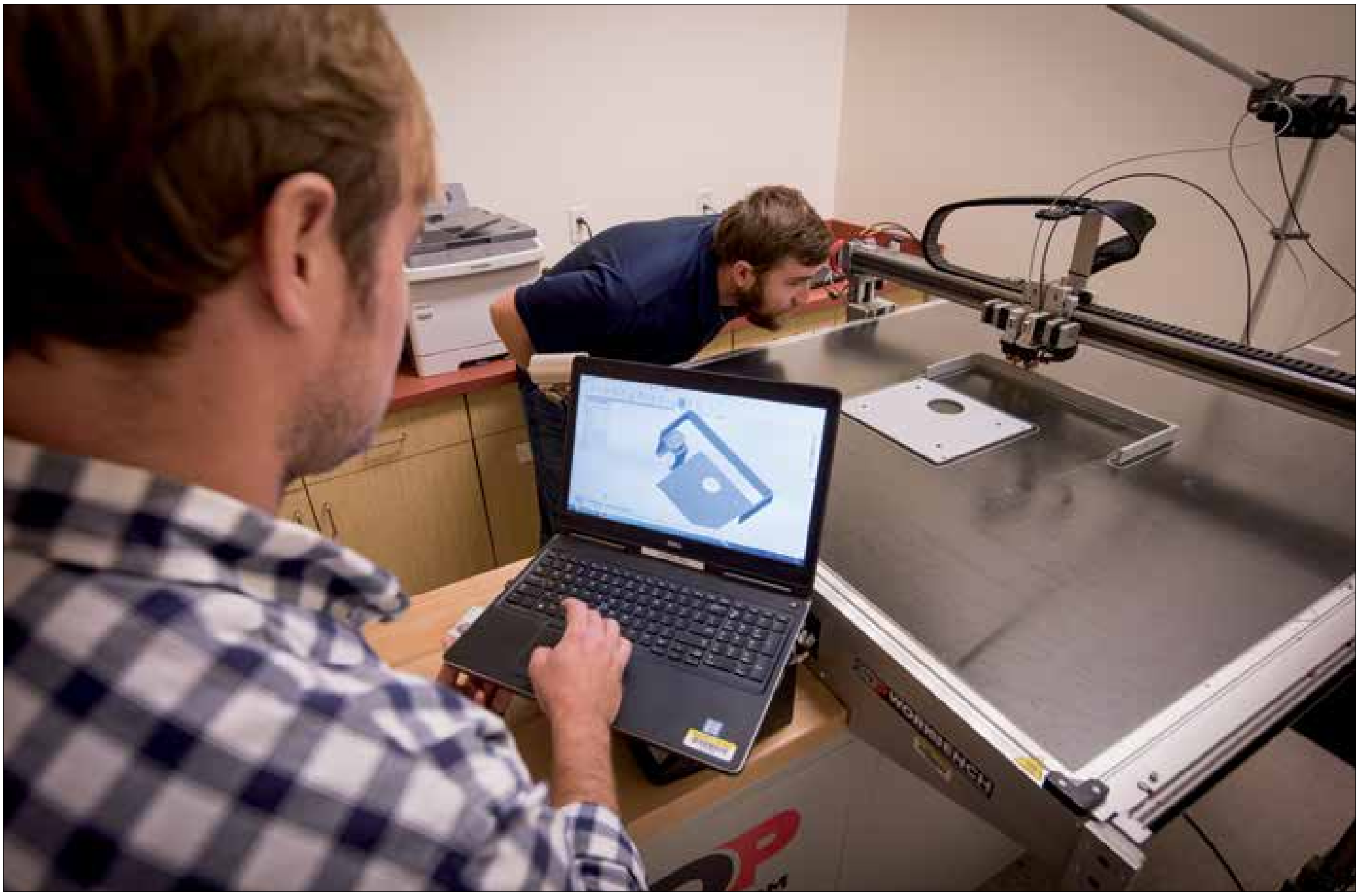
Within each of these cost silos are a number of factors that must be considered prior to implementation. Within the maintenance category, determination must be made on who conducts the maintenance (military or contractor). The former will require development of preventative maintenance protocols as well as significant training. Contractor support allows faster fielding but will have more significant upfront acquisition costs and may result in slower response times to address equipment failures.

Regarding bringing costs under control on the additive manufacturing side of the equation, raw material is second only to data costs. Where injection-molded plastics are available in the ranges of $2 to $3 per kilogram, comparable raw materials for 3D printers can run from $175 to $250 per kilogram. When looking at high-end titanium and titanium alloys, those costs can grow to $880 per kilogram.[25] Though prices will likely drop as the market for these raw materials grow, this is still a significant challenge to overcome.

Driving the largest financial impact is the cost of data. Without quality data, the military would have to engage in reverse engineering of a product, which is expensive and not guaranteed to produce successful results.[26] The technical specifications required may be critical intellectual property of vendors, covered by patents and other relevant regulations that drive up acquisition and management costs. Furthermore, in those cases where the government has an obligation to protect vendors' intellectual property, there will be significant challenges in the information technology infrastructure to store, update, and deliver required secure information to 3D printers.

There are also a number of nuances that should be understood when making decisions. Traditionally, simple and low-cost items will quickly become readiness-limiting factors as technologies and parts become obsolete. This will quickly move an item from inconsequential to highly relevant in the supply chain. An examination of shelf-life shrinkage must also be considered; many parts degrade in storage over time to the point where they must be discarded. Lowering the pre-use loss of parts to shelf-life expiration by on-demand production can reduce system costs.

Warehousing and transportation costs are anticipated to be negligible in the short to medium term due to the volume of production required to affect net requirements. Should the technology expand, its future capabilities for limiting warehousing requirements and downsizing both real estate and manning in the supply chain will further draw costs down. On the other hand, it is important to note that production is not instantaneous. Shifting to 3D printing–based sustainment may decrease time to deliver parts when the part is not locally warehoused; however, it will likely increase delivery time in those cases where one would otherwise issue directly off the shelf for immediate delivery to the flight line or address an emergent casualty.



Space and Naval Warfare Systems Center Atlantic employees review CAD software designs for additive manufacturing and verify printer is properly calibrated, Charleston, South Carolina, October 24, 2017 (U.S. Navy/Joe Bullinger)

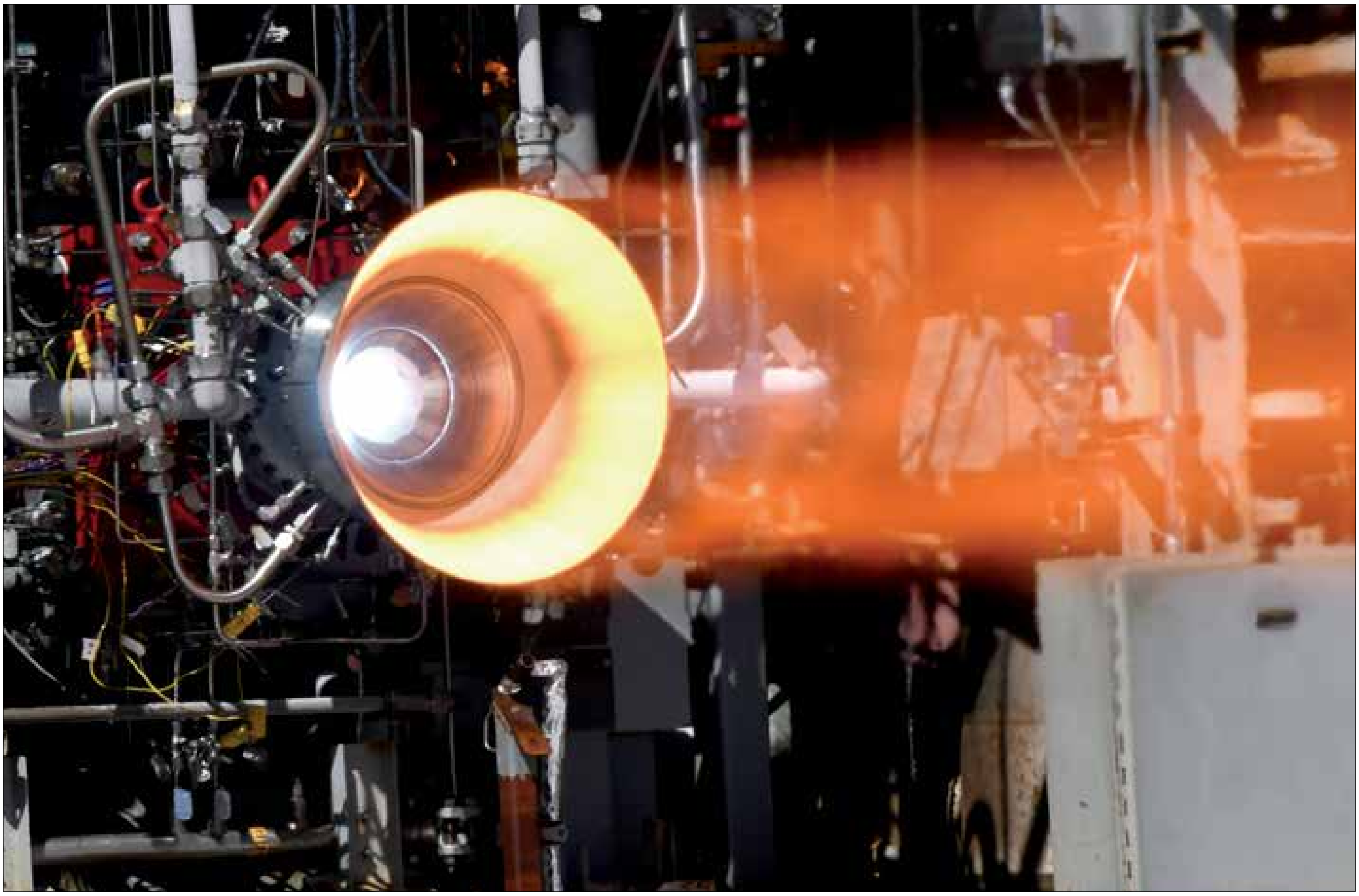
Enabling Factors

Given the possible advantages inherent in this technology, getting it right is a professional imperative for those designing supportability plans for military programs and those supporting warfighters in the field. A new deployment triad of training technicians, equipment fielding strategies, and operational policies must be developed.

Unlike other emerging technologies, training may be less difficult than anticipated. Much like automotive skills 40 years ago, 3D printing and CAD technology are being taught in high schools, community colleges, and universities throughout the country.[27] There is a large population of young people that has exposure to 3D printers, and while there will always be platform-specific training requirements, DOD can leverage existing skill sets within the force. Though maintenance concepts for equipment will be developed in conjunction with specific vendors, resident knowledge within DOD organizations, combined with existing manuals, will cover many training requirements.

Deployment levels and volume of the technology are as important as the training and enabling instructions. Field too few systems and the benefits of short supply chains are lost; field too many and it becomes cost prohibitive. Placing additive manufacturing assets at a central hub with intermediate-level maintenance capability within the theater of operations will balance these concerns. Across the joint forces, the support would need to deploy within the Support Maintenance Company (Army), Marine Expeditionary Unit (Marines), Intermediate Maintenance Centers (Navy), or Logistics Readiness Squadron (Air Force). The assets required in theater can be tailorable depending on who the lead agency is for logistics as well as mission, location, and participants. For instance, if the Army has the lead for logistics during an operation and is supporting ground forces from other Services, it could rely on the Support Maintenance Company as a common user logistics asset. Other environments may be more complicated and require additional assets. For instance, a littoral fight with a smaller footprint could rely on an offshore amphibious readiness group or carrier strike group to support emergent needs, delivering parts via short-hop airlift.

Policy shifts regarding how acquisition professionals approach supportability of equipment will ensure that deliberate assessments of 3D printing's technical feasibility are conducted. There are scores of regulations, policies, and instructions ripe for additive manufacturing–based parts supportability; however, focusing on the FAR, DOD Instruction 5000.2, *Operation of the Defense Acquisition System*, and executive orders will provide the largest impact, due to downstream



NASA successfully hot-fire tested 3D printed copper combustion chamber liner with E-Beam Free Form Fabrication manufactured nickel-alloy jacket, March 2, 2018 (NASA/Marshall Space Flight Center/David Olive)

policy nesting of higher instruction. Requiring programs to examine the feasibility of acquiring technical data for parts capable of additive manufacture during the first article delivery (FAR §52-299.4) will set the appropriate criteria. While data acquisition is a key enabler for locally produced additive parts, drilling down to the DOD instruction will force critical examination of the parts manufacturing process. Specifically, DOD Instruction 5000.2, §3.9.2.4.3, should be added directing sustainment decisions to actively work with Service engineering agencies to examine the feasibility of additive manufacture for parts sourcing.

Executive orders can jumpstart the process of new construct implementation and effectively communicate the value of new processes and technologies to public programs. President Barack Obama's Executive Order 13693, *Planning for Federal Sustainability in the Next Decade*, achieved this by directing utilization of "performance contracting as an important tool to help meet identified energy efficiency and management goals while deploying life cycle cost-effective energy efficiency and clean energy technology."[28] With such constructs in mind, additive manufacturing will increase efficiency and decrease the added resources needed in the process of acquiring, shipping, and distributing resources by producing them locally.

With the growth of Performance-Based Logistics procurements, encouraging manufacturers to establish additive manufacturing as part of their long-term sustainment should be an easier sell. As contracts demand system operational availability as a performance metric rather than time to reliably deliver parts, putting the capacity to produce parts close to end users could bolster profits by limiting the requirement to hold significant contractor inventory on hand.

Additionally, DOD should conduct a review of the existing parts inventory to identify those that could be shifted from traditional inventory levels to print-on-demand strategies. The assessment would require a significant effort, as there are over 5 million line items to be assessed—with countless limitations to review even before a business case is made, including material and item size. Once the technical specifications are validated, business cases are required for each item to determine if additive manufacturing is a viable solution for the DOD supply chain. In addition to setting the criteria to use in this assessment, the study needs to address how to present results to the supply system. End users need visibility regarding any parts to be printed on demand when they are researching parts availability. Any limitations on transparency on observed inventory levels (or lack thereof) may incentivize customers to seek out more expensive alternate options that limit operational availability. Possible criteria for parts to be additively manufactured should include, but not be limited to:

- material availability
- material demand
- backorders
- technical data availability
- type of 3D printer required
- manufacturing lead times
- unit cost
- technical complexity
- quality assurance requirements.

There is little question that additive manufacturing will continue its expansion into additional fields, increasing flexibility and shortening supply chains. It will not be an easy transition and will require significant hurdles to be overcome before the Department of Defense declares it a success. Through a disciplined approach to fielding the technology, including ensuring that trained personnel are operating at well-equipped locations, a wide range of rapidly manufactured items will be available to support the warfighter. By developing instructions and directives to ensure intellectual property is acquired, up to date, secure, and available, DOD can optimize costs and provide required support to the military Services at the best price to the taxpayer. JFQ

Notes

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