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3D Printing

Downstream Production Transforming the Supply Chain

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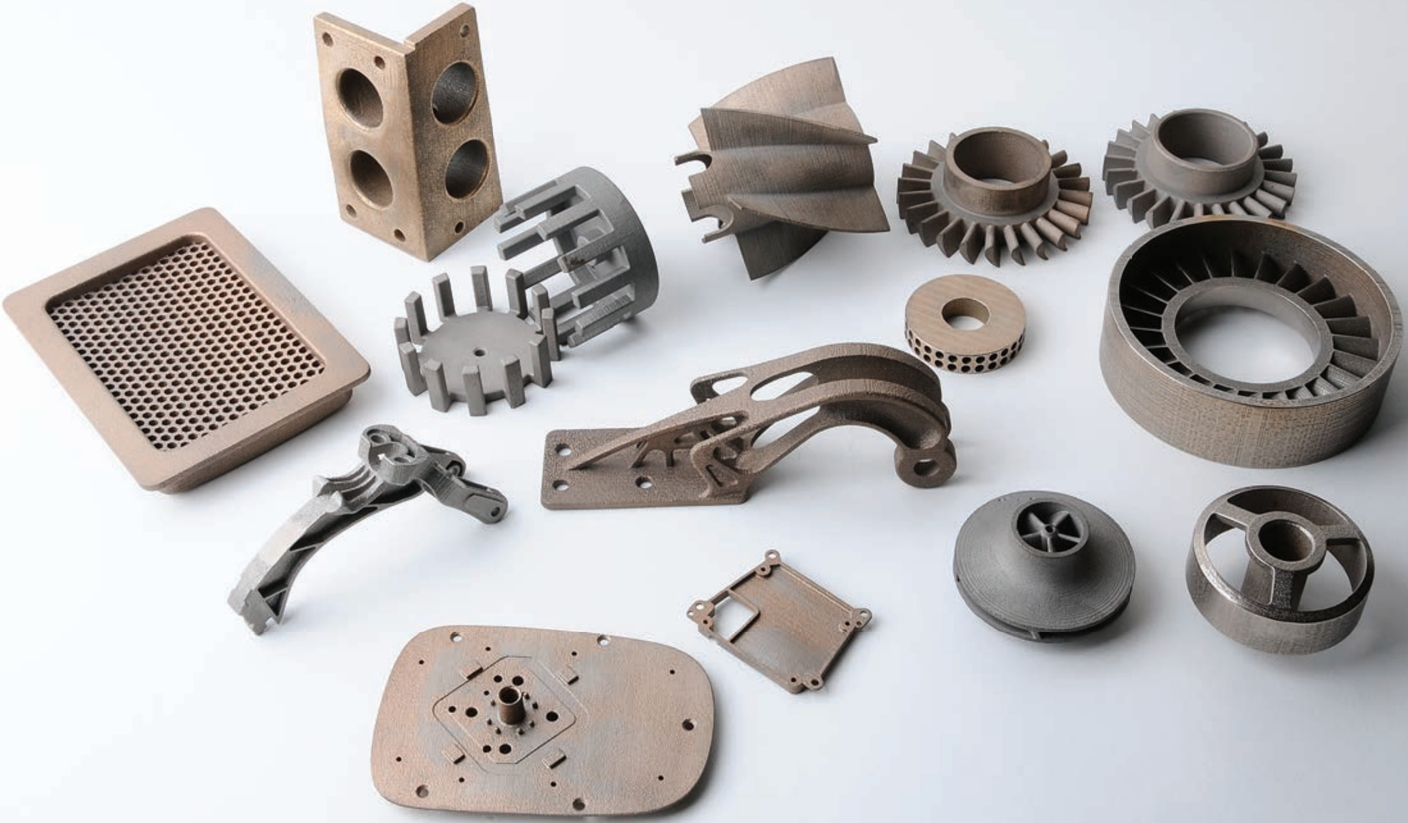


This Perspective explores the potential for 3D printing capabilities to transform supply chains by enabling downstream production. 3D printing, as we define it in this research, is the *capability* to produce a custom object in near–real time with the ease of pressing a button. In doing so, we depart from the prevalent engineering and hobby literature's focus on 3D printing as solely consisting of additive manufacturing (AM) technologies. AM creates physical objects by depositing thin layers of material (e.g., metal alloys, various plastics and polymers) on top of each other based on a digital description of the product's design. Traditional and established subtractive manufacturing (SM) creates objects by removing material (e.g., through drilling or lathing) from solid stock, often with computer control. Our capability-based definition of 3D printing permits us to discuss supply chain process flow and end results through a technology-agnostic lens, instead of focusing on specific engineering processes. As will be discussed throughout this Perspective, 3D printing is more than just AM and SM.

A reevaluation of 3D printing capabilities for organizations that manage large, diverse supply chains is justified now because of the rapid progress of AM technology. Commercial industries are applying AM in a wide range of fields—from toy manufacturing to tooling and prototyping, with new applications being developed at an increasing pace. Interest in AM is also growing within the U.S. government. At the U.S. Department of Energy (DoE) National Laboratories, research programs are using AM technologies to create new materials with properties unavailable in nature, such as lightweight frames and antennas that can also function as structures. The U.S. Department of Defense (DoD) also sees potential in applying AM to support maintenance, repair, and operations (MRO) by providing drop-in replacements for worn-out, costly, or difficult-to-obtain parts.

3D printing applications pose many challenges, regardless of the particular manufacturing technology used. While some benefits and constraints are narrowly limited to respective AM and SM technologies, many general managerial and supply-chain considerations around the digitization of manufacturing operations are similar. Given the rapid progress in AM technologies, a large part of this Perspective will focus on the benefits and challenges that are specific to AM. For technology-agnostic implications for the supply chain, we will utilize our expanded definition of 3D printing.

To help DoD understand the universe of possible applications of 3D printing—as well as the structural and policy changes that might be required to support these efforts—RAND's National Defense Research Institute undertook an exploratory project to examine potential uses and benefits of 3D printing in a military context. This Perspective traces 3D printing technology from its origins to its potential to transform supply chains for DoD. We describe various applications of 3D printing technologies and provide a framework to help DoD think about the future impact of 3D printing in an MRO context. We also analyze the United States' strategic competitive balance in AM technology development and adoption. Finally, we discuss broad implications of these new technologies for DoD's acquisition and other planning processes.

Methods

We used a multimethod approach for our research, similar to that described by Brewer and Hunter (1989). This approach combined literature review, field visits to technology manufacturers, and semistructured interviews with defense personnel and academic scholars to canvass the current state of the technology. Given the exploratory nature of this research, the scope for interviews and data collection was broad, in line with Stebbins (2001). We used a semistructured interview technique similar to that described in Rubin and Rubin (2005) to ask about various technologies, supply chain issues within DoD, and ways in which 3D printing might change the landscape. In some cases, we used nonstructured or casual interviews, as described by Kvale (2008), to avoid disturbing ongoing MRO, which were not conducive to a structured session with the repair technicians. We conducted a rapid review of all available literature—which is a streamlined version of the systematic review allowing for assessment of a timely issue—starting from the inception of AM technology in the late 1980s to the present, using an approach described by Khangura et al. (2012) and Grant and Booth (2009).

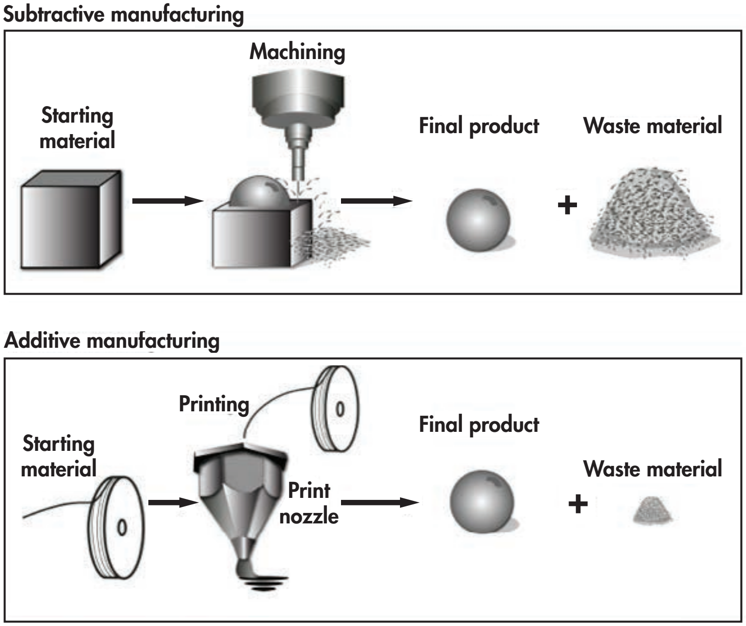
Understanding 3D Printing: Additive and Subtractive Manufacturing

We consider 3D printing technologies to comprise two main processes: AM and computer numerical control (CNC) SM. The term *additive manufacturing* was first used to refer to binder jetting, a technology developed at the Massachusetts Institute of Technology (MIT) and licensed to ExOne and ZCorp in the mid-1990s (ZCorp later became a part of 3D Systems) (Gibson, Rosen, and Stucker, 2015). AM, also known as additive fabrication or rapid prototyping,[1] is a technology used to manufacture physical objects by depositing thin layers of material on top of each other based on a digital description of the product's design (Petrick and Simpson, 2013). The creation of 2D cross-sections of a 3D object allows manufacturers to build products with highly complex geometry in a single process rather than by combining multiple components manufactured by traditional technologies (Gibson et al., 2015). The physical process within any AM machine consists of two general steps: *coating* and *fusing*. In the first stage, a thin layer—typically 0.03–0.2 mm thick—is applied to the working surface. In the second stage, a source of energy such as a lamp, laser beam, or electron beam is used to fuse the new layer to the surface underneath (Petrovic et al., 2011). Postprocessing often follows, using techniques such as sanding, polishing, homogenization, or thermal treatment (Petrovic et al., 2011).

While AM approaches focus on *adding* layers to create a physical object, *subtractive manufacturing* refers to processes, including cutting, drilling, milling, and lathing, that work by *subtracting* material from solid stock to make shapes and components. After these subtracting processes occur, SM components are processed or assembled into a final product (Petrick and Simpson, 2013). SM made significant advances in the second half of the 20th century, and was digitized soon after early computers became available to the business community. In 1955, SAGE, the first computer-based graphics system, was developed at MIT's Lincoln Laboratory for the U.S. Air Force and subsequently, in 1957, Patrick J. Hanratty developed PRONTO, the first commercial numerical-control programming system. These early technological developments enabled the era of computer-aided design and drafting (CADD) and computer-aided manufacturing (CAM) (Inchaurregui, 2007).

The differences between SM and AM are displayed schematically in Figure 1.

Figure 1. Subtractive and Additive Manufacturing



SOURCE: U.S. Government Accountability Office, 2015.

SM has been the most prevalent manufacturing technology for centuries and will remain a significant and useful method in manufacturing. However, it has some disadvantages when compared with emerging AM technologies because it produces relatively more waste and has limitations in the types of structures that it can form. Its main advantages remain its current price point and market penetration in many industries, and its familiar parts certification process.

Many products are created using hybrid additive-subtractive manufacturing approaches. For example, products created using AM may also require the use of SM-produced components. Increasingly, a hybrid manufacturing approach may be the most feasible or cost-efficient.

Given the wide array of advanced manufacturing technologies that could be employed for downstream production, we posit that

DoD should consider 3D printing ability through a “technology-agnostic” lens. That is, the overall focus should be to produce objects in near–real time with the ease of a push of a button regardless of whether that process uses SM or AM technologies. For DoD, 3D printing will likely require a combination of technologies in an expeditionary package that gives the operator downstream in the supply chain the ability to make needed parts rapidly. Given that SM is a mature and well-understood technology, this Perspective will focus on understanding AM and its role in the 3D printing ecosystem. In the next section, we describe the evolution, strengths, and challenges of AM, highlighting those that are of greatest relevance for the U.S. military and its suppliers.

The Evolution of Additive Manufacturing

The commercialization of AM dates to the mid-1980s, with the first patents submitted in parallel in Japan, France, and the United States in 1984.[2] Manufacturers have experimented with using different materials to produce physical objects, including polymers, metals, ceramics, and, most recently, glass.

AM itself does not represent a single approach but encompasses a number of different manufacturing technologies. The roots of modern technologies in AM are tied to the inception of stereolithography and laser technology in the 1950s and 1960s (Zhai, Lados, and Lagoy, 2014). Laboratory testing of AM approaches began in the 1970s; by the late 1980s and early 1990s, four pioneering approaches had emerged: stereolithography (as developed by 3D Systems, Inc. in the United States); solid ground curing (a technology commercialized by Cubital, Ltd. from Israel); selective laser sintering (pioneered by the University of Texas at Austin); and laminated object manufacturing (first launched by Helisys, Inc. in California) (Dolenc, 1994). The oldest of these technologies, stereolithography, is still in use by manufacturers worldwide for many applications, most prominently in the production of hearing aids and other medical devices (3D Systems, undated). In contrast, solid ground curing has experienced several setbacks and is no longer utilized, despite the relatively high precision it offered (Um, 2015). In Table 1, we distinguish between seven AM process categories detailed by the International Organization for Standardization (ISO) and ASTM International (ISO and ASTM International, 2015).

The technical terminology used to describe these manufacturing processes has been continually developing as technological advances have expanded the horizons of what is possible. To assess one measure of growing interest in the field, we summed the number of academic journal articles on AM technology published each year from 1994 to November 2016 using Google Scholar. We found an increase from single digits in the years 1994–2002 to 1,526 articles published in the first ten months of 2016 alone. As another measure, the research firm Wohlers Associates has found that the AM industry has expanded by a Compound Annual Growth Rate of 26.2 percent in the period from 1989 to 2015 (McCue, 2016).

AM can be used for rapid fabrication of repair parts and supply chain optimization, as well as to build parts with capabilities that are infeasible to achieve using conventional design and manufacturing techniques. For example, AM can combine multiple functions into a single component (e.g., sensors and structural elements) or fabricate parts in a single step that would take multiple, disparate manufacturing processes in conventional manufacturing.[3]

AM is uniquely suited to employ *generative design*—an optimization process in which computers are used to explore a large number of variations in forms that meet user-defined criteria in

Table 1. AM Process Categories

Process Category	Definition	Material Type	Search Hits (Google Scholar)	Related Technologies
Material extrusion	A process in which material is selectively dispensed through a nozzle or orifice	• Polymers • Sand	3,510	• Fused deposition modeling
Sheet lamination	A process in which sheets of material are bonded to form a part	• Polymers • Metals	1,920	• Laminated object manufacturing • Ultrasonic consolidation
Powder bed fusion	A process in which thermal energy selectively fuses regions of a powder bed	• Polymers • Metals • Ceramics, sand, and carbon	1,810	• Electron beam melting • Selective laser sintering • Selective heat sintering • Direct metal laser sintering
Material jetting	A process in which droplets of build material are selectively deposited	• Polymers • Metals • Wax and biomaterial	679	• Multi-jet modeling
Binder jetting	A process in which a liquid bonding agent is selectively deposited to join powder materials	• Polymers • Metals • Glass	602	• Powder bed and inkjet head • Plaster-based 3D printing
Directed energy deposition	A process in which focused thermal energy is used to fuse materials by melting as they are being deposited	• Powder • Metals	517	• Laser metal deposition
Vat photopolymerization	A process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization	• Polymers • Ceramics and wax	205	• Stereolithography • Digital light processing

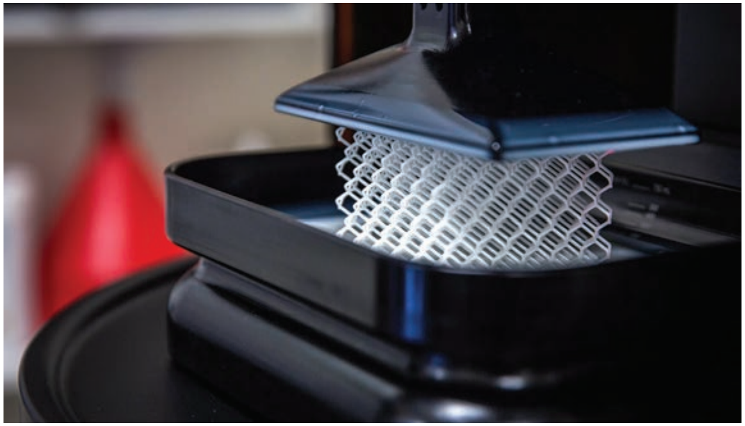
SOURCE: RAND compilation based on ISO and ASTM (2015), Gibson et al. (2015), and DoE (2015).

different ways. Because generative designs in AM are not bound by SM constraints, results often take “biologically-inspired” forms, as shown in Figure 2. An example is the Autodesk Research Project Dreamcatcher design concept, which applies cloud computing and AM in a requirements-to-fabrication workflow (Autodesk Research, undated). By depositing materials in specific 3D patterns, it is possible to realize combinations of mechanical properties that are not available in bulk materials.

Figure 2. Generative Design Applied to Notional Component

SOURCE: Promotional image from EOS.
NOTE: Demonstration part of a nacelle hinge bracket for an Airbus A320 with optimized topology: built in titanium by using an EOS M 290.

Figure 3. Additively Manufactured Replicated Trusses



SOURCE: Carbon3D, undated.

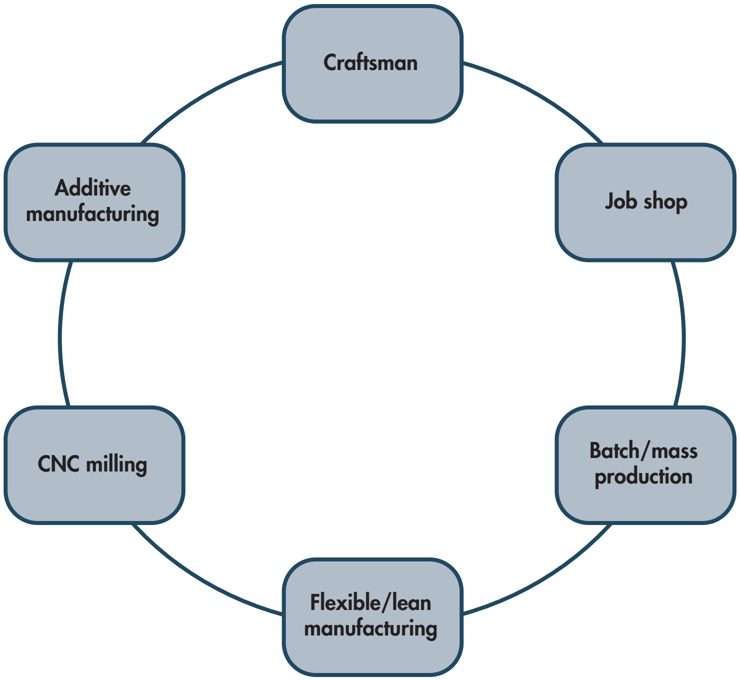
AM technologies are also useful for customizable or novel designs. Figure 3 shows an example of tailorable properties using microreplicated trusses to create materials that maintain the stiffness of the bulk material at greatly reduced mass (Zheng et al., 2014).

These novel capabilities have the potential to build market demand for AM in defense, aerospace, and nuclear applications. Importantly, systems using these novel capabilities will need to be "designed for AM," and, thus, it might not be possible to substitute conventionally manufactured parts in the design later on (Rosen, 2007). We discuss this point further in our Conclusions and Implications section.

AM can be seen as the latest incremental step in manufacturing evolution, combining the promise of single-unit production efficiency, high-quality parts, and alignment to demand. In thinking about the evolution of production modes, we can look back hundreds of years to the early days of object production, which had a focus on the craftsman and various "smiths" (e.g., blacksmith, silversmith), whose goal was to produce, one by one, a single quality article responsive to local demand. Over time, economics drove innovations in production, leading to a focus on producing parts cheaply and reliably on a mass scale. The goal of minimizing cost has remained constant, whether through collectives of craftsmen working in job shops or mass manufacturing. Over time, consumer demand for custom-made items has led to new production approaches, including flexible manufacturing, lean systems, CNC milling machines, and ultimately, to AM.

Although the evolution of production modes is linear when considered over time, one might see AM as a return to localized production: back to the craftsman (as illustrated in Figure 4). That is, 3D printing provides the ability to produce parts locally that are of high quality and responsive to a specific demand, exactly as craftsmen used to do. While the adoption of AM for the general

Figure 4. Quest for Individual Unit Efficiency



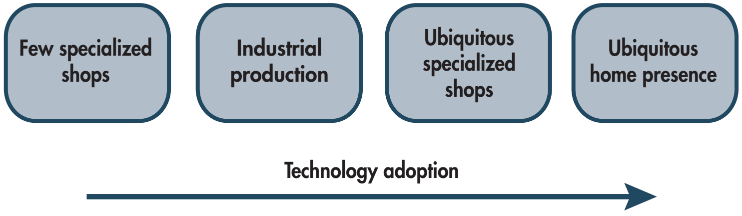
population would be akin to having an individual craftsman in every home, our vision for DoD and commercial applications harkens back to the job shop model, which focuses on producing a highly responsive supply based on the immediate needs of end users, including combat forces.

The Future of 3D Printing

In the previous section, we discussed the evolution of production modes leading to the development of AM. We now look to the future and provide a framework to help DoD think about how 3D printing might evolve, and what its implications might be for the future of supply chain design and management.

Before we present the framework, it is instructive to review the evolution of another technology, conventional printing, or “2D printing,” given the similarities between the evolution and adoption of the two (see Figure 5). Originating in the 15th century with Johannes Gutenberg’s movable type printing press, 2D printing was long limited to small, specialized shops that required skilled labor to achieve a very small throughput. Several centuries later, rotary printing presses revolutionized the printing field by enabling mass production at a few specialized sites. A full century later, in the 1980s and 1990s, neighborhood print shops started offering printing, copying, and scanning services, making the technology available to the general public at relatively low cost. Finally, home printers and scanners became ubiquitous in the 1990s and 2000s, completely eliminating the barriers to 2D printing technology and leaving neighborhood print centers to refocus on specialized printing services and other value-added activities, such as professional printing posters, oversized prints, and providing integrated document distribution.

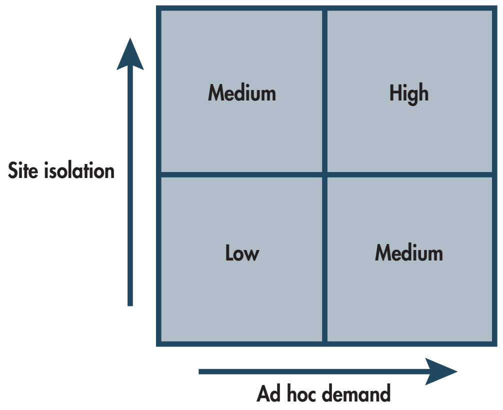
Figure 5. Technology Adoption in 2D and 3D Printing



While the adoption of 3D printing has been compressed into a much shorter time period, it has followed practically identical phases. As of 2016, AM has passed the first two phases and is concurrently entering the latter two stages, as evidenced by the emergence of fabrication labs ("fab-labs") in many big cities, and by basic personal 3D printers being sold to private users for less than $500. Inventors, hobbyists, and businesspeople can use 3D printing fab-labs on a pay-per-use basis, similar to using a paper print shop in the past. Some industries have now partly converted from traditional production methods to AM, especially in specialized niche markets such as the manufacturing of hearing aids. It is only a matter of time until high-quality 3D printers become available and accessible to the general public. Companies like UPS have already started introducing the technology at selected locations (UPS, undated). While highly complex industrial processes, such as powder bed fusion, are unlikely to be widely available within the next few years, plastic composite machines that can build spare parts and other objects using stereolithography or continuous liquid interface production technology are on the horizon for the current decade.

Given the potential size of the growing 3D printing market, our research considered what benefits this technology might provide for DoD and other analogous supply chains. In exploring this question, we identified two primary components driving the potential impact of 3D printing: (1) the relative isolation (or connectivity) of the source of the demand to the supply chain, and (2) the ad hoc nature (or variability) of the demand. Figure 6 shows a two-by-two matrix illustrating these concepts. The figure indicates that the more the demand is ad hoc in nature and the more isolated the site is from distribution centers (for example, a forward operating base or a ship), the greater the impact of 3D printing technology. Conversely, at a location where demand is steady and well connected to existing supply chains, there may be few opportunities for penetration of 3D printing. Figure 6 can be used to understand what types of demand will drive 3D printing technology adoption.

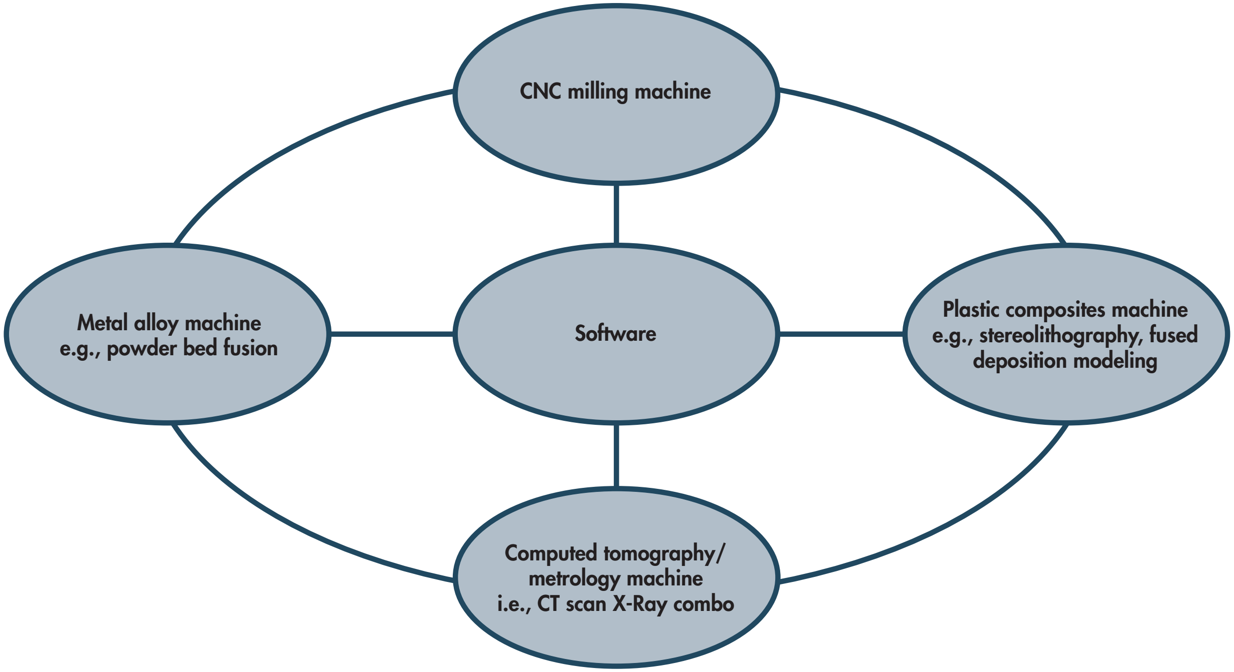
Figure 6. 3D Printing Impact Matrix



To further explore future options for 3D printing, we developed a possible "four-machine solution," drawing on the fab-lab model, which could be used to support MRO downstream in remote environments. While the exact size and capability of machines can vary depending on the space and environmental constraints (e.g., aircraft carrier versus destroyer, or a main logistics base versus a forward-operating base), this fab-lab configuration would provide a full suite of capabilities. Figure 7 shows a fab-lab made up of the following components:

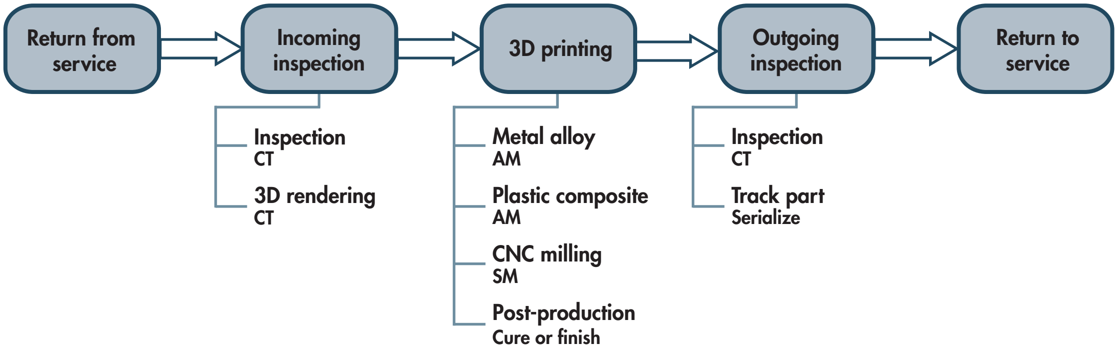
- CNC milling machine
- Metal alloy AM machine
- Plastic composites AM machine
- A computed tomography (CT)–metrology machine, or CT scan/X-Ray combination.

Figure 7. Proposed Fab-Lab Ecosystem for Use in Downstream or Remote Military Environment



The first three types of production machines provide complementary capabilities, while the CT–metrology component provides a relatively underappreciated capability required to leverage 3D printing ability. New X-Ray CT, offered by giants in metrology such as Zeiss and Nikon, enable unprecedented levels of defect and structure detection, characterization, and visualization. These machines perform automated inspection using X-Rays and CT technology to scan parts for defects. When combined with the right software, they can create 3D renderings of complex parts in less than 30 minutes.[4] Hence, these machines can ensure that a part is still qualified for service, generate a 3D printable design, and verify that a newly 3D printed part meets its specification. While inexpensive laser scanners can offer rapid 3D data capture for many applications, they do not offer the ability to see through the parts to render complex structure, nor do they detect defects as part of verification pre- and postproduction. Therefore, while in some instances a compact solution might employ a handheld laser scanner, a fab-lab is likely to require a more advanced imaging solution. Figure 8 illustrates a generic simple process flow for 3D printing using our four-machine proposed ecosystem.

Figure 8. Process Flow Diagram



Sizing a fab-lab requires an estimate of throughput. The total process flow time is hard to predict for every part that could be produced, since each machine will achieve different build times, depending on the complexity and size of the part to be created. However, the CT for inspection and metrology is constant, and hence, at a minimum, we estimate that it would take about one hour to characterize a part for which a 3D diagram is not available. Characterization of a noncritical part, such as a plastic cover that does not require rigorous testing before deployment, could be produced in as little as 45 minutes from start to finish. The actual fabrication and postproduction of a part could be achieved in minutes to hours depending on the part's size, complexity, and postproduction requirements. If standardized 3D printing processes are developed in DoD settings, it may be possible to produce spare parts or components within a standard 8-hour shift, thus making AM a viable option to delivering the product by standard logistical channels, particularly to hard-to-reach environments such as submarines or contested theatres. As of 2016, even Amazon Prime cannot regularly achieve such speed of delivery, especially when considering isolated locations.

To understand the value of 3D printing in the DoD context, it will be important to compare the costs of this 3D printing ecosystem concept with the costs of the total supply chain process that it would replace—including the time required to conduct the many transactions and authorizations needed to procure a part. As DoD considers its options for MRO in austere environments, comparison of the costs of using a fab-lab for local production with the costs of a centralized production system must involve a total supply chain cost approach.

Patent and Strategic Considerations

To understand the strategic competitive balance in AM technology development and adoption, we assessed AM patent activity in the private sector and defense communities in selected countries.

While providing a somewhat limited measure, we draw on Katila (2000) and Acs, Anselin, and Varga (2002), who use patent activity as a proxy for the intensity of innovation activity. AM technologies have the potential to deliver advantages for supply chain operations, obsolescence or end of product life management, and novel material properties, and countries that adopt AM might increase their economic competitiveness or gain a military benefit.

According to researchers at the Institute for Defense Analyses (IDA) who analyzed close to 4,000 AM-related patents, the majority of groundbreaking research in AM has been done by the private sector, and only some technologies received active support of government-funded bodies (Peña, Lal, and Micali, 2014; Weber et al., 2013). According to IDA, U.S.-based companies 3D Systems, Stratasys, Z Corporation, and Solidscape have sold more than 60 percent of professional-grade, industrial machines for AM worldwide (Peña, Lal, and Micali, 2014). Despite flourishing private-sector activity, government support was critical in the early years of the technology, with two out of six foundational patents filed in the United States stemming from National Science Foundation funding. All six foundational patents, as shown in Table 2, were issued in the relatively short time frame of 1984–1995, but patent activity in AM has since further increased.

We reviewed prior work, which has focused on technological emergence and networks using patent data and draw on publicly

Table 2. Foundational Patents for Additive Manufacturing, as Identified by IDA

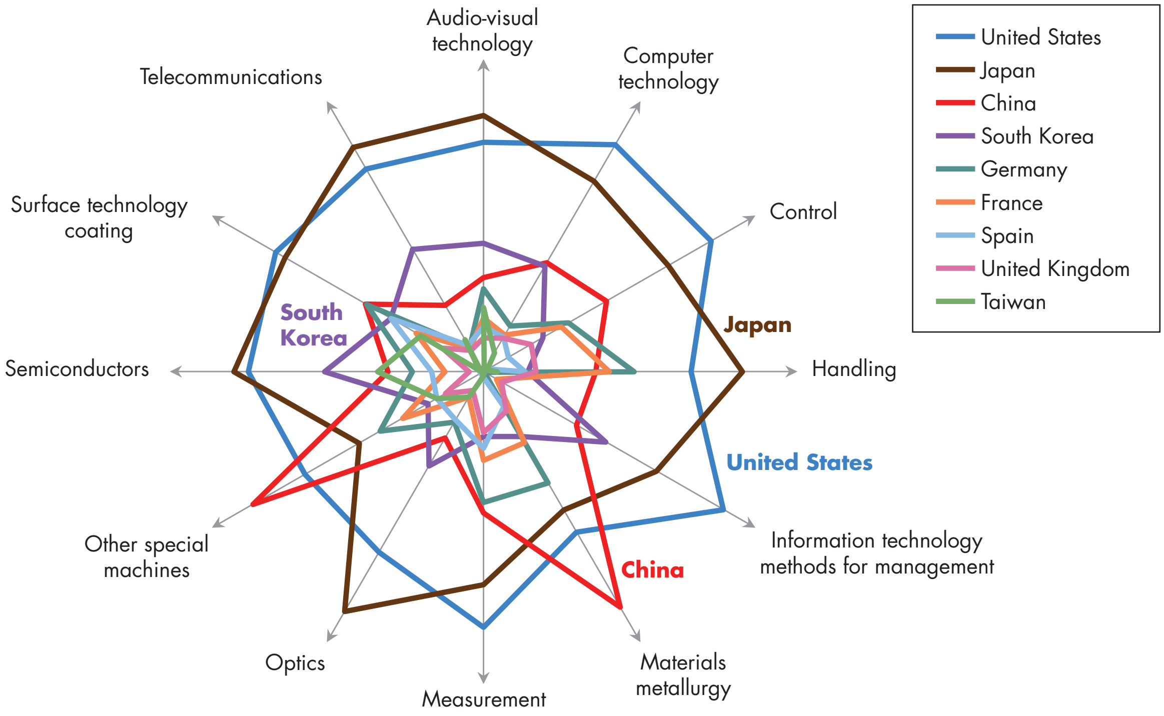
Category	AM Process	Patent Number and Title	Inventor(s)	Year of Application
Foundational	Vat photopolymerization	4575330: Apparatus for production of 3D objects by stereolithography	Charles Hull	1984
	Powder bed fusion	4863538: Method and apparatus for producing parts by selective sintering	Carl Deckard	1986
	Material extrusion	5121329: Apparatus and method for creating 3D objects	S. Scott Crump	1989
	Binder jetting	5204055: 3D printing techniques	Emanuel Sachs John Haggerty Michael Cima Paul Williams	1989
NSF-impacted	Sheet lamination	4752352: Apparatus and method for forming an integral object from laminations	Michael Feygin	1987
	Contour Crafting	5529471: Additive fabrication apparatus and method	Behrokh Khoshnevis	1995

SOURCE: Adapted from Peña et al. (2014) and Weber et al. (2013).

available data to assess the current distribution of patents filed in AM-related areas by country (Eusebi and Silberglitt, 2014). Although patents are not a direct analog of military experimentation or adoption, vibrant economic activity in the commercial realm has the potential to carry over to the military domain. In our analysis, we developed search terms based upon current topics in AM and then searched the U.S. Patent and Trademark Office (USPTO) and World Intellectual Property Organization (WIPO) databases for these terms.[5] We tabulated the number of patents by country in two separate views: by patent class and by search terms.

In Figure 9, we show a radar plot, which represents the proportion of activity in the 12 selected patent classes potentially relevant

Figure 9. Radar Plot of Additive Manufacturing Patent Activity, by Country and by Class



SOURCE: Authors' calculation using data mined by Christopher Eusebi from USPTO and WIPO.
NOTE: The figure shows the relative proportion of patent activity by class for the top nine countries in our search. The distance from the center of the plot indicates the relative level of activity, which is portrayed logarithmically for clarity.

to military, aerospace, and intelligence applications. For clarity, results are shown only for the top nine countries. Generally speaking, the strongest and most diverse AM patent portfolios exist in the United States and Japan. For almost all patent classes, either Japan or the United States is the leader. China has developed a strong position in metallurgy and other special machines, which can support military and intelligence technologies in aerospace, lightweight materials, armor, and tooling.

In Figure 10, we show patent volume by year for our search terms. The intense competition between Japan and the United States is apparent, while China and Europe have lower volumes for most of these technologies. The United States is a clear leader in powder bed fusion, a technique for metal-based AM; Japan has the lead in multi-jet modeling, a process that prints support structures in a softer material that can be removed without manual labor.

While China is investing in specific technologies that may have military relevance, it is a new entrant relative to the United States and Japan, with most of China's filings occurring after 2005. Russia is almost completely absent from the patent record, and while this is not sufficient evidence that their military is not investing in AM, it does indicate a comparatively more limited economic activity. In fact, the relative underrepresentation of Russia and the growing strength of China in AM may have more to do with economic incentives for patent filings in China than with technological development or maturity.[6] Germany is an acknowledged leader in AM, but is relatively underrepresented in our patent survey, although this imbalance is reduced in a per-capita patent count comparison.[7] Potential explanations may include intellectual property protection strategies that rely on trade secrets over patents, different approaches toward creating a 3D printing ecosystem, different distribution of basic research between public and private institutions, different patent quality standards, or other factors.

Multifunctional components, generative designs, and tailorable material properties will transform the way both military and civilian products are manufactured—from simple objects to complete vehicles, airframes, and ships.

Conclusions and Implications

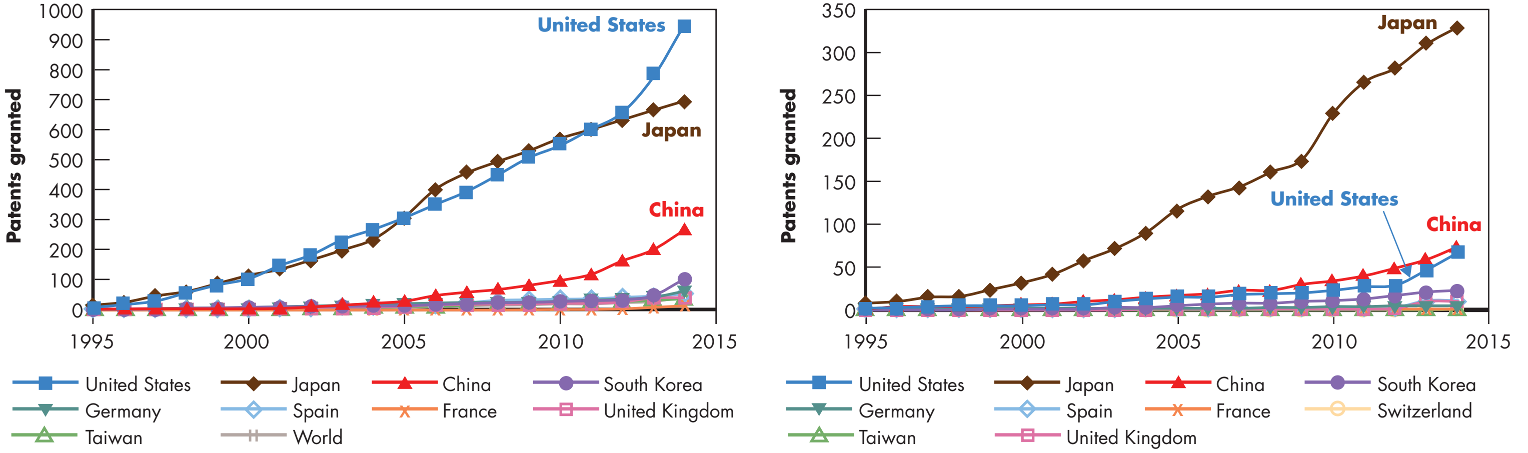
3D printing technologies are evolving very rapidly in the civilian sector. Our research leads us to conclude that the level of capability, stability, and maturity of these technologies is ready for the development of cost-efficient military and civilian applications. Hence, while AM has historically occupied a niche role in prototyping and exotic parts manufacturing, its future will most likely include widespread adoption for MRO at various levels of the supply chain. The subsequent wave will leverage this new technological ability at the very core of the future component and product designs. Multifunctional components, generative designs, and tailorable material properties will transform the way both military and civilian products are manufactured—from simple objects to complete vehicles, airframes, and ships.

The most pessimistic scenario for 3D printing is to view it simply as a drop-in replacement for capabilities within our current toolset. Even if one does not subscribe to the revolutionary material possibilities of AM, the new capabilities it can bring to isolated sites

Figure 10. Patent Volume, by Year and by Search Term

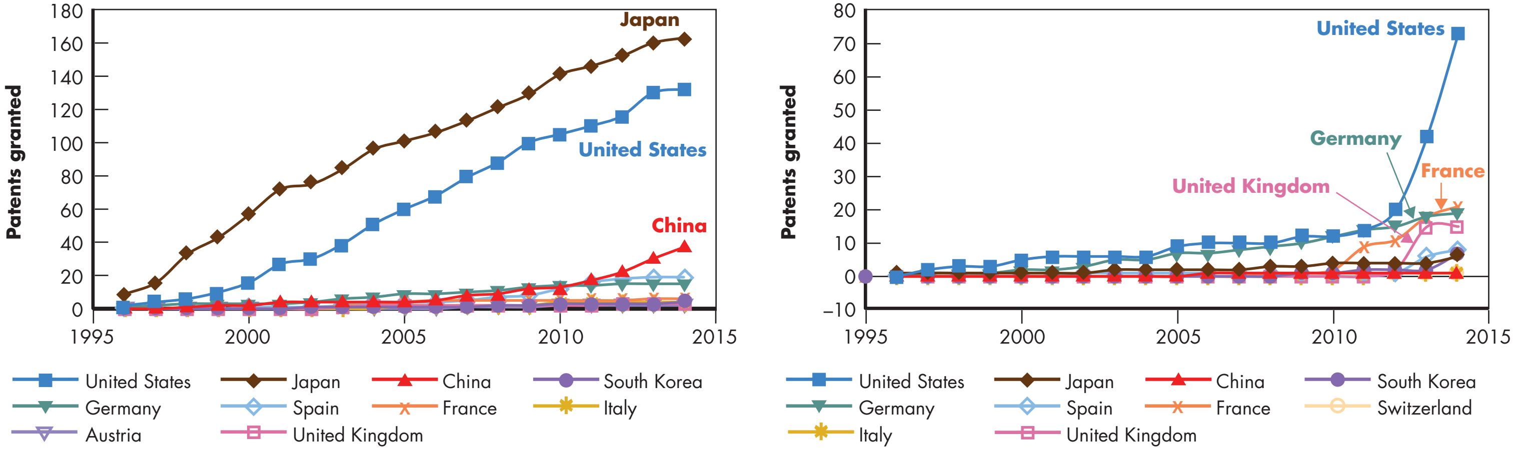
a. Patent search terms: filament or paste

b. Patent search terms: multi-jet modeling



c. Patent search terms: material extrusion sand polymer

d. Patent search terms: powder bed fusion



NOTE: The charts show the absolute number of granted patents by country and by patent class for four search terms from ISO and ASTM (2015). For our calculations, we used data from USPTO and WIPO.

with an ad hoc demand profile should be recognized and leveraged by U.S. military leaders. While consumer applications remain unclear, commercial applications for tooling, prototyping, and MRO are ripe for widespread adoption in the defense context. Our research identified four key considerations for DoD if it chooses to move forward with 3D printing technologies.

There are potentially significant advantages in implementing 3D printing technologies. 3D printing has the potential to be an essential tactical asset by increasing a unit's performance, capabilities, and readiness in remote or isolated areas. 3D printing can generate greater equipment readiness in cases where items cannot otherwise be procured, whether due to obsolescence or a defunct supply chain. It can also be used to create parts more quickly than would be the case if the part had to be obtained through the normal supply chain, and will enable tailored part production unlike any technology in use today.

Further, some monetary savings could be achieved by deploying downstream or distributed production capabilities using 3D printing. Given our findings, we believe that a comprehensive cost-effectiveness evaluation of the technology should be conducted, and we expect that the potential savings will be significant when considering the total supply chain cost relative to the existing process. In some instances, the cost of a 3D-printed part might in itself be less than it would be through traditional manufacturing. Using 3D printing to create parts that are not currently procurable could bring tremendous savings by preventing the early scrapping of systems due to the loss of a few components.

However, intellectual property ownership and licensing issues, as well as cybersecurity issues, must be addressed. Determining intellectual property ownership and licensing of parts so that inventors and original equipment manufacturers can take advantage of downstream production may be the biggest hurdle for implementation. With limited policy guidance and significant uncertainty on the intellectual property implications of the existing technology, it is important that DoD engages in a comprehensive discussion with relevant stakeholders to address concerns about intellectual property ownership and profit-generation in an era of localized production. In some ways, this digitization of manufacturing can be compared with the digitization of music, calling to mind the disruption to the licensing and revenue structure for the record industry caused by iTunes and monetization challenges in the digital age. Until a policy resolution is developed, this will remain an important consideration.

In addition to resolving the legal and monetary implications of the technology, DoD will have to make internal decisions on safeguarding sensitive designs and find an approach to securely and reliably store proprietary and sensitive part designs. Cyber attacks will likely aim at such repositories and adaptations to existing secure networks may be necessary to accommodate 3D printing needs in remote locations.

Relative to other players in the field, the United States has a strong position, complemented by a relatively strong industrial base in some allied nations, particularly in Japan, Germany, and the United Kingdom. We expect competition in AM to increase given the significant potential of the technology. Japan is nearly even with the United States in its intellectual property holdings, and while underrepresented in the patent database, Germany is widely considered by experts in the field to be a world leader. There is also a serious concern that countries such as China and Russia could surpass the United States in developing AM capabilities.

Components which are “designed for AM” could be weaponized, for example, using multifunctional materials to provide new properties for passive and active armor, as well as actual weapons. Without an active military research program, adversaries may be more likely to find and exploit advantages of which the United States is unaware. DoD should capitalize on commercial activity where it can, but should supplement this with selective development of novel components in areas offering military advantage.

Existing acquisition policy and processes must be revised to consider the implications of AM for military platforms. Articulating the need and even mandating a requirement for AM utilization is one potential approach. Others include rationalizing the certification and testing approach for components manufactured by AM technology, ensuring that parts for MRO will be 3D printing–compatible as part of the original design, and increasing procurement flexibility in cases where AM parts and tools provide comparable or superior performance to existing products. Within the next few years, it is reasonable to expect to see weapons systems that include parts designed for AM, which will require AM capability to replace.

Conclusion

Affordable local or downstream 3D printing will impact manufacturing industries worldwide, and may offer DoD significant advantages in supply chain management, readiness, and new capabilities. However, challenges in areas like managing intellectual property, cybersecurity, and acquisition policy must be addressed to ensure success. Intense international competition in the economic and military domains provides strong motivation for a robust DoD investment. For the U.S. military to be successful in deploying this technology, structural changes will be required to achieve an effective transition. As AM supplants some traditional manufacturing and supply chain management processes, collaboration among the U.S. military, industry, and academia will be critical to ensure that the resultant capability gains and cost savings are realized to their fullest extent.

Notes

[1] Other terms previously used for AM are automated fabrication, freeform fabrication, and layer-based manufacturing.

[2] Gibson et al., 2015; U.S. Government Accountability Office, *3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing*, GAO-15-505SP, June 2015.

[3] See Mohammad Vaezi, Srisit Chianrabutra, Brian Mellor, and Shoufeng Yang, "Multiple Material Additive Manufacturing—Part 1: A Review," *Virtual and Physical Prototyping*, Vol. 8, No. 1, 2013, pp. 19–50; and Joseph E. Grady et al., *A Fully Nonmetallic Gas Turbine Engine Enabled by Additive Manufacturing* Part I: *System Analysis, Component Identification, Additive Manufacturing, and Testing of Polymer Composites*, National Aeronautics and Space Administration, NASA/TM—2015-218748, May 2015.

[4] Nikon's performance claim, as witnessed by the research team during a live demonstration on August 21, 2016.

[5] We used the following search terms: material extrusion sand polymer, sheet lamination, powder bed fusion, multi-jet modeling, binder jetting, filament or paste. The total number of patent records analyzed was 102,947.

[6] See China IPR, "China to Provide Financial Incentives For Filing Patent Applications Abroad," blog post, June 12, 2016. See also Foreign Ministry of Finance of the People's Republic of China, "Notice on Printing and Distributing the Measures for the Administration of Special Funds for Patent Assistance to Foreign Countries," April 14, 2012.

[7] Authors' conversation with staff at Lawrence Livermore National Laboratories, June 28, 2016.

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About This Perspective

This Perspective describes potential uses and benefits of 3D printing in a military context to help the U.S. Department of Defense (DoD) understand possible applications and the structural and policy changes that might be required to support these efforts. It discusses different types of 3D printing technologies, tracing 3D printing from its origin to its potential to transform supply chains for DoD. By applying a capability-based definition of 3D printing, this Perspective provides a framework to help DoD think about future impacts on its supply chain.

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