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Key Points

- **Additive Manufacturing is becoming more cost-effective and widely available. Products ranging from titanium components to human tissue can now be "printed." Its use is increasing dramatically with new materials and applications, so national security opportunities and challenges must be addressed proactively.**
- **National security advantages come from manufacturing and medical applications, namely, the ability to create specialized parts cheaply from an ever-growing list of materials. Additive manufacturing could reduce material use, build time, weight, and delivery times. This will bear directly on U.S. security operations.**
- **The ubiquity of this technology means that these advantages will be available to consumers and America's rivals. Its consumer applications may create legal challenges.**
- **This technology could be part of a U.S. manufacturing revolution, allowing innovation and production especially when considered with other technologies.**

Toward the Printed World: Additive Manufacturing and Implications for National Security

by Connor M. McNulty, Neyla Arnas, and Thomas A. Campbell

Additive manufacturing (AM)—commonly referred to as "three-dimensional" or "3D" printing—is a prospective game changer with implications and opportunities that affect not just the Department of Defense (DOD) but the economy as a whole. The technology allows the "art to part" fabrication of complex objects from a computer model without part-specific tooling or human intervention.[1] AM has already impacted a variety of industries and has the potential to present legal and economic issues with its strong economic and health-care benefits. Because of its remarkable ability to produce a wide variety of objects, AM also can have significant national security implications. The purpose of this paper is to provide a general introduction to these issues for nontechnical readers through a survey of the recent history and the current state of technology. Included in this paper is a brief review identifying key individuals and organizations shaping developments as well as projected trends.

AM refers to the production of a three-dimensional object through the layer-by-layer addition of material according to a geometrical computer model. AM contrasts with other forms of manufacturing that require either the removal or alteration of material to produce a completed object. For example, a 3D printer could build a crescent wrench by adding a layer of material and stacking another layer on top of that one and fusing them together, repeating the process until the wrench is complete.

There are distinct benefits to objects produced in this manner. Considering the above example, if a customer wanted a wrench to be fashioned with a grip unique to his hand, he could scan his hand by computer and modify the existing design accordingly before the 3D printer begins production. Additionally, since the wrench is not

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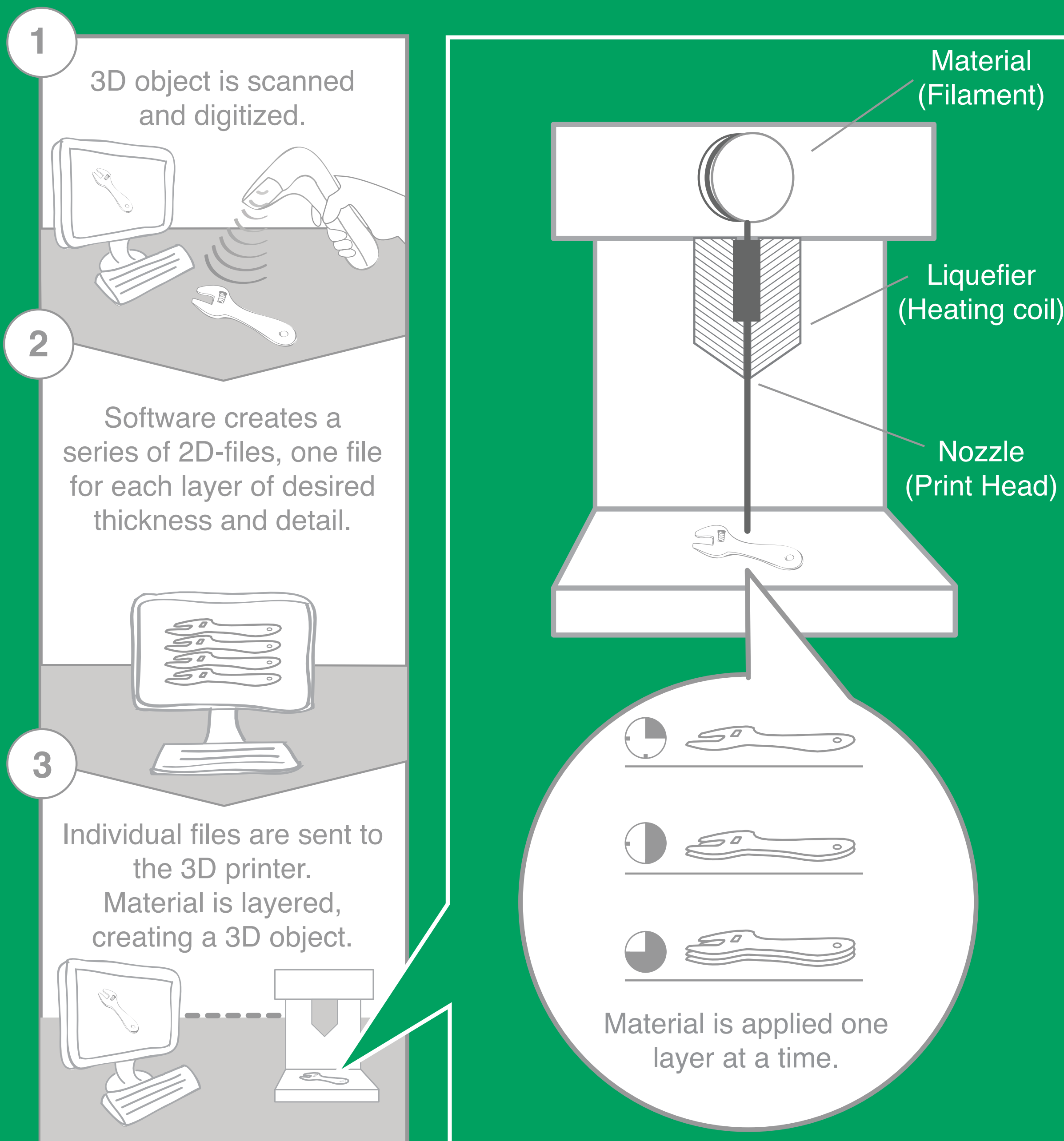
Additive Manufacturing (3D Printing)*



* **Fused Filament Fabrication (FFF) is only one example of the many available 3D printing processes. As building materials such as metals, food, and tissue cells become more sophisticated, so do the manufacturing processes and machines.**

Source: Figure concept by Neyla Arnas, illustration by Olivia Foss, and layout by Joshua McGee.

assembled from preexisting parts, it would be a complete entity—unable to break into component parts as there is only one "part." Since the wrench is made by additive manufacturing as opposed to conventional "subtractive manufacturing"—taking a block of raw material and removing excess until the finished product remains—the process as a whole is more efficient and less wasteful.

Another major benefit of AM is the fact that complexity is "free." In conventional manufacturing, increasing design complexity entails increased costs. AM allows for complexity to increase independently of cost. By AM's very nature of layer-by-layer additions, one can optimize in advance via 3D software a given engineering component's strength, durability, and other material properties. For example, in the aerospace industry, one typically desires high strength but low weight. Weight savings translate into savings on fuel consumption. Traditional subtractive manufacturing is fundamentally limited in its ability to remove material from the interiors of aerospace components to optimize these conflicting parameters. With AM, however, one can design a part to have more material where strength is needed, and less where it is not. Moreover, the changing of a digital design and reprinting of it via AM are more cost-effective than retooling subtractive systems and remanufacturing the same part.

Developed in the late 1980s, 3D printers are becoming more affordable and dynamic, able to handle a greater variety of material than before. Researchers at Wake Forest University have used AM to produce a range of living tissue, including human skin. This potential has not gone unnoticed by the defense community—the Armed Forces Institute of Regenerative Medicine (AFIRM) has funded such initiatives and fostered collaboration between research institutions. Commerce and industry have also been shaped by these developments. The relative ubiquity of 3D printers, combined with the increasing range of materials these devices can handle, has fostered the growth of a new industry around manufacturing specialized components. Likewise, this technology has begun to remove barriers between innovation and production, with smaller firms producing goods quicker and cheaper than ever. This has attracted the interest of government research organizations such as the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA).

The propagation of this technology has generated a host of national security considerations, which connect to broader economic and policy developments. AM can benefit the national security and defense community because of its economic potential. Additionally, it can allow for greater interaction between the national security community and the private sector, as businesses will be able to produce prototypes and sophisticated components more inexpensively and quickly than before. The health-care applications of this technology are remarkable, with 3D "bioprinters" producing viable human tissue and simple organs, for which Food and Drug Administration approvals are pending. Researchers under AFIRM and National Institutes of Health (NIH) sponsorship are now pursuing more ambitious goals, such as producing kidneys and livers viable for human transplantation, as well as durable bioprinters that could be deployed to the battlefield to provide more immediate treatment of soldiers' wounds.

Nevertheless, like any new technology, AM has the potential for uses both good and bad. As AM brings economic benefits, it will also be easier for individuals or small organizations to counterfeit goods and steal intellectual property. Several recent criminal activities have used AM to support fraud and theft. It will be incumbent upon law enforcement and the legal profession to cooperate in protecting entrepreneurs; furthermore, the diplomatic community will need to work with foreign partners to protect American intellectual property abroad. A more troubling prospect involves the technology being used to render detection of nuclear proliferation more difficult, which by itself makes the case for understanding the possible uses of the technology.[2] Addressing criminal and legal concerns will require active cooperation across multiple agencies in the national security community.

Just as the Internet changed the flow of information, AM has the potential to change the range of goods and services available to individuals. Commercial AM systems are now available for purchase (desktop 3D printers cost a few thousand dollars); these systems bring manufacturing to the individual, enabling customized design and printing of anything from hearing aids to shoes.[3] Leaders in the national security field have a unique opportunity to capitalize on these nascent developments and confront emerging concerns stemming from this technology.

Technology Overview

Additive manufacturing is a fundamentally different process of creating a product from raw materials than more traditional manufacturing. Consider a coffee cup: a traditional artisan would take a piece of clay and then mold it into the necessary shape before allowing it to dry or baking it in a kiln. A modern factory would take a block of raw material and then use machinery to pare away unnecessary material until a coffee cup remained (a process referred to as "subtractive manufacturing"). In contrast, AM would stack successive layers of materials until the product was in the shape of a coffee cup and would then fuse it together.[4] Depending on the specific product and manufacturing throughput desired, AM presents a potentially more efficient and environmentally friendly manufacturing approach than traditional manufacturing.

History. AM was initially conceived by several European, Japanese, and American inventors as early as the 1970s, but the technology emerged more rapidly around the same time personal computers and peripherals began to see widespread commercial use. Chuck Hull established the company 3D Systems in 1986, following his invention of the Stereolithography Rapid Printing System.[5] Two years later, Scott Crump developed Fused Deposition Modeling and established Stratasys to market his inventions.[6] Both firms were early pioneers of AM, creating a niche market for specialized components. AM met this need because it could respond to minute variations in design and produce small orders more cost-effectively than could traditional manufacturers.

These two technologies were referred to as "rapid prototyping" for the segment they occupied in the market. Their speed, efficiency, and minimal material waste allowed these early companies to cheaply produce models and small prototypes before mass production would begin. At the same time, others sought to use lasers to melt metal powders for AM. Ross Housholder's 1981 patent first described this process, but the technology was further developed and commercialized by the DTM Corporation, which licensed Housholder's patent.[7] DTM combined Housholder's work with the work of Carl Deckard, then a graduate student at University of Texas, Austin. DTM produced the first 3D printing device that employed Laser Sintering. Finnish researcher O. Nyrhilä drew upon this work to develop Direct Metal Laser Sintering. The former process uses a laser to solidify metal powder layer-by-layer, while the latter uses laser sintering to build metal parts during the building process.[8] Since the development of these processes, there have been myriad novel variations on them to manipulate different materials and create more complicated products.

The basic research for AM was dominated by the United States through the late 1990s when public funding decreased, hoping that industry would fill the gap. Today, the applied research is dominated by Europe, especially Germany.

The aforementioned developments in manufacturing processes have also dramatically changed the range of materials that AM can employ. Whereas early systems employed only plastics, higher temperatures and lasers have allowed for the use of metals, including titanium, which has a high melting temperature. Using a variety of materials, different composites can be manufactured, as 3D printers can join many materials together seamlessly. Recently, Objet announced that one of its AM systems can print with over 100 materials.[9] This sophistication encouraged recent experimentation with organic materials.

With the increasing commercial availability of AM, medical researchers and bioengineers are working to adapt this technology to develop bioprinting, where 3D printers produce organic material.[10] Gabor Forgacs, a professor at the University of Missouri, is leading a team of researchers to develop the underlying bioprinting technology. Forgacs is the founder and current Chief Scientific Officer at the biotechnology company Organovo.[11] Though this technology is in its infancy, the ability to produce a three-dimensional biomodel directly from a design could create a new generation of capabilities for tissue regeneration and organ transplants.

State of the Art. As with the personal computer, the maturation of this technology has seen the price per unit decrease. As 3D printing technology became more readily available, the range of materials it can handle has also expanded. The combination of these two factors has resulted in a steadily increasing output of goods and services provided by additive systems. This technology is widely distributed throughout the developed economies, especially in the United States, Europe, and Asia.

For manufacturing and services, AM has strong potential. Niche manufacturers and producers of specialized components have used the new technology to produce specialized components, especially complicated ones and devices whose function could not be adequately performed if they were produced by older types of manufacturing. Examples include aircraft components and customized health-care devices such as hearing aids. 3D printers are now able to produce titanium and steel components, which will greatly expand the range of goods that these devices can produce. As with personal computers, miniaturizing 3D printers has done much to help their distribution.[12]

The "printing" of food is also being explored by several groups. For example, students at Cornell University designed and built the Fab@Home extrusion printer for its unique capability to extrude food pastes into products such as wedding cakes.[13] More recently, a graduate student researched the design and construction of a printer for making burritos.[14]

Beyond their potential for revolutionizing production, 3D printers have fostered significant developments in health care. The Wake Forest Institute for Regenerative Medicine (WFIRM), based at Wake Forest University, has successfully used 3D printing technology to create human tissue. Cells were used in place of an inkjet cartridge to create a two-chamber heart. While this process is strictly experimental and not for use in patients, its potential could revolutionalize organ transplants. Dr. Anthony Atala of WFIRM has demonstrated an ongoing effort to grow human kidneys using 3D printers. To describe the process succinctly, the 3D printer constructs a frame from organic material and then places human tissue into the frame so that it grows and connects to form a functional human kidney. Creating an implantable kidney would represent a quantum leap in medical progress. At present, Atala's team has produced a kidney; however, additional research is needed before this process can be used clinically.[15]

The above examples provide a sample of the various projects being undertaken using AM. These changes in manufacturing and product distribution, as well as the potential revolution in regenerative medicine, are inextricably linked to national security issues.

Economic Impacts and National Security Implications

Developments in AM have captured the imagination of many writers and commentators. They see the technology as strengthening entrepreneurship by removing entry barriers in the manufacturing sector, while appealing to the green movement by substantially reducing waste. The predominant development of this technology in the United States has led some analysts to claim that AM offers a means to achieve an economic advantage in the face of rising Chinese manufacturing.[16] *The Economist* predicts the technology will have as profound an impact on manufacturing as modern assembly-line factories have had, since 3D printing will undermine economies of scale by making it as cheap to produce one item as many.[17] Further, by undermining the need for some factories, 3D printing could challenge the necessity of low-cost, low-wage countries to produce goods.[18] It is also worth exploring the potential impact on employment rates. The New America Foundation, a Washington, DC–based nonpartisan think tank, has noted these trends and detailed an economic recovery strategy that highlights this technology as one of several that could stimulate American manufacturing.[19]

Though forecasters see tremendous economic potential, there has been little analysis of the national security implications of this technology. For example, questions remain about the impact of AM on energy consumption.

Potential AM Implications for DOD

Revolutionary Production	
Efficient use of resources	Fewer processing steps, net-shape, less assembly, post-processing, less waste material, less energy
Small lot productions	Production in lot size of 1, mass customization
Rapid manufacturing	Tool-less, extreme cycle time reductions
Agile manufacturing	Spare parts on demand, no stockpiles, simplified supply chain/logistics
Reverse engineering	Scan and manufacture parts for legacy systems
Cost reduction	Expendable/disposable products

Enabling New Technology	
Lightweight structures	Weight removal increases mission capabilities
Modularity	New designs to switch components in and out
Complexity	Exotic structures, functionally-graded materials, fabricated moving joints, embedded electronics

Local Production	
Factory-less production	Remote, mobile fabrication
Agility/flexibility	Rapid response to changing missions
Shortening of supply chain	Potential use of local raw materials

Source: Jennifer Fielding, National Advanced Manufacturing Innovation Institute (Additive Manufacturing Symposium, Washington, DC, August 20, 2012)

According to the Department of Energy (DOE), generalizations cannot be made in terms of the entire AM sector. Energy savings are product-specific and vary extensively.[20] In fact, the low-end, high-volume consumer market poses the biggest potential for environmental waste. The plastic materials most commonly used in commercial 3D printers could pose recycling challenges.[21]

DOD has aggressively pursued these technological developments through its various research arms. Partnering with industry and academia, DOD has pursued AM initiatives to address strategic needs, especially through the ONR. The National Network for Manufacturing Innovation (NNMI) announced the single awardee for a $30 million pilot institute with a focus on AM.[22] Funded by multiple agencies, including DOD, DOE, Department of Commerce, and the National Science Foundation (NSF), this pilot institute serves to accelerate commercialization of various AM processes. These initiatives, as well as emerging opportunities and concerns presented by this technology, are considered in this section.

Several organizations have been involved in fostering this technology. Of these, AFIRM and ONR are directly promoting the development of additive manufacturing. In 2010, AFIRM funded several completed and ongoing research projects that contributed to miniaturization or the use of novel materials in additive systems.[23] ONR contributed by providing grants to academic institutions active in advancing the technology,[24] and by soliciting designs from industry to meet future strategic goals and operational requirements. ONR has shown special interest in desktop manufacturing, a process developed by Stratasys (and commercialized by firms such as Makerbot) using smaller and cheaper additive systems to produce plastic components.[25] The Defense Advanced Research Projects Agency (DARPA) has shown interest in this technology, most recently partnering with Georgia Tech and Stratasys to provide 3D printers for high schools across the country.[26]

As the volume of investment suggests, the defense community sees significant potential for AM. The above pattern of investment suggests that there is pressure to integrate the currently developing technology into ongoing defense projects. The joint initiative between Georgia Tech and DARPA was conducted through the latter's MENTOR (Manufacturing Experimentation and Outreach) program. As noted above, there are parallels between the development of the personal computer and the gradual propagation of additive systems. As the personal computer became both affordable and easy to use, information-sharing dramatically increased while the associated cost decreased. By funding this technology before it fully enters the consumer market and collaborating with those developing the systems, the aforementioned government agencies will have an advantage in its future gains. Likewise, DARPA's investment demonstrates the possibility of addressing U.S. science, technology, engineering, and mathematics (STEM) deficiencies while creating a pool of individuals who have experience with a technology that a *Forbe*s columnist claimed could keep U.S. manufacturing ahead of China's.[27]

Despite the decreasing costs and lowered barriers to entry, Terry Wohlers of Wolhers Associates, Inc., writes that additive systems will not become a household product in the same way the personal computer did.[28] The vast range of materials used in creating household products will make personal use prohibitively expensive and impractical, while the average user would not have the requisite skills to use the device effectively. Instead, Wolhers contends that retailers such as Amazon may become directly involved in producing the products they market.[29] For example, if Amazon wanted to offer customers greater variety in its electronic reading device, the Kindle, it might invest in 3D printers to make the casings rather than outsourcing to an outside manufacturer. Likewise, a company would hypothetically invest in 3D printing to cheaply produce replacement parts rather than ordering in bulk from a manufacturer and keeping the stock in inventory, or requiring the customer to purchase a new device. Taken a step further, one could imagine a digital library from which parts or objects would be built on demand, on site. This sort of "focused logistics"—the right part, at the right place, in the right time—would translate into important implications for the DOD supply chain and logistics.

The ability to produce replacement parts seems like an attractive notion from the perspective of the military, by allowing reduction of logistics costs associated with transportation and storage, for example. One of the big issues regarding the potential for AM in the military is the "diminishing sources of manufacturing supply," or DSMS. While DSMS is not an issue solely related to AM, the challenges posed by DSMS to the use of AM for replacement parts are illuminating. For instance, DOD has the challenge of maintaining equipment for which the replacement parts have gone out of production. This is a complex problem because, in many cases, not only has the part gone out of production but the capability to produce the part has gone away. The ability to affordably produce components in small quantities is a key element of supply. The challenge is that producing these replacement parts is intimately tied up with reverse engineering: it is not enough to print something that looks like the replacement part in question; it has to meet the same specifications so the original item will function as intended. Therefore, the companion problem is that in many cases the critical specifications have not been recorded. This means that while we may know the size and shape and weight and material of an item, we do not know which of those are there because they are essential to working the system. Reverse engineering the critical characteristics of replicating a part is very important. This in turn raises pervasive policy issues such as the kind of data we need to capture for everything we buy that we may need to replace in small quantities later.[30]

The long-term macroeconomic effects of this technology are difficult to predict; however, some of the possible developments could directly impact national security. As 3D printers become cheaper, prototyping becomes cheaper and, as noted above, more firms can become directly involved in production. As the defense and security community addresses a greater variety of threats, small firms or even individual entrepreneurs can use this technology to provide a wider range of services to the government. Though there are many benefits to such cooperation, the downside is that more individuals will have access to sensitive information. Likewise, reduced cost and increased efficiency make illicit reproduction of this sensitive technology easier. On a larger scale, the productivity gains of AM could plausibly lead to increased productivity per employee in the United States, which itself could result in additional economic benefits. As mentioned earlier, however, it could also displace currently employed workers producing results similar to the impacts automation and robotics had on the U.S. manufacturing industry. In any case, widespread manufacturing use of the technology will require a workforce specifically trained for it. The machinist in an AM future would be a worker skilled in computer-aided design (CAD)[31] who understands materials and process options as well as capabilities and limitations.

The propagation of this technology also entails new crime concerns that need to be considered. Recently, there have been reports of criminals reproducing small parts of computers or other machines (including guns which we discuss below) and using them to defraud consumers. For example, a criminal group used a 3D printer to produce a device that, when installed on an ATM, stole bank customers' information.[32] This suggests both the potential for criminal activity and the possibility of using additive systems to reproduce proprietary technology. The legal considerations of both these issues are considerable. The potential economic disruption, insofar as it applies to national security, is that with the spread of this technology, there will be a new need for law enforcement to protect inventors' rights. Likewise, it will raise issues regarding security of export-controlled technology, especially since 3D printers will make reproduction easier. Shortening the distance between innovation and production means the relationship between inventor and invention will change; protection of both the inventor and the consumer should be a priority for policymakers as this new technology develops.

Impacts on Health Care and National Security

As earlier sections of this paper show, substantial innovations in health care made possible by AM have allowed small firms and individuals to produce unique objects that would have otherwise been impractical or required increased investment. The bulk of this has come in the field of regenerative medicine—the synthetic reproduction of lost or damaged tissue, organs, or limbs. AFIRM has contributed extensively to the financing and direction of this research. Wake Forest University and the firm Organovo have succeeded in growing several varieties of human tissue, with the latter considering using laboratory-grown human tissue to test experimental drugs on behalf of pharmaceutical companies.[33] The implications of this technology suggest a Kuhnian revolution.[34] By scanning a patient's organ to create a three-dimensional template on a printer, a replacement organ could be constructed that is specific to that patient. In doing so, many complications from transplantation could be avoided, while the supply of organs for transplantation could theoretically be rapidly expanded. Critical injuries sustained on the battlefield or in a mass casualty incident could be treated more effectively than current technology permits. The availability of living human tissue for experimentation would lead to a wealth of new empirical data to improve both treatment and understanding of the human body. Worth remembering, however, is that much of this technology is still largely theoretical and requires substantial development before application. Issues such as cost, access to the technology, and patient security will accompany positive developments in this field and cannot be overlooked by policymakers in considering this technology.

Wake Forest University has developed one of the first successful printers to produce human skin; it is presently capable of printing skin directly onto a patient's wounds.[35] AFIRM has leveraged this technology and, collaborating with Dr. James Yoo of Wake Forest and with industrial partners Lexmark and Organogenesis, Inc., is undertaking a program for the printing of skin on the battlefield to treat wounds. This program has so far resulted in a portable skin-printing device that has produced full-thickness human skin.[36] Both Organovo and Wake Forest have yielded significant advances, and many other researchers are finding potential uses for bioprinting, from bone regeneration to industrial-scale production of biomaterials.[37]

Additive manufacturing impacts health care beyond bioprinting. As noted earlier, one of the most significant segments for firms using AM is specialized medical components. Beyond orthodontics and hearing aids, manufacturers such as Bespoke Innovation use the customizable aspects of AM to produce parts for prosthetic limbs.[38] As specialized components become easier to produce, there is the potential that associated health-care costs could decline.

An implication that has not yet been discussed within AM technology circles is personalized body enhancement. Inorganic hybrid materials (electrical, optical, etc.) are being intensively researched now.[39] The potential for printing a bio-compatible heart with perhaps an Olympic athlete's capability or a prosthetic leg with enhanced performance is hypothetically feasible. The authors here anticipate such innovations will be considered once the technology becomes available.

The impact from AM on health-care economics will most likely be much more complicated than a matter of changing costs. Many economists have observed a growing disparity between the capabilities of a technology and the skills required to use it, especially in health care. Though new components and tissue may become available, additional expenses are also likely as this industry will require a new class of experts. This disparity could also potentially require fundamental reconsideration of how health-care resources are made available to patients. These issues will be critical in the future and require further evaluation, but an extended analysis falls beyond the scope of this paper.

Despite the uncertain impact 3D printing will have on health-care economics, this technology has the potential to take part in a larger trend in medicine: namely, the growing potential for care specifically tailored to the patient. Dr. Henry Miller at Stanford University recently commented on the potential that individual biological indicators could have in guiding treatment. These indicators can show how receptive a patient is to certain drugs or other therapy and can allow physicians to deliver more sophisticated care.[40] As noted earlier, developments by Wake Forest University researchers have shown the possibility for growing tissue using biological material from the patient, while the company Organovo is exploring the potential for growing organs to better study how drugs are absorbed. AM can potentially contribute to this larger trend of delivering more personalized medical care, whether through the design of specialized medical components or printing organs using material harvested from the patient as a template.

In sum, AM's contributions to health care have a direct bearing on U.S. national security. As discussed, technological developments now allow for the efficient production of human tissue, which, under certain conditions, can be applied directly to a wound or infection. This could dramatically change the way battlefield injuries are treated and reduce the number of fatalities during combat operations. This potential has not gone unnoticed—indeed, DOD is both funding and actively directing research in this field. Furthermore, bioprinting has the potential to significantly reduce organ shortages and provide a host of tissues grown from a culture provided by the patient. If successfully developed, this technology could make future transplants much more successful, as the human body would not reject something produced from its own DNA. Such a major change in health care would have concomitant impacts on the national health-care system, the health-care industry, and the general practice of medicine. These changes, in turn, have a direct bearing on societal functions, and will bring with them a new generation of security questions.

National Security and Legal Considerations

As noted previously, AM dramatically reduces overhead costs and material requirements for creating finished products, especially complex, individualized ones. This allows for a host of new producers, each capable of making specialized components to meet specific needs. Though it appears unlikely that additive systems will reach the same popularity in the near term as the personal computer (due to material, cost, and skill constraints), they will be readily available to those who see financial incentive to engage in small-scale manufacturing. This creates the potential for criminal activity. Much of the value produced in the U.S. economy arises from research and innovation. AM makes it easier for small-scale producers to violate copyright laws and patent restrictions, especially if they are servicing a discrete market or operating outside the range of U.S. enforcement. This presents a novel threat to U.S. economic interests that will need to be addressed as part of larger national security policy. An associated threat is the easier propagation of U.S. export-controlled technology. Since AM is already used to produce highly sophisticated components, the spread of this technology will make it easier for foreign agents to simply copy a physical component after scanning an original. Finally, there remains the concern arising from criminal use of this technology to defraud consumers or circumvent security measures. This will require renewed cooperation between law enforcement and industry to prevent such criminal efforts.

As AM has made the production of simple components easier, the distinction between original idea and physical product becomes blurred. Michael Weinberg reviews the host of legal issues presented by AM.[41] Of particular concern is how the enforcement of copyrights, trademarks, and patents should be handled given the potential to easily reproduce components or entire parts; the oncoming struggle between intellectual property holders and small producers needs to be resolved. The outcome of the legal battle will necessarily determine how law enforcement and prosecution are conducted, which will require the participation of national security policymakers. The precise role of law enforcement and the national security community will have to be determined by the legislative and judicial branches.

Legal and security challenges are emerging from AM because of its relative availability and the range of products the machines can be used to produce. As noted earlier, a group of criminals used a 3D printer to produce devices which could retrieve bank customers' information from an ATM to steal several hundred thousand dollars.[42] Weapons production is also a concern. August 2012 news articles[43] describe the complete fabrication of a .22 caliber pistol (excepting the precision metal rifle bore) via 3D printing. The finished system was able to shoot 200 rounds with no evidence of wear or tear. More complex, perhaps even enhanced, weapons will be made eventually by individuals. National security implications of such weapons production are obviously substantial. These developments raise a host of concerns for law enforcement and antiterrorism organizations as 3D printers could allow production of firearm parts which otherwise would require a license to purchase commercially.[44]

The security and legal concerns presented by AM come from the equipment's ability to cheaply and efficiently produce fully functional components on demand. At present, 3D printers can create a limited range of products, but their capability is expanding. With increased availability, these printers will make it easier for local and foreign producers to circumvent U.S. intellectual property law. Protecting American manufacturers and businesses will require cooperation from the law enforcement and legal community, as well as the diplomatic community, to disrupt overseas counterfeiting activity. Additionally, since this technology will open manufacturing to smaller producers, the national security community will need to exercise additional care in protecting information and technology when working with the private sector. Lastly, relevant actors in the government will need to be aware that 3D printing technology in the immediate future may afford individuals and small organizations access to weapons or other devices they may not have previously had access to. Weapons supplier middlemen could be removed from the supply chain if terrorists were to obtain high-end 3D printers and digital designs of weapons systems. Addressing such concerns requires foresight and cooperation across all organizations involved in national security policy.

The recently launched National Advanced Manufacturing Innovation Institute (NAMII)—a pilot program within the National Network for Manufacturing Innovation—is poised to help AM transition to commercialization of products and processes, and by doing so, improve U.S. economic competitiveness. NAMII aims to bridge the gap between basic and applied research with a strong emphasis on workforce development. The education component will focus on enabling the future workforce to be cognizant of and trained in AM.[45]

The Center for Technology and National Security Policy (CTNSP) at National Defense University (NDU) has proposed an additive manufacturing initiative that will be launched in the form of a challenge under the America Competes Act. This challenge will examine the uses of additive manufacturing for humanitarian assistance and disaster relief (HA/DR) operations. The challenge will be to produce a fabrication environment under austere field conditions (such as might be found during HA/DR situations) using additive manufacturing systems. The initiative will also leverage the knowledge base within Transformative Innovation for Development and Emergency Support (TIDES), a DOD knowledge-sharing research project located within CTNSP.[46]

Significant Actors and Trends

Recent developments in AM have been closely linked with the development of the personal computer and CAD software. Some of the earliest technology that expanded the range of materials that designers could use came from engineering students and researchers at the University of Texas, Austin. Drawing upon early theoretical work, engineers and researchers there received the first patents. These patent-holding, individuals-turned-entrepreneurs successfully commercialized 3D printing technology, with Scott Crump of Stratasys, Inc., and Chuck Hull of 3D Systems as prime examples. These early firms have successfully continued to develop the field while acquiring additional patents and licenses from other noncommercial entities. 3D printing has gained an increased commercial presence, with firms such as MakerBot producing desktop 3D printers—small, cheap 3D printers that offer a robust array of design options. Reports are coming from China about the development of the MakiBox, "an easy-to-assemble 3D printer that will retail for about $300. It will also offer a new way to feed plastic source material into the machine, eschewing the conventional string filament used by most printers in favor of much cheaper pellets."[47]

It is this combination of an increased variety of materials handled by the printers, miniaturization, and declining cost that has accelerated development. The unclassified literature and news reports show that the Department of Defense and Federal Government research organizations have been and will continue to encourage these developments, with the former seeing immediate tangible benefits for national security. Virginia Polytechnic Institute and State University (Virginia Tech) researchers Thomas Campbell and Christopher Williams have partnered with NDU to explore incorporating AM into NDU projects such as TIDES; they are also advancing the AM field even further by researching its convergence with nanotechnology.[48]

Commercial application has become extensive, ranging from a British firm "printing" cars,[49] to Reebok using 3D printers to prototype new shoes,[50] and even to Hollywood producing costumes in movies.[51] These commercial applications, as noted above, have attracted the defense community, with the military looking to use this technology to produce replacement parts for vehicles.[52] Also of interest to the defense community is the notable potential this technology presents for the elimination of the costly logistics chain by allowing on-site production of parts, eliminating costly transportation and storage.

A Sampling of Firms Employing Additive Manufacturing

Firm	Product/service
Apple	Prototype custom design service and 3D printer
Bathsheba Sculpture, LLC	Custom design and sculpture
BMW	Car manufacturer
Boeing, Inc.	Aerospace systems
Choc Edge Limited	Baking and confectionary equipment
EADS	Aircraft and defense company
EnvisionTec	Dental equipment manufacturer
Fisher-Price	Toy company
Ford	Car manufacturer
General Electric	Electronics, defense, and heavy manufacturing
Harley Davidson	Motorcycle manufacturer
Northrop Grumman	Defense company
Raytheon	Embedded electronics
Reebok	Footwear and clothing company
Shapeways	New York City–based specialty design firm
Stratasys	AM systems supplier
3D Systems	AM systems supplier

Note: This list is by no means complete or extensive, but it illustrates at a glance the extent to which this technology is employed across a range of industries and products.

AM has successfully propagated through much of the advanced manufacturing sector,[53] but, to quote a blogger for *Computer World* magazine, it has yet to reach its "iPad moment"—the point at which it is easy to use and attractive to the average consumer.[54] The potential that AM has for changing the innovation process has also impacted art and design, with sculptors using it to create novel three-dimensional figures.[55] In Washington, DC, the Renwick Gallery's exhibit "40Under40: Craft Futures" features an artist whose works are manufactured from a 3D printer.

Bioprinting has grown through the collaboration of federal research organizations and academia, and has since drawn attention from the private sector as medical and high-tech industries seek access to organic materials similar to human tissue without endangering human or animal subjects. The NSF grant to Gabor Forgacs led to the research that the firm Organovo uses in its business. Likewise, a researcher at the ONR, Douglas B. Chirsley, collaborated with University of Manchester researcher Brian Derby and several other academics to hold an international conference on bioprinting in the early 2000s. Convergent, if not collaborative, developments have also occurred at the McGowan Institute and Wake Forest University. The latter recently demonstrated the capability to grow a variety of organs, including kidneys, which are much more complicated than earlier tissues produced. Bioprinting continues to grow both independently and in partnership with government research organizations such as the NIH and AFIRM.

The most attentive coverage of developments in the field has come from the consulting firm Wohlers Associates, which offers periodic reviews and projections of future developments. Media coverage most reliably comes from science and technology–focused publications, notably *Wired* magazine and the *The New York Times* science section; also, articles in *The Economist* and *Financial Times* have drawn increasing media attention.[56] Such media coverage, technological developments, and growing federal interest have led several think tanks to consider AM's impact on science and technology policy. The Atlantic Council and the Brookings Institution have issued reports on the matter, and additional coverage will likely be forthcoming as new developments are announced.[57]

In spite of growing media visibility of AM, impediments to its wider adoption remain. Barriers include material types and properties, part accuracy, surface finish, fabrication speed, data formats, among others. Of particular note is the lack of AM standards, domestically or internally. Improved measurements and standards will help overcome existing AM limitations. The National Institute of Standards and Technology (NIST) is working on new measurement methods and standards with promise to drive industry growth and widespread adoption of AM technologies.[58]

Additive manufacturing/3D printing has the makings of becoming a game-changing technology that would impact applications of critical importance to DOD. It bears continued monitoring and DOD involvement. The Center for Technology and National Security Policy at NDU will continue to assess this technology's impact on science and technology policy, while monitoring and advising on its effects on national security.

Conclusions

Recent developments in additive manufacturing have exhibited the potential to improve manufacturing and create new products. Using less base material and capital equipment than other manufacturing procedures, AM has led to affordable, commercially available 3D printers and has been a boon to designers seeking custom-designed, inexpensive prototypes and to manufacturers of specialized components requiring variation from product to product. The marketing and development of 3D printers may be led by broad consumer interest, especially as the availability of affordable desktop 3D printers grows. The increasing array of materials these devices can handle means that a wider variety of products could be made by 3D printers. That said, much growth potential remains in the field of materials research and development as well as hardware and software improvements and innovations. AM has benefited some designers who have been able to use it to cheaply and quickly build their designs, shortening the distance between the design and production phases. The technology has also been expanded into research in organic materials. As AM can respond to minute variations between production runs better than earlier manufacturing processes, it would be ideal for producing human tissue to help the sick or injured. Already producing skin, bladders, intestinal segments, and bones, this technology could possibly create viable kidneys and other organs in short supply.

The benefits of AM to the national security community stem largely from economic and health-care developments. Additive manufacturing is already used to make specialized components such as aircraft parts and health-care devices, and could be used to respond to the various needs of government agencies. Likewise, the military is actively investing in this technology through its programs in regenerative medicine, seeing this as a means to treat severe battlefield injuries. ONR sees 3D printers as a way to address its own equipment needs, and DARPA is supporting the further propagation of this technology. It is difficult to predict future outcomes, but current trends suggest that AM has much to contribute to U.S. national security.

Nevertheless, the same factors that make this technology so potentially beneficial also give rise to concerns. Because AM can produce equipment for the national security community, additional security measures for government projects may be necessary. Since there will be fewer barriers to entry for potential manufacturers, the legal, law enforcement, and diplomatic community will need to take steps to prevent counterfeiting and protect intellectual property

AM Research Opportunities

Process modeling and simulation	Need to further the basic science underlying AM
Process control	Need for real time monitoring to adjust for errors to ensure quality output
Part certification and reliability	Need for part quality certification with industry- wide standards
Printed electronics and hybrid AM systems	Need to develop "printable" conductive materials and inks that can be integrated into existing AM processes. Need for development of hybrid AM systems that incorporate multimaterial deposition capability to enable the creation of parts with embedded electronics.
Open architecture AM systems	Need for systems that provide researchers the freedom to experiment in order to advance the basic understanding of AM technologies
High-throughput AM systems	Need to develop AM systems with higher printing speed and/or reduced process inefficiencies
Bio 3D printing	Need to develop bio-compatible materials and AM processes capable of being certified for medical device fabrication
Anti-counterfeit measures	Need to develop anti-counterfeiting measures for AM part creation (e.g., selective embedding of nanoparticles to create part-specific signatures)
Design for AM guidelines and methodologies	Need to create new design guidelines within new manufacturing paradigm
Workforce education and developments	Need to update educational curriculum to include AM as a merger between design and manufacturing

Source: Many of these opportunities were outlined in D. Bourell, M.C. Leu, and D.W. Rosen, eds., *2009 Roadmap for Additive Manufacturing*, and were summarized and expanded by Christopher Williams, Virginia Tech.

both locally and abroad. Likewise, the national security community will need to be aware of potential moral hazards as it invests in the health-care capabilities of AM, as well as the economic impacts of health-care developments. Lastly, the spread of this technology brings associated legal concerns ranging from how patents, trademarks, and copyrights will protect improvements made by additive systems, to individuals using 3D printers to perform increasingly sophisticated criminal activities.

AM is already changing manufacturing, retail, and health care. DOD has committed substantial resources and effort to furthering this technology, as have other government organizations such as the NSF and the NIH. Given the wide-ranging effects of these technological advancements, it is imperative that policymakers within the national security community be aware of these developments.

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