

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

YOUR NEXT AIRPLANE:

JUST HIT PRINT

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ABSTRACT

In 2011, very few people had ever heard of 3-D printing. By early 2012, 3-D printing was buzzing daily on most technology news feeds. Articles by the dozens promised every American access to cheap and near instant fabrication. If left to development only by those envisioning cheap plastic gimmicks, 3-D printing will fail to significantly impact the market, but if properly managed, 3-D printing can revolutionize the military through three principal benefits: cost, capability, and flexibility.

3-D printing will enable the military to save costs by decreasing the material used for production, decreasing the requirement for supply chain infrastructure and movement, decreasing the requirement to keep large quantities of back stock in anticipation of part failure, and by enabling more cost efficient production for limited run or obsolete parts. The capability improvement comes from lighter parts made possible by 3-D printing, cheap customization increasing warfighter effectiveness, decreasing mean time to repair, and decreasing supply lines. Finally, flexibility comes with 3-D printing's already significant contributions to rapid prototyping.

While DARPA has promoted many programs at universities, in order to maximize influence in shaping the applications of this new technology, the military must continue to get more involved. Each day, new applications arise, many of which can be tailored to either commercial benefit or military utility. For the military to steer the dialogue over the upcoming 30 years, involvement is required now.

Your next airplane – just hit print

In 2011, very few people had ever heard of 3-D printing. By early 2012, 3-D printing was buzzing daily on most technology news feeds. Articles by the dozens promised every American access to cheap and near instant fabrication. If they could conceive it, 3-D printing could manufacture it. Demonstrations by emerging printer makers turned out everything from custom chocolate sculptures, to firearms printed in your basement, to light-weight, fuel-efficient printed cars. University research grants promoted even more high-tech printing, allowing prototypes of completely printed aircraft, NASA rocket parts, nano-structures, and even human body parts printed with stem cells. One could quickly be caught up in the revolutionary craze; but in a minute of sanity, one would ask if 3-D printing could live up to the imagination or if it would fade back into obscurity with so much promised but relatively little delivered.

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BACKGROUND

3-D printing, including the processes known as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM), is an additive process. This means that it adds material to build, rather than whittles or machines down a larger block of raw material. The standard 3-D printer prints in the X, Y-axis only, creating one Z-axis layer at a time with a vertically moving print tray. Some newer adaptations move the printer head instead of the Z-axis, potentially allowing for a larger and more stable print area, since the object doesn't have to move in relation to the environment.¹ A computer aided design (CAD) model of the desired object is loaded to the print software, which slices the model along the Z-axis to the

machine's resolution, typically between 10 and 100 micrometers. In the filament fusing process, usually with plastic, but possible with many low melting point substances, liquefied material is deposited on the print tray from a heated syringe, building upon itself with each subsequent Z-layer. With SLS/SLM/EBM, usually with metals, the printer deposits a bed of raw material powder on the print tray and the laser selectively melts and fuses the powdered material particles. If desired, the user can achieve better resolution by printing the object slightly larger and then using a subsequent subtractive process to smooth the shape.

Many "home enthusiast" models are readily available for as cheaply as \$300. These lower end models are mostly low power, creating their product from various plastics. Recently, more innovative companies have expanded the materials base to soft metals, other polymers (like nylon), and even candy or chocolate.² These machines typically have smaller production chambers and lower resolution. However, even these "low budget" products offer significant capability including the ability to rapidly prototype products and even print most of the printer's own parts, meaning once purchased, a user could print himself additional copies of the printer³.

Further, an important companion technology is available even for entry-level manufacturers. 3-D scanning allows quick replication and customization of objects for printing. Phone and video game cameras now have enough resolution to 3-D scan merely using open source software. More advanced 3-D laser scanners allow the user increased fidelity. For only a few hundred dollars, users can either utilize existing hardware and software, as evidenced by open source adaptations of the Microsoft Xbox Kinect⁴, or create their own 3-D scanning solution, as one engineer did with commercially available components⁵. The almost negligible price tag allows even the smallest of start-up entrepreneurs to leverage the tool. Once scanned, users import the file into any number of CAD programs that eventually translate to the 3-D

printer. 3-D scanning increases the power of 3-D printing by enabling rapid replication and modification of existing objects.

Industrial 3-D printer models typically retail for between \$2000 and \$1M, allowing more resolution, fabrication size, and a wider range of materials, including metal alloys, titanium alloys, complex polymers, and even multiple materials simultaneously.⁶ Some users have removed fully functioning machines from the printer tray upon completion of printing.⁷ In fact, Southampton University in the United Kingdom produced multiple working UAV prototypes from a 3-D printer.⁸ The aeronautical engineering college course allowed students to design and build their own aircraft, then further modify design as flight test pointed to deficiencies. Printers that output multiple materials, including circuitry, increase capability while decreasing complexity at the user end of production. NASA recently announced that they are producing steel and titanium parts for their next rocket booster system with 3-D printing, displaying a steel rocket engine part from their 3-D printer.⁹

While 3-D printing has been around since the 1970s, the recent improvements in consumer computing power and internet based open source collaboration merged to allow a surge in both the profile and development of the technology.

COST

One of the first considerations any industry gives new technology is subject to the ultimate question of its effect on the bottom line. Recent history has put the military-industrial complex on notice to reduce costs. With tightening corporate purse strings and government imposed austerity measures to relieve pressure from massive debts incurred in a long recession, the military will not be immune to continued budget cuts. Often, the easy answer is to sacrifice research and development in such an environment, cutting the risky ventures that might lose

treasure. When, in fact, the smarter path is to devise new methods to be more efficient, invent new products, and adapt legacy techniques, else risk losing capability when losing funding.

3-D printing will enable the military to save costs in four ways. It will decrease the material waste (or left over metal shavings that would then be recycled) found frequently in the subtractive manufacturing methods. It will decrease the requirement for supply chain infrastructure and movement. It will decrease some of the base and depot level requirement to keep large quantities of back stock in anticipation of part failure, which will decrease the footprint of logistics, saving warehouse space and real estate. Finally, 3-D printing will enable more cost efficient production for limited run or obsolete parts by allowing made-to-order parts without specialized tools.

While traditional manufacturing processes mainly use subtractive processes, meaning that a larger piece of material is machined or cut down to the desired size and shape, this additive process builds only the desired shape, eliminating much of the waste inherent in traditional techniques. Traditional subtractive techniques sometimes result in as much as 90% of the original material being trimmed and discarded or recycled as waste in the process.¹⁰ While trimmed material may be recycled, typically the recycling would result in continued upsizing of the logistics lines to support collection, movement to the recycling center, and recasting. The 3-D printing process must have raw material available, often in the form of powdered metal or filament plastic, but only uses the desired amount, leaving the rest of the raw material available for the next manufacturing run. Since recycling and raw material waste is essentially eliminated in additive manufacturing, one major cost is eliminated. A cost tradeoff may still exist, though, when one questions the price difference of the raw material when supplied in a refined, powdered, or filament form versus the standard manufacturing block form.

3-D printing will decrease supply chain costs as the service finds itself shipping fewer parts to each local unit, each unit finds a decreased requirement to store those parts, and the military discovers a decreased requirement for its logistics support, protection, and infrastructure. Because geographically separated units will be able to manufacture parts from raw material, the service merely has to procure the raw material, which is potentially similar across multiple uses. For example, the folding blades of a navy helicopter may require up to seven different hinge mechanisms, each made from the same material. The classical supply doctrine would require the aircraft carrier maintain one or more spares of each hinge. With a local 3-D printer, the carrier would only have to maintain the quantity of raw material required for one or two hinges, as anticipated, and then print them as required, decreasing the requirement to both ship and store the unique parts. If a unit could decrease the storage requirement for spares the DoD could save money buying less real estate, building or renting fewer warehouses, and employing fewer personnel to manage large back-stocks. Finally, after the organization realizes the decreased shipment and storage requirement, it would find that it could employ fewer truck drivers, maintain fewer trucks, and decrease security forces required to defend traditionally vulnerable supply lines.

One can even envision technology to “shred” previous parts into raw material for reprinting into the new, required part. Much like paper, plastic, or glass recycling, one could grind the metal of a damaged aircraft panel back into powdered form and load it into the printer to reprint the same panel in its original, useful state. In the combat zone, an aircraft might return to base with battle damage to its exterior. Normally, maintenance would order a new panel and dispose of the old aircraft panel. A shredder could break the damaged panel down to raw material so a 3-D printer could create the new piece with material waste and no requirement for

resupply. On a limited scale, users have shown the ability to cheaply recycle old material into new raw plastic 3-D printing filament.¹¹ Potential exists for industry to accomplish this on a commercial scale.

During manufacture of parts, two broad areas highlight savings. First, tooling and retooling costs nearly disappear.¹² While cheaper for mass run operations, injection molding requires the tooling and molds to be set up prior to manufacturing. Injection molding, even for limited run, small, low precision pieces runs in excess of \$1,500 to create a mold.¹³ Similarly, with large metal operations, creating jigs pay off in only high quantity throughput operations which average out the start-up cost of the original machines. In limited runs, tooling expenditures may drastically increase the cost of the manufactured item. Like 3-D printing, CNC (Computer Numerical Control) manufacturing does not require significant retooling between different parts, but at the same time, is a subtractive process, giving the drawback of waste material. Additionally, CNC manufacturing requires both extra structural material to support the manufacturing process, increasing product weight, and an entry hole for any internal sculpting, precluding internal mechanics in a single run. In recent history, the Air Force has not only produced fewer copies of each aircraft, but also kept many of its aircraft in service longer than originally envisioned. Old aircraft give rise to another benefit. Airframes such as the KC-135 and B-52 no longer have production lines allowing mass production of parts, leading to excessive costs to generate spares. 3-D printing will allow instant and relatively low cost spare production on an as-needed basis with no unique tooling, providing not only more cost efficient maintenance year-to-year, but renewed service life in older aircraft fleets. The biggest hurdle for the military to collect on this savings potential is the requirement to own the intellectual property of each part's design, or CAD file.

Since the printer does not require machinists with expertise on every possible part, but merely designers to build the CAD files and printer technicians to ensure the printer is aligned and optimally functioning, with widespread adoption of the technology, labor costs could be expected to drop. With a drop in labor requirements, one could further expect that companies would have a decreased desire to outsource manufacturing to low labor cost countries, resulting in increased manufacturing incentive in the United States.¹⁴

CAPABILITY

The capability improvement the military will see from 3-D printing overlaps with the cost savings. Lighter parts made possible by additive manufacturing will result in weight and fuel saving allowing for more mission payload. Cheap customization will give warfighters tailor-made solutions increasing effectiveness. Additionally, quick repair of unique parts will decrease mean time to repair (MTTR), a key performance metric for military effectiveness. Finally, repair and part manufacture in remote locations will allow the military to operate with decreased supply lines in distant theaters.

In traditional manufacturing, the machining process often requires a part to contain excess material, or be bulkier, to support the manufacturing process or ensure enough strength to survive machining. Additive manufacturing only puts material where material is desired for the part use, not requiring extra structure for manufacturing, resulting in lighter components.¹⁵ A 3-D printed car, allowed for fewer pieces in the manufacture process (since things like the dash components were printed in place, rather than requiring a separate plastic mold for each part), allowed the designer to distribute strength only where strength was required (rather than requiring strength where screws and fasteners would have attached in legacy cars), and all around decreased weight of the vehicle.¹⁶ Of course, the biggest disadvantage is when the car

experiences a fender-bender, the mechanic would have to replace the entire front end, rather than just the bumper. For aircraft, this weight savings results in better fuel efficiency and opportunity for additional payload. For the A-380 aircraft, according to Airbus, “a reduction of 1kg in the weight of an airliner will save around \$3,000-worth of fuel a year and by the same token cut carbon-dioxide emissions.”¹⁷ EADS recently manufactured a titanium cargo door hinge for the A380, resulting in a hinge that was 65% lighter than the existing model, saving 10kg of aircraft structural weight.¹⁸ In other words, for a single small 3-D printed part on a single aircraft, operators allegedly saved \$30,000 per year. If that magnitude of savings could be realized across the fleet on multiple parts per aircraft, the savings would be immense. Similarly, if instead of fuel savings, the operator was attempting to increase payload, multiple 3-D printed parts could quickly add up in weight allowances.

In combination with other emerging technology, embracing 3-D printing in design has even greater benefits. Nano-materials are enabling new applications for many materials, and much of the nano-manufacturing advancement harnesses 3-D printing. In studies to reduce weight and increase strength of structures, researchers have found that nano-truss structures can support 15x the weight to strength capacity of more traditional materials.¹⁹ Therefore, materials printed using nano-truss design may reduce item weight, increase item strength, and decrease the cost of raw materials required to build any given structure. As the two technologies advance in parallel, scientists promise massive benefit to adopters. Researchers at The University of Technology Sydney have learned to print metals at the molecular level using electron beam induced deposition (EBID), a new form of 3-D printing. They speculate this will lead to increased speed and purity of nano materials, allowing lighter, smaller structure in real world applications.²⁰ Wake Forest University printed nano-structure plastics that generate light. These

light bulbs can be manufactured in any shape, contain no metal or glass, do not break when dropped, and emit light with the efficiency of LEDs.²¹ Best of all, they are 3-D printed. While in the lab today, 30 years should place 3-D nano-printing capability well within industry's cost conscious toolbox.

3-D printing is also enabling printed clothing²². In combination with the nano-materials science and the expanding material options, soldiers could customize equipment and body armor on-site in combat zones. As Microsoft joins the discussion with developments in 3-D cameras and 3-D modeling spreading through every living room in America, it seems computer technology is an enabler of cheap customization.²³ Armor and personal protective equipment (PPE) could even be customized to each soldier's body type, size, and shape, much like some of the clothes displayed at the New York and Paris fashion weeks.²⁴ For that matter, as cost-benefit analyses show payoff, any number of items could be cheaply and easily tailored to individual soldiers, from weapon handgrips, to combat helmet liners, to glasses or goggle frames, to boots, much like New Balance's new custom shoe line.²⁵ With low cost for one-off items, the soldier can become more integrated to his equipment. Armor, sensors and equipment could be printed directly into soldiers' uniforms. 3-D printers could repair and replace damaged armor in the soldier's custom size at the nearest FOB. While all within the realm of possibility, the military must weigh the cost versus benefit of performance enhancement with such customization, and reign in the potential for individuals to "tinker" with design beyond safe or prudent limits.

Even after the soldier leaves the field, 3-D printing will continue to affect his capability. For example, 3-D printing has allowed advances in prosthetics. Artificial limbs can be quickly and cheaply customized to individual injuries, allowing the mechanical body parts to be more effective, more integrated, and much cheaper.²⁶ At less catastrophic levels than prosthetics, 3-D

scanning and printing has allowed doctors to replace joints and bones on a customized scale, allowing for better fit and faster recovery.²⁷ Sports medicine, a field relevant to soldiers humping their rucksack through Afghanistan, uses the same 3-D imaging and 3-D printing to customize joint bandages and supports that are more effective to treating and preventing injuries.²⁸ 3-D printing allows doctors to print human tissue templates allowing a scaffold for a person to re-grow lost bone.²⁹ Further, researchers at Herion-Watt University in Edinburgh printed human stem-cells, promising to fabricate human organs in the future.³⁰ It is possible that soldiers will not even need the prosthetics when new tissue can be rapidly engineered. The patient's own stem cells combined with cartilage from rat or cow allowed scientists to print a living donor ear in as short as a few days.³¹ In the future, 3-D printers in the military hospital may be replacing soldiers' body parts before returning home, lessening both the psychological impact and longer term VA cost. 3D printing while not a medical panacea, is already and will continue to allow significant medical benefit.

Should 3-D printing develop in maturity so far as to allow on-site manufacturing at numerous basing locations, mechanics could potentially walk in from the flight line with a broken part and have that part printed and replaced real time. At a minimum, they could order the part from a near-by facility rather than awaiting the part from depot. Especially internationally, where many aircrew sit on the ground awaiting a part to clear customs, 3-D printing could allow much faster MTTR, getting stranded aircraft off the ground and back into operation faster, increasing operational efficiency.

Beyond aircraft, 3-D printing technology is showing promise in the use of local raw material combined with liquid binder to create larger structures on site. The Institute for Advanced Architecture, Catalonia, Spain is experimenting with solar powered 3-D printing that

operates in the environment, printing advanced structures from sand.³² While the university envisions beach cabanas and sand bridges, the military could read this as troop shelters, compound walls, and equipment shades in desert theaters.

Even if “sand castles” were not on the military’s list of desired structures, MIT envisions the next step from 3-D printing. In what they dubbed as “4D Printing”, engineers printed structures that further morphed when exposed to a stimuli at a later time. They printed a 3-D item in the shape of a long tube. Later, when exposed to water, the tube morphed shape into another 3-D structure, a frame.³³ One might see this application become self-erecting tents, or aircraft structures. If the 4D trigger mechanism evolves to heat or radiation, one could even see self-configuring satellites. In either case, a smaller printer would be capable of printing an object much larger than the print tray size.

The capability to create a number of our most common expeditionary needs on site rather than rely on extensive and expensive logistics lines is revolutionary in military operations.

FLEXIBILITY

Finally, 3-D printing will allow for rapid prototyping, decreasing acquisition costs and timelines, allowing the military-industrial complex to advance technologies much more quickly, and staying ahead of near-peer competition.

Rapid prototyping, 3-D printing’s main use and benefit today³⁴, will continue. When producing parts for test aircraft or new UAVs, significant cost goes into the configuration of production resources and manufacture, resulting in a requirement for more robust prediction and analysis prior to manufacture. Often these predictions are significantly in error resulting in requirements to remanufacture parts. Some estimates place the manufacture cost decrease at 50-80%³⁵, meaning, with 3-D printing additional prototypes could be built, resulting in larger

selection for the customer and opportunity for better designs, hence acceleration of technological development. Since much of that cost is the process and knowledge, and much of the production cost is managerial in nature (legal, bureaucratic, financial), the end user may not see major price drops. But, since often production is required merely to make back the costs of R&D, a cheaper, faster development cycle, where more ideas are pouring in from research, might allow faster advances in the technology before going to production.

Numerous allies and international peers are experimenting in 3-D prototyping, meaning if the DoD is not actively pushing this technology, it may be falling behind. While Mercedes, Honda, Boeing, and Lockheed are aware of and using 3-D printing technology on limited scales, few companies have fully harnessed and embraced the true potential.³⁶ Instead of widespread prototyping, they are using it for limited prototyping and for small, customized parts. The US Army's "Expeditionary Lab – Mobile" may be closer to the mark on understanding 3-D printing's capability, building tools on-site for Army units in Afghanistan.³⁷ But, even this lacks vision as it is mostly limited to small one-off tools, rather than new ideas or new product production.

In China, 3-D prototyping has allowed product improvement in the cast mold industry. Mixing the new technology with the ancient art of sand casting, 3D printers allow detailed design of a product prior to casting. The 3-D printer is not a tool for manufacture of the finished product in this case, but an opportunity to use computer design to arrive at a desired product. Once correct, the manufacturer prints the item with meltable plastic. Previously accomplished with wax, the 3-D printer turns out plastic that is the template for the cast mold. The final product is cast in that mold from the desired material.³⁸

The USAF and DoD should make 3-D printing more available to its lower level institutions, leveraging its workforce intelligence and making the AF IDEA program even more productive. Further, in acquisitions, the AF should leverage the technology and encourage its contractors to do the same, so product customization and refinement during developmental test can occur more quickly and cheaply.

LIMITATIONS

3-D printing technology is not yet mature enough to print all products. Its chief limitations are the material properties, inability to print certain finished products, its size and speed limitations, and copyright concerns.

One very acute drawback to 3-D printing is the immaturity of material research. First, refinement of material for use in 3-D printing is not a common market, so until the refined raw material is widely used, manufacturing processes may not exist to produce the raw material efficiently or cheaply. Second, if 3-D printing continues to require powdered metals, some material properties could introduce handling considerations. For example, while powdered aluminum is not dangerous in controlled conditions, it is not only flammable, but highly reactive or explosive when exposed to moisture.³⁹ Shipping to theater would require HAZMAT considerations, and sitting on an airfield ramp awaiting transportation might pose problems if potential existed for damage to the packaging. Finally, many metals are treated and manufacturing processes are tailored to the metal properties desired. For example, steel is cast with carbon to create a high melting point but easily fractured product, while quenched and tempered with low carbon concentration to create long crystalline grains and a more pliable product. The industry will either have to determine how to change material properties through

variation in printing methods, or merely add 3-D printing as yet another tool to produce steel with specific properties.

Products such as generators, complex line replaceable units (LRUs), or complete computers are not within 3-D printing's current repertoire. Manufacturers have only shown an ability to print up to 7 materials simultaneously. And, while integrated circuits were printed in multiple cases, more standard techniques remain faster, cheaper, and reliable. Further, very complex assembled machines may contain 3-D printed parts, but are not yet ideal for reaping the benefits of 3-D manufacturing. For example, a fully assembled generator contains numerous materials, as well as built up systems within systems. Electronic generator control units, coils of wire, magnets, conductors and insulators arranged in a complex layout would be a challenge for envisioned 3-D printing, even on the 30-year horizon. The DoD may be better off relying on legacy technology for such parts and leveraging its 3-D printing on more promising opportunities.

Size and speed limits, while present today, are merely a construct of an infant technology. As seen with the Spanish architecture project, soon the print tray will not be necessary and manufacturers will build larger machines that can break free of size restrictions. Similarly, because speed limits are mostly a factor of the heating and cooling properties of the raw material, construction may significantly expand as developers understand manufacturing techniques and material properties better. So, while size and speed are a current criticism of 3-D printing, in 30-years, as the technology advances, these shortfalls will be decreased or eliminated.

The military will have to wrestle with the industrial complex as to how many of these benefits can be realized. The perceived military-industrial-political handshake where the government must buy proprietary parts from the prime defense contractor who sold those

exclusive and lucrative sub-contracts to additional vendors will require a decision. The government must decide if it will purchase the intellectual rights (or possibly a site license for manufacture) to the design of their weapons systems or merely employ those sub-contractors to stand-up an office on the desired 3-D printing site, a financial decision commonly wrestled with even in conventional manufacturing today. 3-D scanning would allow users to replicate old aircraft parts, but also might violate copyright law. Even the industry itself may slow the otherwise rapid advancement by lodging patents that restrict other companies from leveraging promising techniques in the field.⁴⁰ However, many have suggested that recent technological developments require a paradigm shift from big industry to the military owning and completing its own acquisition.⁴¹ In such a construct, the military could leverage intellectual capital at will, enabling individual and small business ideas to advance product development more rapidly.

Further, the government will have to decide how much liability it would accept for quality assurance at each location, and where liability would fall when the military modifies a contractor's design. Presumably, the political and industrial complex would resist the push for the military to build products in-house, as the perception would be loss of contractor income and loss of political constituency jobs. The military might also resist the trend as this would mean more local training and manpower moving away from the military depot system. Liability and quality will become greater concerns if the industry moves toward "basement production" by many individual innovators instead of the more expensive, possibly slower, but known and controlled quality assurance of larger corporations.

The move toward centralized repair, where line technicians merely swap LRUs and depots accomplish required in-depth troubleshooting and repair, may decrease the utility of 3-D printing in some aspects of front-line maintenance. Nevertheless, in other ways may decrease

depot workload while empowering local maintenance. For example, when the SPO releases a TCTO that replaces x-steel plate with y-steel plate, he could quickly email the CAD file to the base for implementation at the lower level, rather than task the depot with management of the parts.

Despite potential limitations, and while not ideal for all manufacturing efforts, 3-D printing stands to benefit military operations overall.

CONCLUSIONS

Looking to the 30-year future, one can forecast 3-D printers as a critical piece of most expeditionary endeavors. The international space station will have a printer for replacing and repairing parts far from NASA's supply system.⁴² Most aircraft carriers will have them as standard equipment in their machine shops to repair the ship and broken aircraft. 3-D printers will be fabricating shelter for troops in Africa, the Middle East, and Pacific islands.⁴³ Every maintenance line will have one in their back-shop for quick repair.

Further, since flight safety and configuration control might restrict large programs like the F-35 A, B, and C, or the HC/MC, AC, and CC-130J from extensive modification, 3-D printing's rapid customization will push further proliferation of cheaper, customized UAS and non-safety critical system advancement. Aircraft units with different mission requirements will customize unique kit such as mounting brackets, plates, and panels more cheaply and quickly. Major defense contractors will present the user with a broader selection of end-units that can proceed to testing and fielding more rapidly.

The 30-year future of military operations will bring a changed strategy with the addition of 3-D printers across a broad range of activity. While large vendors will still produce the powerhouse products, in a dynamic much like Apple's "app store", rapid prototyping will

proliferate, allowing the military to diversify its vendor base and acquire more varied, specialized COTS products on a small scale. In turn, this will increase the variety of equipment, requiring more decentralized execution in missions whose personnel will have tailored their equipment suites to their missions and tactics. Subsequently, it will enable increased efficiency and mission effectiveness in continued diverse global military operations.

Within the military integration of 3-D printing, military units, unarguably the real experts in their mission, will innovate and possess the capability to back-up that innovation with indigenous fabrication. Battlefield commanders will assume more for flexibility in their AOR, but will also have to take responsibility for managing and utilizing new equipment. The DoD will require policy to bound commander's options, but will have to allow increased autonomy if it hopes to realize the benefits of this technology.

Although logistics will remain a critical enabler of military operations, containerized manufacturing facilities, essentially ruggedized robots that can 3-D print, will deploy alongside troops to take care of many support needs, resulting in a transformed supply system. Resupply will consist of more raw materials, and local sourcing of raw material will become more important. When leveraged correctly, the military will have a more agile and expeditionary structure.

To conclude, one must ask, "How do we achieve this miracle science? How can we reap such benefits?" First, the military must recognize the importance and potential of this technology and institute partnerships with those on its forefront. While DARPA has promoted many programs at universities, in order to maximize influence in shaping the applications of this new technology, the military must continue to get more involved. Each day, new applications

arise, many of which can be tailored to either commercial benefit or military utility. For the military to steer the dialogue over the upcoming 30 years, involvement is required now.

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