OUR FABRICATED FUTURE

The 3D printing revolution will transform how we live – and how we fight.

BY HOD LIPSON AND MELBA KURMAN

From the factory floor to outer space to the front lines of medical care and the battlefield, 3D printers are changing how, where, what and how quickly objects can be manufactured.

As the technologies continue to improve and drop in price, military interest and investment in 3D printing is increasing dramatically. While most applications for military 3D printing are in the experimental phase, potential future applications range from making on-demand mission-critical replacement parts and food to printing customized prosthetic limbs – and, someday, living tissue to help wounded soldiers and veterans heal.

More formally known as "additive manufacturing," 3D printing is a digital manufacturing process that fabricates physical objects by carefully adding material, layer by layer, according to a digital blueprint. Objects can be printed in plastic, ceramic and even metal (such as stainless steel and titanium). When the situation calls for a custom part to be made according to exact and unique specifications or manufactured on the spot – or, in some cases, both – 3D printing shines.

In the civilian world, 3D printing is catching on fastest in industries where customers are willing to pay a premium for special-order, custom-made objects, whether a replacement machine part for a vintage automobile or a custom hearing-aid insert. Aerospace manufacturers are beginning to adopt the technology for making complex aircraft parts like lightweight frame components and optimized fuel injectors. Although the circumstances differ, military personnel could also take advantage of 3D printing's capacity for rapidly and automatically manufacturing custom parts and objects made out of a wide range of raw materials.

Two unique characteristics set 3D printing apart from traditional manufacturing processes. First, unlike traditional manufacturing techniques that carve away or mold raw material into shape, a 3D printer forms objects by adding, depositing or solidifying raw material – be it polymer, metal, living cells or food – into precisely placed layers. Second, 3D printing is completely computer-guided. With no error-prone human operator involved, a 3D printer is capable of automatically creating physical objects whose shape precisely matches the instructions laid out in the digital blueprint that guides the printer through its paces.

The process begins with a digital blueprint in the form of a file created in computer-aided design (CAD) software. In some cases, the blueprint may have originated in an optical scanner or medical imaging device like a CT scanner. Next, the digital blueprint is ported over to the 3D printer. Similar to the way a desktop inkjet printer formats an online document for printing, the 3D printer processes the digital blueprint by translating the digital description of the physical object into explicit printing instructions that will set the printer's machinery into motion.

Although the term "3D printing" has come into popular use, additive manufacturing is actually more descriptive of the way these machines form physical objects. Some 3D printers form objects by extruding soft raw material through a print head, typically molten plastic. In more exotic cases, foodstuff or even living cells safely encased inside a "squirtable bioink" gel can be processed. Other 3D printers don't actually print at all. This class of machines forms objects by aiming a laser, a thin spray of adhesive or a focused electron beam onto a bed of raw material – either powder or liquid polymer – that solidifies into an extremely thin layer. The process is repeated thousands of times until micron-scale layers build up into a fully formed object.

The cost of a 3D printer is determined by its manufacturing capacity. Small 3D printers that squeeze out slow streams of brightly colored plastic, popular with hobbyists and schools, cost about as much as a laptop. However, their use is limited to making crude plastic objects that don't need to meet high performance requirements, such as simple toys or replacement knobs for home appliances.

In contrast, an industry-grade additive manufacturing machine using laser or electron-beam technology to print specially engineered blends of ceramic, metal and patented polymers can cost well into six figures. These high-performance additive manufacturing machines, while costly, are used to manufacture machine components or orthopedic implants whose dimensions must meet exacting requirements at the micron scale.

LONG TIME COMING 3D printing is a classic example of an overnight success that was decades in the making. The first commercial 3D printers were available in the late 1980s. For its first 20 years, the technology was used by engineers and designers to make temporary plastic

LEFT: A 3D printed stainless steel motor impeller contains curved cooling channels that cannot be manufactured in any other way. Photo by Hod Lipson prototypes of products that would later be manufactured using conventional mass-production processes. In the past decade, as printing materials have improved and metal printing has matured, designers and engineers are applying 3D printing to create real, functional parts. Currently, approximately 30 percent of 3D-printed parts are for end use.

After a slow start, 3D printing finally graduated to mainstream use thanks to a combination of forces, including dramatic improvements in computing power, easier-to-use design software, advances in novel materials and plummeting costs of the electronic components that go into machines. Today, the manufacturing machines people call "3D printers" span a sprawling and diverse family of technologies. Regardless of cost or manufacturing technique, what all 3D printers have in common is their appeal: additive manufacturing is an ideal method for making elaborately shaped custom parts or products in small batches.

3D PRINTING AND THE MILITARY What makes 3D printing an ideal mode of manufacturing for military applications? After all, revolutionary as it may be, 3D printing has very real and plentiful limitations. Unlike traditional factory manufacturing machines that efficiently carve or stamp out thousands of flawless, identical objects each day, 3D printing is a slow and expensive process. There's no widely accepted framework for verifying the performance and safety of 3D-printed parts. And the vast majority of 3D-printing technologies can handle only a single material – a grave limitation in a world where even the simplest products contain dozens of different components.

Business-model challenges are also a complicating factor. A frequently asked question is at what point the cost of 3D printing a product breaks even with the cost of mass-producing that same product. The answer depends on the complexity of the part and how many parts you need to make to achieve a profitable economy of scale. However, although the question of profitability vs. mass production is a worthwhile and interesting one, we think it's the wrong question to ask. A better one, particularly in the case of military applications, is what kind of new opportunities are opening up that up until now were not possible.

Despite its challenges, 3D printing is well suited for military applications because it's precise, portable and – thanks to the computer-guided additive manufacturing process – can make unique and complex new shapes.

Another way to examine its potential value is by using a framework we call the "10 Disruptions of 3D Printing." These 10 principles took shape over the course of years of research with 3D-printing experts across different industries. We found that although the design and manufacturing challenges people were solving using 3D printing looked quite different on the surface, underneath they shared a set of similar patterns.

In our book "Fabricated," we distill these underlying similarities into 10 core characteristics:

- *Manufacturing complexity is free.* Making more complex shapes is not more expensive. For example, printing a shape with a hole, rounded corners and inscription is not more expensive than printing a rectangular block of the same weight.
- *Geometric variety is free.* Printing 50 identical items or 50 different items costs the same.
- *No assembly required.* Parts that typically required assembly of multiple components can be printed as a single monolithic unit. For example, the GE LEAP engine contains a fuel injector that is printed as a single unit, where previously it was made by assembling 20 parts. Reducing assembly cuts labor costs, tolerance errors, fasteners and failure points.
- *Small manufacturing footprint.* A 3D printer is portable and packs a lot of printing capacity per square foot. This make it ideal for printing jobs in the field.
- *Lead time to product in hand is diminished.* The duration between end of design and beginning of production is virtually eliminated, compared to traditional production methods that could require days, if not weeks or even months. This allows on-demand fabrication as well as rapid iteration.
- *No skill required.* The entirely computer-guided printing process means there's little technical skill required once the design blueprint has been created. Compared to traditional manufacturing processes that require quite a bit of training, this allows for use by ordinary personnel.
- *Less waste.* Metal printing is a precise and clean method for making objects, since it uses material only where it is needed. The "buy to fly" ratio (the amount of metal you need to buy compared to what ends up on an aircraft) is 1:2, compared to about 1:10 using traditional processes. This means less waste and less material shipping and storage.
- *Infinite shades of material.* It's possible to create precise new blends of raw materials to create novel

Carolyn Lambeth, a mechanical engineer at Combat Direction Systems Activity Dam Neck, explains the process of additive manufacturing to sailors at the Navy's first Maker Faire, a series of workshops called "Print the Fleet," in 2014. "The quantity of supplies we carry on board could be reduced significantly if we 3D print those products on the ship," says Capt. Jim Loper of the Navy Warfare Development Center. "There really are no limits." U.S. Navy photo by Mass Communication Specialist Seaman Jonathan B. Trejo

materials that behave in unusual and interesting ways, sometimes surpassing the performance of the base materials. This is a new design space that has not been fully explored.

- *Perfect replicability.* 3D printing brings some of the freedom and repeatability of the digital world to the still largely analog processes of creating and copying physical objects. It is fairly easy to 3D scan an existing part and supplicate it, with or without modifications.
- *Zero constraints.* The additive nature results in a new design space, with new complex geometries that simply could not be made any other way.

FRONT-LINE PRINTING Considered within the framework of the "10 Disruptions," 3D-printed manufacturing is set to transform how the military manages three core challenges.

- *Maintaining equipment in remote locations.* An ancient proverb sums it up nicely: "for want of a nail … the kingdom was lost." 3D-printed manufacturing is an ideal tool for front-line manufacturing because a single 3D printer can form many different shapes, has a small manufacturing footprint and can print objects on the spot.

"One of the biggest challenges in the Army is that there is a huge logistics burden," writes Thomas Russell, director of the Army Research Laboratory. "If we could forward-deploy manufacturing capabilities, we would have the opportunity to manufacture parts in theater, or repair parts."

In addition, 3D-printed manufacturing would help cut the supply-chain cord for ships far out at sea or submarines submerged for long periods. Often, mundane parts urgently needed by sailors are out of stock. Replacing a part can involve placing a special order and waiting weeks. In a future scenario, if naval vessels were equipped with portable 3D printers, the process would work much more quickly. A sailor would download a design file from a database of replacement parts, print the part and, without missing a beat, continue the mission. Known as digital inventory, this process is relevant to many civilian industries also burdened by a long tail of parts.

Currently, front-line 3D-printed manufacturing is in the exploratory stages. In Afghanistan, the Army created two portable manufacturing centers called Expeditionary Labs, or "Ex Labs," that were housed inside 20-foot shipping containers. Each pod had its own generator, scientist, engineer and assistant along with a plethora of manufacturing machines, including CAD software and a printer. If these early exploratory test beds prove successful, 3D-printed manfacturing could liberate soldiers stationed at remote forward operating bases from the bureaucratic chokehold of a military supply chain, potentially improving the "tooth-to-tail" ratio.

While front-line press-button manufacturing capacity could revolutionize the logistical burden that accompanies modern warfare, battlefield 3D printing faces the same formidable challenge faced by industrial manufacturers: most replacement parts are not made out of a single type of material. Whether you're trying to 3D print a replacement plastic knob for the dashboard of an armored vehicle or a metal gun component, the fact is that most parts are made from multiple raw materials or composites. Multi-material 3D printing will someday mature, but until then engineers and scientists will continue to experiment with printing techniques capable of blending together different raw materials into a single print job in a way that's reliable and repeatable.

One of the exciting opportunities afforded by front-line manufacturing is to allow soldiers in the field to modify and improve tools directly, based on firsthand experience. Design software that allows some form of customization could enable end users more control of the final product, allowing agile adaptation. While individual adaptation runs the risk of loss of standardization, such front-line innovations could find their way up to headquarters and, when appropriate, be disseminated more widely.

■ *Healing the wounded.* The same characteristics that make 3D printing useful on the front lines also make it a powerful tool to create replacement parts ... for people. In the civilian world, one of the earliest commercially successful applications of 3D printing has been the creation of custom medical devices. Market research firm SmarTech estimates that in 2014 alone, 1,100 3D printers were sold with the intent to be used to create hearing-aid inserts, surgical guides and models, and custom dental braces and crowns.

For years, the Walter Reed National Military Medical Center has been a pioneer in medical 3D printing, creating models for military surgeons. The center makes custom titanium cranial plates from medical scan data that's converted into a format suitable for 3D printing, then implants them into injured soldiers. It also prints polymer jigs for use in surgery to precisely guide surgical tools and reduce errors.

One of the most exciting medical applications of 3D printing is the creation of living human tissue, a process known as bioprinting. The availability of increasingly detailed medical scan data, combined with the ability of a 3D printer to precisely place raw material, is opening up new frontiers in wound repair and tissue replacement. In particular, bioprinting shows promise as a technique to repair burn wounds suffered by soldiers in combat.

Bioprinting is a tissue engineering technique in which a machine equipped with several different syringes loaded with hydrogel is used to "print" living cells into place. First, the injured area is scanned to create a digital 3D map. Next, healthy cells are drawn from the injured person's body or sourced externally, then incubated and loaded into a special medical printer. The bioprinter then deposits different types of cells into a 3D configuration that after a period of incubation will grow into viable tissue.

Back in 2006, in our lab at Cornell, we were able to print a living meniscus of the knee. The meniscus lived in an incubator for three months, but it was not strong enough to serve in a functional knee. Since then, research groups at universities around the world have been working on improving the printing and incubation processes to produce implantable tissue.

It's likely that the first real application of bioprinting will be to create new skin and cartilage, since these relatively simple tissues contain no vascularity. As digital technology advances, scientists hope to someday print more complex organs such as kidneys and livers, for both implanting and for drug testing. To accelerate the development of bioprinting, the Department of Defense set up the Armed Forces Institute of Regenerative Medicine (AFIRM). This multi-institutional team of 30 universities, military laboratories and investigators is developing technologies to replace or regenerate human skin cells, tissues and organs. Bioprinting is currently in the experimental stages and will require regulatory approval before the process can go into clinical trials.

■ *Feeding the force.* A cousin to bioprinting is food printing. When we first released our experimental open-source printer "Fab@Home" in 2006, we were surprised to see that people eagerly tried it out by printing food materials such as chocolate, cookie dough or cheese. Like bioprinting, food printing also involves working with a broad range of unwieldy materials that are difficult to deposit accurately. Initially, the 3D-printed cookies we toiled to make were dismissed as a frivolous side activity. However, a consistent trickle of interest from food companies and the public has proven that there may be more to food printing than meets the eye.

Much like conventional 3D printing, food printing is not about replacing mass production of food. Instead, the ability to print food and cook it inside a 3D printer enables the fabrication of fresh food and gives the software chef exquisite control over quantities and nutritional composition. Following the "10 Disruptions," food printing could allow the military to produce custom healthy food for its personnel with less waste, less training, less personnel and less infrastructure.

WHERE 3D PRINTING IS HEADED Today, 3D-printing technologies are in their early stages of adoption, similar to where computers were in the mid-1980s. When computers were new on the scene, many people knew that computing technology would disrupt a few processing-intensive activities – for example, accounting or military command and control. Few, however, were able to predict the broad range of ways in which computers would affect almost every aspect of our lives. Similarly, we can predict that 3D printing is going to open up new possibilities and disrupt conventional manufacturing, medicine and even cooking. Printers are becoming faster, cheaper and better every day. But where will this technology go next?

We can look at the progression of 3D printing in three stages. The first, one that is now maturing, is our ability to create, shape and form on demand. Today, almost any shape you can describe to a computer can be 3D printed, and that is in marked difference from most of history, when the shapes and forms we could manufacture reliably were limited by our manufacturing tools. We are now limited only by our imagination and our design tools. New design tools and, in particular, new design algorithms driven by artificial intelligence are needed to allow us to explore this vast new design space.

The second stage is the ability to create new "meta-materials" on printers by combining and patterning base materials. Just as millions of shades can be created by combining just three primary colors, a vast range of new materials can be created by combining a few primary materials in new and interesting three-dimensional patterns. For example, we already know that it is possible to make meta-materials that are both stronger and lighter than any natural material. But the full range of 3D patterns' and potential materials' properties achievable is territory yet to be explored.

Finally, the third stage involves moving from printing passive parts to printing complete integrated, active systems. Most printers today can print only passive parts. But most real-life products involve multiple interacting components – not just structural materials, but electric wires, batteries, transistors, sensors and actuators. The ability to simultaneously 3D print multiple, integrated active materials would open the door to fabricating optimized systems on demand. This would move us from printing just replacement parts today to fabricating complete systems, such as an on-demand custom UAV or a robot that could walk out of the printer – batteries included.

Over the past 30 years, 3D-printed manufacturing has gradually risen from obscurity to become an advanced manufacturing process used by leading defense, aerospace and medical companies. Its unique characteristics disrupt several cost factors and logistical barriers associated with traditional mass manufacturing and medical engineering techniques. In the coming decades, as the technology continues to improve in performance and drop in price, 3D printing will fundamentally change the way physical objects are designed and made. For both civilians and military personnel, 3D-printing technologies have the potential to change life as we know it, shortening the length of supply chains and improving medical care and food production.

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