International Defence Review

Make and mend: the revolutionary promise of 3-D printing

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Nick Brown, Marina Malenic and Huw Williams explore the potential impact of 3-D printing in defence

It is rare that a technology or manufacturing method can actually change the world, but 3-D printing promises to do just that.

Although the basic technologies have been around since the 1980s, the growing availability of printers and increasingly ambitious uses of the technology - along with attendant headlines about freely available 'printed' handguns - have accelerated its prominence.

From an economics perspective, the impact could be seismic.

Imagine a world where rather than factories in China churning out consumer goods such as mobile phone cases in vast numbers, shipping them around the world and distributing them to shops and market stalls, the user can just print a new case on their desktop. Why stop at the case? Instead of standing in line for a new iPhone 6, why not download a computer aided design (CAD) file, personalise it, and then print the whole phone?

At a stroke this imperils the world's great consumer goods manufacturing economies as today's vast shipping and transport infrastructure shifts from transporting manufactured items to cartridges of plastic or metallic powders.

On the surface, that sounds far-fetched, but that situation is getting nearer, with 3-D printers now widely available for a few thousand dollars - the price of a desktop PC 15-20 years ago - and prices are dropping all the time. At one level this democratises production back into the hands of the consumer - overturning and adding another spin to the industrial revolution - and on another it risks undermining free market structures. It is not hard to imagine the bit torrent data-sharing sites that terrorise the film and music business making CAD files available for physical products, with obvious implications for defence and security. The already substantial challenge of protecting intellectual property rights and sensitive design items - including weapons and sensors - are only going to get harder with the advent of advanced scanners and 3-D printing simplifying retro-engineering and the growing threat of cyber attacks and industrial espionage.

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Printing on demand

With 3-D printers coming down in size, their potential to print spare parts at the point of need is very attractive for some operators. Although the UK Royal Navy is not believed to have a formal requirement in place yet, one source told *IHS Jane's* that the service is "very interested". Another added that "anybody who has been on a frigate out hunting submarines when the gearbox on the ship's helicopter has gone unserviceable, or when something important has snapped on a radar and spares can't be delivered for days, will understand the attraction of being able to print appropriate spares as you need them".

Predictably, the US Navy (USN) is also closely studying the potential to revolutionise logistics. For one example, the Naval Air Systems Command (NAVAIR) held an Additive Manufacturing industry day in July 2014, looking for new ways to use the technology and is currently acquiring a third 3-D printer, having bought its first system for rapid prototyping and development risk reduction in 2007.

In an official release from the command, Eric Merk, head of the Logistics and Maintenance Information Systems and Technology Division at NAVAIR Lakehurst stated that "as parts become more transferable to additive-based solutions, the implications to logistics support are gigantic in scope". He explained that the ability to swiftly mock up and trial a part greatly reduces turnaround time and could eliminate packaging, handling and transportation issues as the part could just be printed locally.

The US Army's Rapid Equipping Force (REF) has forged ahead with 3-D printing for rapid prototyping, having deployed two 20-ft ISO containers - known as Expeditionary Labs - containing scanners, milling machines, fabrication tools and 3-D printers into Afghanistan. The labs' teams surveyed deployed soldiers seeking ideas for innovations for problems that they were having with their equipment, before looking to develop and test solutions for them built locally in the containers.

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New parts - a battery hookup, folding grappling hook and a USB hub - created in the field by the REF *in Afghanistan. (US Army)*

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Material concern

Despite all of these advantages and its undoubted potential, there is still widespread recognition that AM is not yet a panacea, and one of the biggest current concerns is the lack of material certification data, with the attendant difficulty that this imposes on stringent (and costly) military accreditation processes. Composite material manufacture, tempering, hot pressing, forging and all of the other more traditional forms of 'metal bashing' are all well understood and produce predictable and repeatable physical properties from known quantities, unlike 3-D printing from powdered elements, which currently comes with no guarantees of hardness, rigidity and so forth.

This is partially a result of the novelty of the technology and a relative lack of finite element analysis (FEA) and non-destructive investigation (NDI) on 3-D printed structures, so the understanding of the resultant materials will improve over time.

There are a host of US organisations already working toward that aim. The US Army's Aviation and Missile Research, Development and Engineering Center (AMRDEC) - along with several academic institutions - are working to grade and qualify printable steel alloys that can then be tested against known and certified examples of the 'real thing'. Other materials will undoubtedly follow a similar path.

Likewise, the army's Research, Development and Engineering Command (RDECOM) is working closely to establish a "comprehensive knowledge base" of the materials' characteristics that could play into a government-wide database of approved AM parts that could be printed to replace legacy items. In an admittedly commercial example, Airbus has recently created 3-D printed versions of a no-longer available part for its elderly A310 airliners, showing that it is at least possible to make airworthy replacement parts.

An RDECOM engineer (inset) creates a rapid prototype part for the US Army's Medical Materiel Command. (US Army)

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Meanwhile, the Defense Advanced Research Projects Agency (DARPA) has studies underway in a couple of locations - including one at Penn State University - to assess 3-D printing methods and decide which ones are best for given roles and requirements under the agency's Open Manufacturing initiative.

In time, the availability of certified operators, material powders and manufacturing techniques should enable certified parts to be printed, although this will require substantial testing and research.

Another challenge is the requirement to document and track designs and revised parts printed in the field in a centralised and systematic way, because the opportunity to make revisions locally using a 3-D printer risks a return to individual artisanship and divergence from the standardised parts and capabilities that many forces have striven for over the last couple of decades.

Away from equipment, the army's Natick Soldier Research, Development and Engineering Centre is looking at the potential to print foodstuffs from basic long-life storage ingredients. Testing to date has focused on relatively simple candy crafted from sprayed layers of sugars, but engineers are planning to expand into adding plant-based cells and "meat-derived proteins" into the printer.

In theory, this could simplify logistics, storage and delivery of meals to forward-deployed forces who could then print their own meals on demand. However, one of the key advantages that the engineers hope to be able to achieve is to tightly control and tailor the nutrients to the soldiers, their environment and missions, increase or decreasing fat, protein, carbohydrate and fibre levels etc as required, without having to 'guesstimate' based on recipe, chef skills and the variable quality of ingredients.

Although much attention has been focused so far on creating rigid structures, engineers are also working on the ability to print textiles from synthetic material, which should enable clothes to be closely tailored to individuals for a relatively low cost. Additionally, the clothing should perform better as wear resistance, ventilation or comfort and warming characteristics can be seamlessly engineered into the correct positions without having to mix and stitch together different panels.

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Industry's take

AM also offers substantial promise for the more mainstream manufacturing industries, some of which have been using 3-D printing for some time now.

Boeing has been an early adopter of 3-D printing, having begun printing parts for the Super Hornet in 2001. (Boeing)

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Boeing, for example, has been using printed parts on USN F/A-18E/F Super Hornets since 2001, according to Michael Hayes, the company's lead engineer for polymer-based additive manufacturing research.

"We've been an early adopter of what initially started as rapid prototyping using stereolithography machines for proposals or to just look at parts to see how they came out of the models back in the early 1990s," Hayes told *IHS Jane's* . "We were one of the first ones to transition from rapid prototyping to additive manufacturing, actually using that process to make production parts [for Super Hornets]", he said. Specifically, environmental control system ducts were printed for the Super Hornets using polymers.

David Dietrich, an engineer who deals with metal-based additive manufacturing for the company, noted that there is a "growing application space to use other materials" for additive manufacturing, although he described his attitude toward the technology as "bridled enthusiasm".

He said: "Everyone is enthusiastic based on our past history with the technology, but at the same time we want to implement it in a very smart way. You do not want to implement it…in programmes where the structural requirements are too high for the technology in its current state."

Dietrich asserted that additive manufacturing "isn't necessarily a replacement of existing technology. It's simply a tool in the toolbox of engineers. So it complements conventional technologies". Boeing currently uses the process internally for prototyping "to try things out and see how parts look and function before we machine out a big piece of titanium. We use it for tooling all the time".

Conventional processes will still be useful for many years to come, he said.

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Lockheed Martin has also begun incorporating the technology into its toolbox, and senior figures within the company now see possibilities for the method that are literally out of this world. Dennis Little, Lockheed Martin's vice-president of production in the company's Space Systems division, spoke of "huge potential" for the use of printed parts on spacecraft. "It will revolutionise our business," Little told *IHS Jane's* . "Some day we will be able to print a [whole] satellite."

3-D printing may prove to be a key enabler for space exploration and long-duration missions beyond the practical reach of resupply. NASA is currently working on a '3-D Printing in Zero-G Technology Demonstration' having given hardware certification of a microwave oven-sized printer from Made In Space Inc for space flight in April 2014. The control software is currently undergoing integration testing before the machine can be delivered to the International Space Station by the SpaceX-4 resupply mission, where it will conduct live testing, building parts and tools in situ.

Meanwhile, Little noted that a vent cover for NASA's Orion spacecraft, scheduled for launch in December 2015, was printed out of a heat-resistant nickel-based alloy, in a lattice structure that would traditionally have required using an elaborate five-axis machine to build or the time- and labour-intensive welding of many small parts together. The Orion Multi-Purpose Crew Vehicle (MPCV) is a beyond-low Earth orbit (LEO) manned spacecraft for small manned missions to the moon, asteroids, and beyond.

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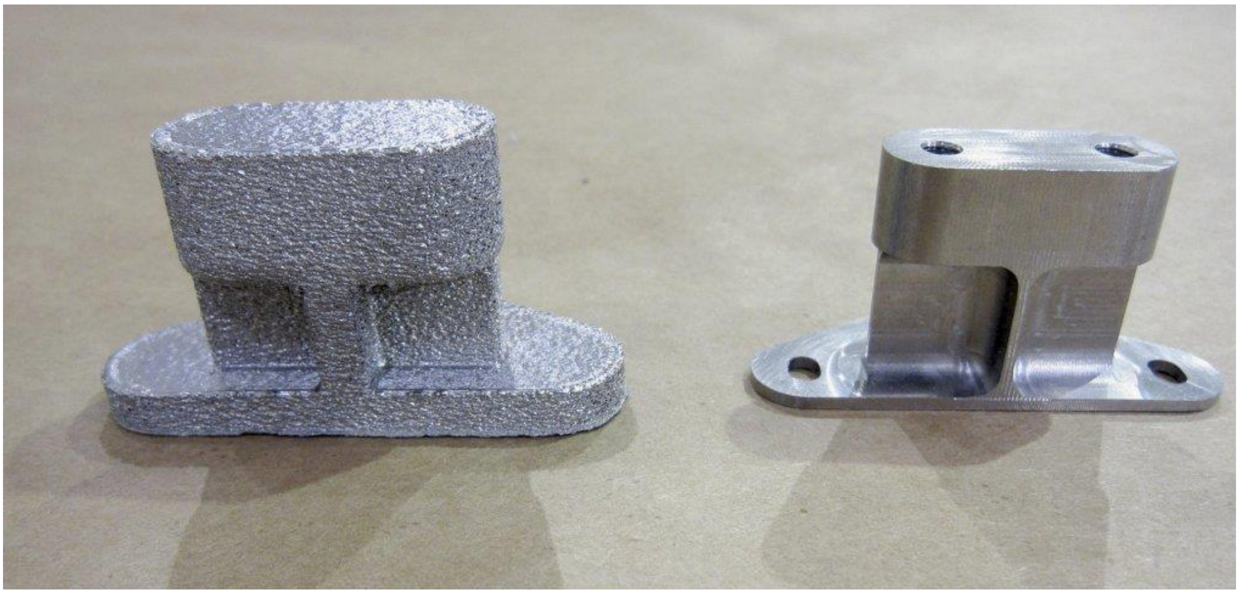

Juno is Lockheed Martin's first spacecraft to use 3-D printed parts. On its way to rendezvous with Jupiter, Juno features eight brackets connecting structures. Compared to traditional methods, 3-D printing reduced the cost and weight of the brackets. Lockheed Martin plans to continue using additive manufacturing to produce future spacecraft components. (Lockheed Martin)

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US propulsion companies have already invested heavily in the technology on the commercial side of their businesses. For example, United Technologies' Pratt & Whitney engines unit has been working with additive manufacturing techniques for 25 years, according to Lynn Gambill, the unit's chief engineer for manufacturing engineering and global services.

"We were one of the first adopters on the plastic side," Gambill told *IHS Jane's* . The company now uses plastics, polymers and metal-titanium and nickel-based alloys in additive applications. Gambill said it is "likely" that the company will someday use printed parts on the F135 turbojet engine it builds for the Lockheed Martin F-35 Lightning II Joint Strike Fighter. However, she added that Pratt & Whitney will proceed cautiously in making such a move.

A fuel bypass manifold for a PW1000G commercial engine manufactured using the Electron Beam Melting process and titanium powder. An optimised version was designed by the additive manufacturing process in order to remove weight and material. (United Technologies)

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"We'll consider current technology and compare it to what we can do with additive," she explained. "If it is more cost-effective, we will introduce it. There is always a sweet spot for selecting a manufacturing technique. There is no 'one-size-fits-all'."

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The UAV potential

Still within aviation, the production of unmanned aerial vehicles (UAVs) has emerged as an early practical application of 3-D printing with a range of designs available for small aircraft that are suitable for printing from commercially available systems. However, while these may meet the needs of hobby aircraft flyers the military requires more advanced and robust examples and the US Army Research Laboratory (ARL) is leading efforts in the US.

The ARL has a wide-ranging interest in the field of UAVs, undertaking the development of concepts for systems scaled from small and hand-launched aircraft through to millimetre-sized examples, which is where engineers at the lab see significant opportunities for the application of 3-D printing technology.

"As the army is starting to move more and more towards unmanned systems - and the size of those systems is getting smaller and smaller - we foresee a lot of capability that the soldiers are going to have that is going to be handheld, backpackable or something that you can put in your pocket", explained Elias Rigas, chief of the ARL's Vehicle Applied Research Division. "As part of that it becomes much more viable to look at technologies such as 3-D printing because they'll be inexpensive and [disposable] assets, but can also be built in unique configurations and on-the-fly in theatre."

John Gerdes, a mechanical engineer at the ARL explained that as the nature and needs of modern militaries are evolving, more responsive technologies are required. "With the emerging need for smaller, disposable and multifunctional UAVs, 3-D printing has really emerged as the manufacturing method of choice. When you have needs that can't really be defined until soldiers are in theatre and you start fielding a prototype it makes it awfully difficult to say up front what it is that you need."

Gerdes has worked with staff from the University of Maryland to develop the Robo Raven, a small UAV that is powered by flapping wings and features 3-D printed components.

The precision-manufacturing capability provided by 3-D printing lends itself to producing the small and complicated components that are required for Robo Raven and advanced systems. "As you get down to smaller size parts a lot of them can be very complex … 3-D printing is a very inexpensive alternative [to traditional manufacturing]. You don't have to go through the manufacturing process of building moulds and low-rate production. It's quicker and easier, and allows us to do significantly more complex shapes and contours," Rigas said.

Gerdes explained that Robo Raven would not have been possible with traditional manufacturing methods, not least because of the prohibitive cost and the complicated design of some of the components. Several handheld UAVs are now set to take part in experiments this upcoming fiscal year at the US Army's Maneuver Center of Excellence (MCoE).

One significant advantage of 3-D printing for UAVs that Gerdes pointed to is the ability for engineers to design systems to meet the requirements of their application, rather than for manufacturability. "Speaking from experience the difference is enormous. Freeing the engineers and designers from the constraints of manufacturability, simply allowing them to focus on the design effectiveness and how well a given part or process is meeting the needs of a soldier is tremendous. You have the ability to focus on what really matters as opposed to the extraneous constraints that are technically important but don't mean a thing to the actual user."

Rigas said that work examining the concept of operations for the deployment to theatre of 3-D printing capabilities is already under way. If fully realised, that concept would enable the army to print full systems and components on demand. "By setting yourself up with a 3-D printer you can field a generic platform which then can have, for example, modules that can be interchanged quickly and easily to meet the always-changing demands of the soldier in an efficient manner and not to just provide a half-hearted solution. Nowadays 3-D printing technology is sufficiently good enough that you can get a finished part out of it, it's no longer just a prototyping device, it's an actual manufacturing tool," Gerdes explained.

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MATERIALS AND SUBSTRATES: THE ELEMENTS OF PRINTING

Rapid advances in build and substrate materials are pushing advances in additive manufacturing almost as much as the printers themselves.

At root, printers traditionally use a heat source, such as lasers, to fuse materials in the sintering process. However, highly conductive build materials or 'inks' that contain nanoparticles of copper, gold or silver can be used to print electronic components - such as conductors, semi-conductors, dielectrics, resistors, parallel-plate capacitors and connecting wires - directly onto weapons, clothing or armour. Inks with ceramic, piezoelectric and graphene elements enable complex, multilayer and vertically integrated electronics. Using these materials, instead of machining intricate holes and/or grooves for wiring, circuits can be printed directly onto complex parts, enabling encapsulated, less fragile sensors, antennas or sensitive elements such as UAV controls to be printed in the build process.

A group of researchers lead by Jing Liu from the Technical Institute of Physics and Chemistry in Beijing recently demonstrated that a gallium and indium metal alloy, which is liquid at room temperature, can be used to print electronics onto a wide range of flexible or curved surfaces. Then, in 2014, Brisbane-based Cartesian introduced Argentum, a 3-D printer able to print circuit boards on various substrates. Via these methods, circuits have been printed on paper, plastic, glass, rubber, ceramic, silicone, cotton fabric, and even a leaf.

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Anika Torruella