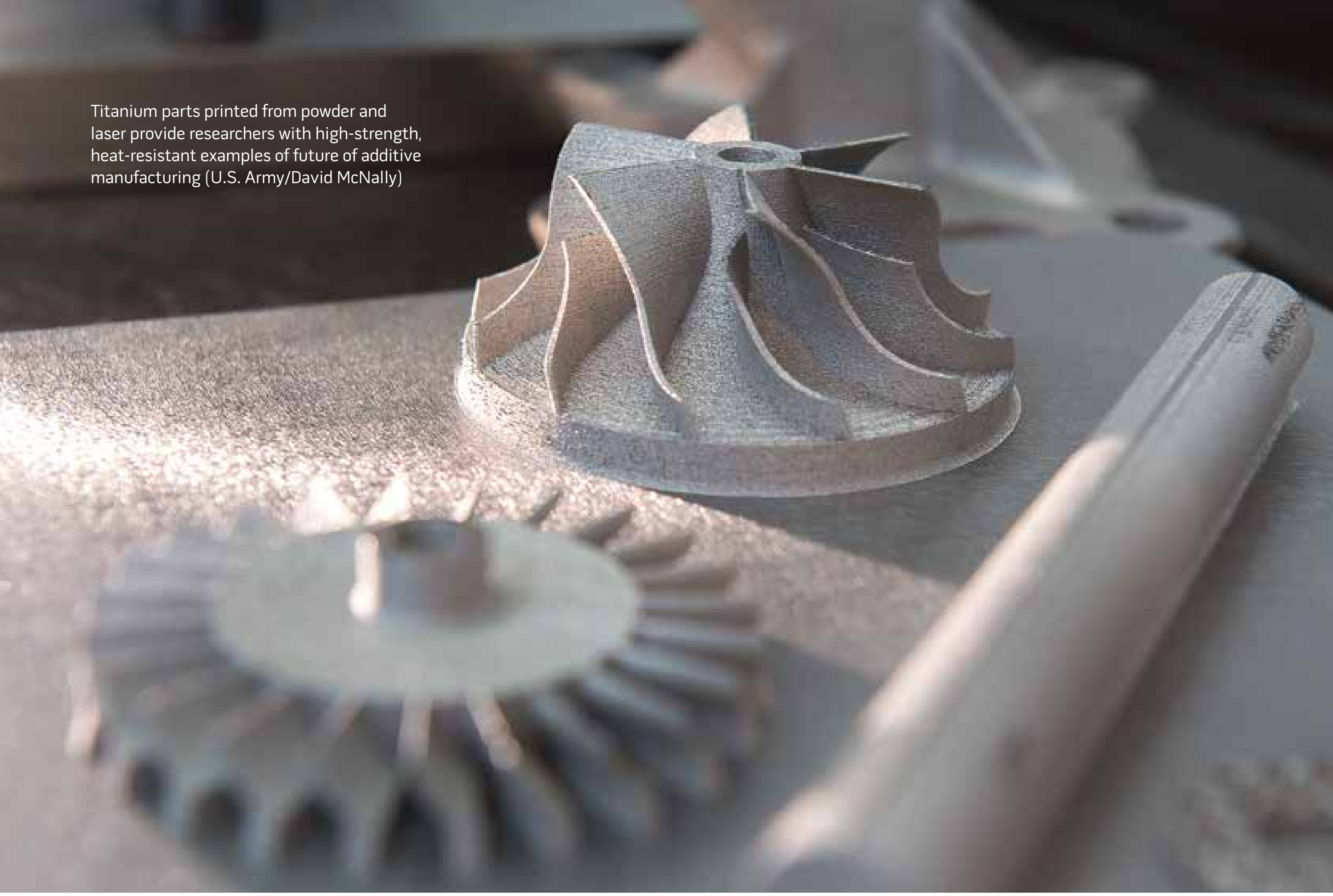

Titanium parts printed from powder and laser provide researchers with high-strength, heat-resistant examples of future of additive manufacturing (U.S. Army/David McNally)

3D Printing for Joint Agile Operations

By Jaren K. Price, Miranda C. La Bash, and Bart Land

The Navy seabase off the coast of Africa is like a floating hive, with personnel moving about aboard multiple ships and both aircraft and landing craft launching to deliver the second wave of the assault force to their objectives. Teams of mechanics examine several Army and Marine Corps vehicles recovered from the beach via landing craft air cushion. One team triages damage in preparation for repairs required for expedited return of the vehicles to the field. Another team assesses the more significant damage done to a joint light tactical vehicle (JLTV) that struck a mine. The mechanics submit requests for repair parts. Some parts are immediately retrieved from stores located on the seabase, while manufacturing specialists load blueprints from a database for those parts not already on hand. Soon, three-dimensional (3D) printers hum. Meanwhile, the specialist engineering team develops a repair solution for the JLTV, and an engineer drafts the 3D design. The new plans are also transferred to print production. The parts are delivered to the mechanics who then complete the repairs. Within hours, the vehicles are ready for return to their units.

In the near future, this scenario could become reality. Additive manufacturing (AM), also known as 3D printing, could enable future agile operating concepts. AM has the ability to significantly shorten the Department of Defense (DOD) logistics chain, especially where repair parts are concerned, by producing the parts as they are needed. This would enable rapid, flexible response to unanticipated faults or battle damage with reduced stockpile requirements, increasing the agility of the operational force. However, to

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fully and efficiently capitalize on the potential of AM, DOD must develop common data solutions and standardized safety, certification, and requisition processes for AM, leveraging data science to prioritize development efforts by cost savings and implementation impact. An integrated effort by the joint enterprise is required to overcome Service independence and technology implementation challenges to make joint agile sustainment a reality.

The December 2017 National Security Strategy identifies Russia and China as revisionist powers that are actively competing with the United States across all domains.[1] They have developed weapons to asymmetrically exploit U.S. weaknesses and create standoff through antiaccess/area-denial and area-denial strategies. Outside the realm of nation-state competition, the United States continues to carry out humanitarian and antiterrorism operations in austere environments. These developments mandate that the United States devise the means to operate in contested environments and in places where access to bases and infrastructure does not readily support operations.[2] A key aspect of future operations is how to effectively sustain the joint force.

Based on this vision for the future, the Services have laid out concepts and started to develop capabilities and procedures for agile operations in an array of denied environments. The new operating concepts envision sustained ground, naval, and tactical air operations being conducted without access to ports, airports, or staging bases for extended periods and operating from austere airfields with only the minimum logistics support. These tactics require logisticians to develop new ways to meet the needs of the force, providing timely sustainment without the use of large land-based logistics facilities. These concepts include the Navy and Marine Corps' Seabasing Concept, a variety of Air Force Disbursed/Agile Basing Options, and the Army's Multidomain Operations.

Whether operating from floating seabases, dispersed airfields, or remote operating bases, these concepts call for U.S. forces to be able to maneuver from strategic distances and integrate capabilities across time and space to overmatch the enemy. Implementing these concepts requires "precision logistics that provides a reliable, agile, and responsive sustainment capability."[3] The enemy is expected to specifically target U.S. sustainment capabilities both at home and at deployed locations by conventional, unconventional, and cyber means. Thus, sustainment forces must often be dispersed to multiple locations, be resilient to attack, and have enough redundancy to maintain baseline capability in spite of attacks on some locations. They also call for sustaining, maintaining, and repairing units and equipment as far forward as possible.

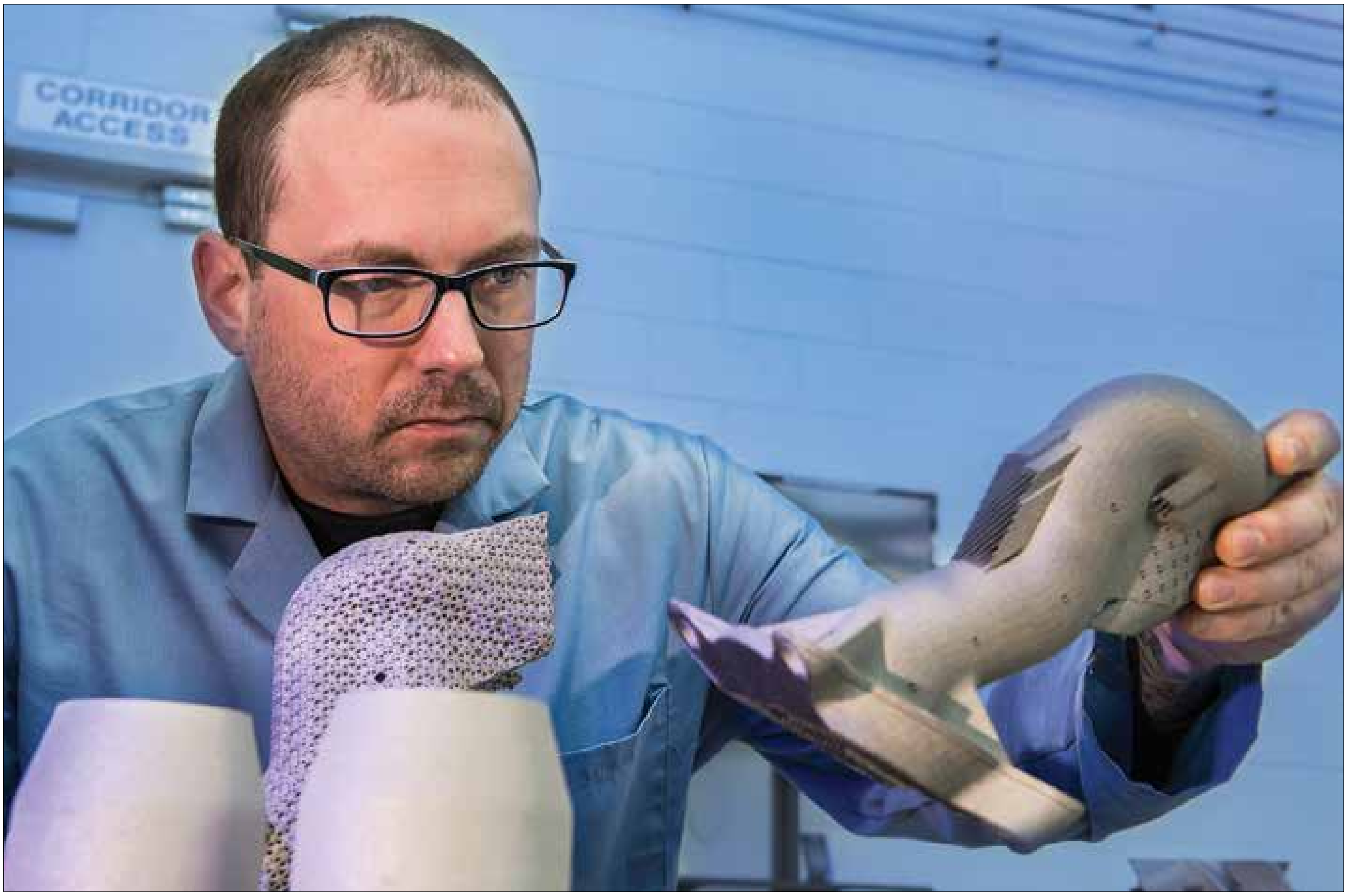
The common theme among all the operating concepts is the ability to deliver sustainment support as far forward as possible, reduce the requirement for large logistic bases, and protect the joint force through minimizing its size and operational footprint. While equipment and spare parts make up only a small fraction of sustainment requirements compared with fuel and ammunition, AM at forward locations would help realize these concepts by reducing required spares inventory, shrinking lift requirements, creating more flexible prepositioned stocks, and providing redundancy.

The term *AM* appropriately describes a process that involves adding and bonding consecutive layers of material, whereas traditional (subtractive) manufacturing involves shaping and milling and usually secondary materials specifically engineered for the creation of one design (such as a mold). The removal of material during traditional manufacturing results in a much larger percentage of waste of the base material than AM does. AM generates the capability to rapidly manufacture spare parts in the local vicinity, eliminating supply chain distances and often prolonged acquisition processes. It has fixed per unit costs, enabling the efficient production of small quantities of custom parts. Besides the ability to recreate previously out-of-production parts, AM facilitates unit-level innovations such as the production of custom tools to solve niche problems.[4] Other potential benefits of AM for manufacturing include networked smart factories, improved quality control, rapid innovation, individualization with voxel-by-voxel[5] digital modifications, and on-demand production, reducing inventories.[6] Incorporating AM into the manufacturing process can also reduce part count, assembly time, and weight "while creating complex internal and external geometries that could not be made any other way."[7]

At a distance from both repair facilities and spare parts storage, units employing agile operating concepts could manufacture their own replacements or leverage a nearby forward base, significantly reducing stocked inventory, transport requirements, and time to get needed parts to repair facilities. To maintain operations in denied areas, avoid detection, reduce equipment downtime, and maximize repair opportunities while under way or in the field, units with AM capabilities could create parts on demand.

Currently, each Service has its own system of mobile warehouses that contain replacement parts for specific weapons systems such as fighter aircraft. Mobile warehouses enable our current expeditionary capabilities but require significant enhancement in order to support agile operating concepts. These mobile warehouses rely on extensive amounts of demand data to forecast with modest accuracy what should be maintained in stock. Demand data can be best described as the frequency with which certain items are required. Collected over years, this data forms a picture of the replacement parts required over time for each system on record.

Demand data, however, cannot predict all critical failures, leaving weapons systems susceptible to mission degradation for prolonged periods of time. New systems have no demand data, making predictive schedules for replacement parts difficult. Legacy weapons systems have failures that were never anticipated, meaning no replacement parts were ever produced. They may also have components that are no longer manufactured. AM has the potential to reduce risk associated with unanticipated demand by



Army researcher Dr. Brandon McWilliams holds sample part created from powder at U.S. Army Combat Capabilities Development Command's Army Research Laboratory, Aberdeen Proving Ground, Maryland, February 25, 2019 (U.S. Army/David McNally)

enabling production at the point of need. In addition, AM enables leaner mobile warehouses because the risk generated by out-of-stock parts is reduced or eliminated through on-site manufacturing.

The technology does not yet allow for the elimination of these mobile warehouses, but it will allow stocks focused on low-density, high-demand parts, particularly complex parts or parts requiring materials or precision not easily produced under current AM capabilities. More effective and condensed mobile warehouses and global stocks will lighten the burden on transportation assets and the distribution system. On a large scale, this would result in reduced personnel and materiel-handling equipment at distribution hubs, en route locations, and agile bases. Some of these personnel could instead be trained to become AM specialists. With fewer aircraft, ships, trucks, and rail cars required to move items through the supply chain, these transportation assets could instead concentrate on the delivery of operational forces and equipment to and from agile bases.

Transportation assets, such as cargo aircraft and ships, would also benefit from an onboard or isolated location AM capability to support organic repair capabilities. Units could make their own critical parts on-site, allowing distribution missions to continue on schedule. This would be especially useful when transportation assets do not include mobile warehouse capabilities or are themselves long distances from logistics support. The increased availability of transportation assets created by this capability would allow resources to be committed to other operational needs. It would also enable more frequent trips to isolated agile bases without increased investment in transportation assets.

Adding an AM capability to prepositioned stocks would directly support agile basing concepts. The Army, Marines, and Air Force depend on these ships to be ready to respond to crises, but there are only a few ships maintained worldwide due to the immense investment required to operate each. These stocks consist of a large variety of items that enable crucial weapons systems and combat personnel including, but not limited to, materiel-handling equipment, construction equipment, generators, radios, refueling equipment, medical equipment, and ammunition. AM could be utilized to allow more robust maintenance and repair actions on board for both the ship and stock, averting frequent returns to port to restock. Returning to port takes days to weeks and often includes significant homeport maintenance periods, reducing platform availability for crisis action and increasing risk to potential operations. AM would provide a means to mitigate this risk.

Another advantage of utilizing AM is the avoidance of sunk costs due to obsolescence or end of service life. As military equipment is modernized over time, prepositioned stock must be updated, incurring periodic reinvestment costs. Some of this replacement stock is also discarded due to expiring shelf life despite having never been used. AM helps reduce these costs by enabling production of equipment when it is actually needed. When AM technology matures, the increased equipment produced at the time of need may allow for the conversion from a few large prepositioned stock vessels to a larger number of small but equally capable ships. This will be possible because AM will be able to produce complex pieces of equipment custom made for the mission. These ships could more effectively provide coverage for global operations, creating a much more responsive prepositioned stock. Improving the prepositioned stock fleet in this way is critical to making agile operating concepts a reality.

Units across DOD are already beginning to innovate utilizing AM to develop new tools and to streamline maintenance and supply procedures. The Marine Corps Iwakuni Engine Ship Kit, created by a technician in the unit using a 3D printer, allows for the movement of aircraft engines requiring repair without draining oil and hydraulics.[8] Marine Corps Systems Command and Marine Corps Installations and Logistics have created a transportable 3D print lab prototype, X-FAB (Expeditionary Fabrication Lab), for use with deployed maintenance forces. The Chief of Naval Operations' Rapid Innovation Cell has permanently installed one printer on the USS *Essex*[9] and has plans to install 3D printers on two additional ships.[10] Naval Sea Systems Command (NAVSEA) has also approved the first metal part created by AM for a 1-year trial on the USS *Harry S. Truman*.[11]

To support forward-deployed Soldiers, U.S. Army Research, Development, and Engineering Command (RDECOM) has partnered with the Rapid Equipping Force to help manage, staff, and support its own 3D printing Expeditionary Labs (Ex Labs), which can be deployed worldwide. The Army Ex Lab is a fabrication laboratory, self-contained in a 20-foot shipping container. It contains four 3D printers, currently limited to polymer printing.[12] One is deployed to Bagram Airfield in Afghanistan, and another is operating out of Camp Arifjan, Kuwait.[13] This enables solutions to problems discovered on the battlefield, but current policy strictly confines AM to only emergency repairs. Furthermore, to produce a repair part, Soldiers are required to simultaneously requisition the item through the supply system.[14]

The Defense Department has already made significant investments in AM technology, and America Makes—the National Additive Manufacturing Innovation Institute—was established in 2012 as a public-private partnership between the Federal Government, private industry, and universities. It is managed by the Air Force Research Laboratory (AFRL).[15] As a significant marker of progress in the partnership, in June 2018, America Makes and the American National Standards Institute published version 2.0 of the AM Standardization Roadmap, highlighting the gaps in and steps to standardize the lifecycle of an AM part.[16] This work will go a long way to boost industry development of AM that can eventually be used by DOD.

Meanwhile, disparate organizations within the Services are pursuing database design and parts validation for AM. The Navy has designated OPNAV N4 as lead Navy synchronizer for AM.[17] RDECOM and U.S. Army Materiel Command are creating a product data management system to retain and share design data.[18] RDECOM, the Office of Naval Research, and AFRL all have laboratories that conduct AM research activities.[19]

The U.S. Government Accountability Office recommended in October 2015 that DOD designate an Office of the Secretary of Defense (OSD) lead for the development and implementation of a systematic approach to Department-wide activities and resources that facilitate the adoption of AM technology across DOD. The primary driver is an ability to track actual or potential performance and combat capability improvements, cost savings, and lessons learned.[20] Over a year later, on November 30, 2016, a joint committee composed of Service, Defense Logistics Agency (DLA), and America Makes leads published a DOD AM Roadmap containing high-level goals for continued development and implementation of AM objectives. The committee assessed significant coordination across the Services but suggested that more formal sharing mechanisms and progress assessments were required, including the assignment of a lead integrator to coordinate DOD AM Roadmap revisions.[21] Despite coordination, it is unclear if an OSD lead was ever named, and each of the Services has developed or is developing its own AM roadmap and independent capabilities.

In order to enable AM for maintenance and logistics, the whole of AM implementation across DOD must be matured. The independently produced AM implementation plans for the Army, Navy, and Air Force take separate approaches to developing AM across the force. Only with unity of effort can DOD efficiently overcome nine key implementation challenges:

- material standards and availability
- part selection
- skill set development
- configuration control
- reproducibility
- cyber security
- part validation and qualification
- process validation and qualification
- ability to reverse-engineer components.[22]

And these challenges must be overcome in order to achieve AM capabilities that can support agile operating concepts. For shorter term limited employment of AM for repair parts, most critical is the ability to develop, share, and retain Technical Data Packages (TDPs), which make parts printable, and the ability to reproducibly print to adequate precision and quality in the design-specified materials. To enable AM for part production more generally, a prerequisite for reliable, competitive sourcing of spare parts is a mature industry of AM manufacturers using comparable printers, with a defined set of material standards and file formats.[23]

The engineering and post-processing intensity required for most parts means that printing qualified parts will be difficult to achieve in austere environments. A part must be qualified, or certified, to meet certain design specifications (temperature, pressure, forces, and motion over certain amount of time), in order to be installed in a DOD system. For a 3D part to be qualified, it must be printed from a qualified printer: an AM printer that has been itself certified as able to reproduce the part to the same specifications with each use. Competitive bidding is also required among potential manufacturers, translating into a requirement to certify multiple models of printer (in use at different companies or built by different manufacturers) that would need to be qualified for each part.

Materials must also be certified by a defined standard, increasing the developmental work required by DOD to leverage a still immature field to this task. In alloy production, there are currently only a few metals with an American Society for Testing Materials standard defined for AM. And for metal AM techniques, significant facility and operational requirements exist to accurately and consistently create parts, including controlled temperature, humidity, movement, and reliable electrical power, containment of powders to prevent accidental transport and contamination of alloys on hand, specialized equipment to clean the machine, and material that must be disposed of—the creation of soot-laden waste water in the machine itself.[24] To date, these constraints have restricted field printing to polymers.

The variety of raw materials required to manufacture repair parts is another limitation that will need to be considered. Systems design engineers will need to find ways to reduce the diversity of materials in order to permit leaner AM material stocks. For example, it may be advantageous to use more expensive materials for some parts that do not actually require them in order to use a single material across several components, simply to reduce AM raw material variety required in stock. To implement AM in support of mobile warehouses, the right balance between stocking replacement parts and raw materials is also required to maximize the effectiveness and minimize the overall size of all stock.

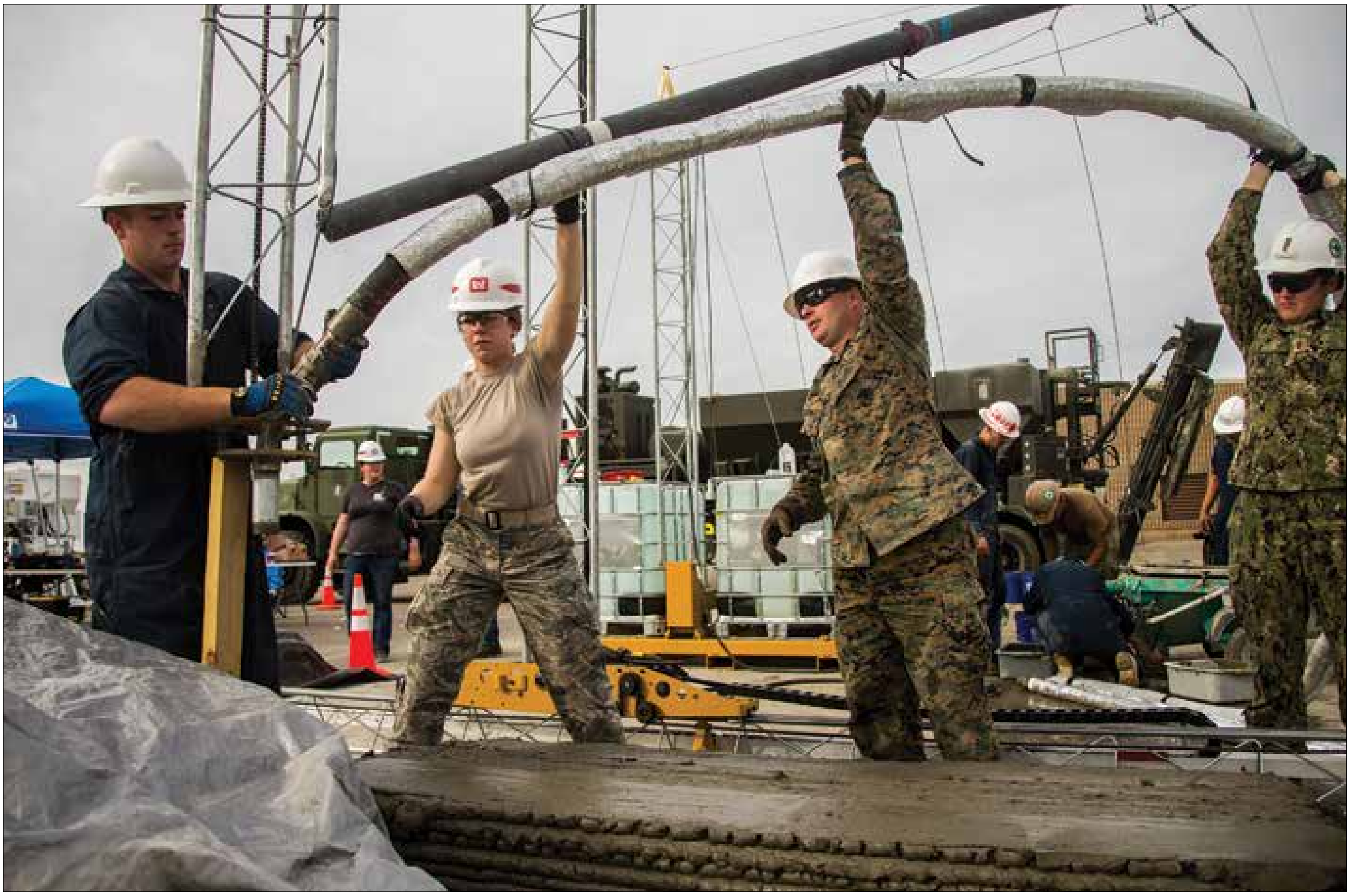
In order to most effectively develop AM to support agile logistics, several things must occur. First, a secure unified digital network across DOD, containing certified TDPs themselves as well as metadata regarding the printer, supplier data, and certifying engineering activity, is required. DLA Logistics Operations Research and Development is developing such a database in coordination with the Services. It is also developing a repeatable supplier qualification process and has developed a limited Additive Part Candidate Identification Tool to help identify which parts to prioritize for production using AM.[25] For the development of new systems, contract language to handle intellectual property issues and enable future access to precise technical data will be key to successfully harness AM capabilities in the long term.

Second, DOD must develop standardized processes across the Services. NAVSEA, the Naval Warfare Centers, and DLA are building standardized processes and guidelines for AM and developing TDPs for parts that can no longer be acquired through normal supply channels. The Naval Warfare Centers, Systems Centers, and Naval Research Laboratory are studying how best to qualify and certify 3D printed parts. Naval Surface Warfare Center Port Hueneme is also looking at applications on ships, specifically on the logistics, data libraries, contracting mechanisms, and issues regarding data rights.[26] Process validation remains rather intensive, with three different printers at three different locations test printing a single TDP in order for DLA to then put out a bid for the contract manufacture of that part. One Warfare Center materials engineer, however, has suggested that eliminating the requirement to qualify every individual part is required to realize AM's true potential.[27] Because it is not cost effective to validate in this way every part that a unit might want to print or design, there should be a streamlined process for those parts meeting a lower threshold of system criticality. Whatever the standard, there must be a single standard implemented across DOD.

Third is shifting the requisition process to incorporate AM, leveraging a centrally managed database of qualified parts to print where they are needed instead of requisitioning parts through normal supply channels. Robust multifunction printing would then be viable at in-theater depots. Although the Services would largely print different parts, there is likely to be some overlap in parts and significant overlap in qualified printers and materials, making unified and compatible systems by design as well as federated testing absolute must-haves for efficiency.

Fourth, safety standards must be published and implemented. This includes safety considerations for closed spaces, such as shipboard environments or conex boxes. The AM work environment must both contain materials and allow adequate ventilation in order to prevent hazards to personnel, such as toxic gases released during fusion of metal powders.[28] The use of personal protective gear and adequate detection of and ventilation for a possible gas leak from within a metal printer's inert gas atmosphere are required. This capacity must be integrated within safety procedures and hazardous waste programs.

Depending on part complexity, material, and the AM capabilities forward, some parts offer greater differential advantage to stock rather than print. An important fifth step in implementation is prioritizing which parts should be developed for AM. Paired to part prioritization is developing the level of printer capabilities that would be most useful forward. Costs and capabilities vary widely for 3D printers, pricing anywhere from $2,000 for a home plastics printer to $50,000 for a basic metal printer to over a million dollars for a larger, more accurate multi-material printer. Differentiating both parts and printers across a range of attributes, including size, material, and resolution requirements, is critical to establishing which parts can realistically be fabricated locally and which would be better produced in more specialized facilities, whether land-based, in-theater, or back with the manufacturer. Some parts, critical but difficult to precisely print, would need to be retained in stock. For mission-critical parts that can be precisely



Marines with 7th Engineer Support Battalion and Sailors with Naval Mobile Construction Battalion 5 attach hose onto 3D concrete printer during 3D Concrete Printing exercise at Camp Pendleton, California, December 9, 2018 (U.S. Marine Corps/Betzabeth Y. Galvan)

3D printed—such as engine components—whether steam plant or aviation, weapons systems, and safety systems, a long lead of material, printer, and part qualification is required to ensure the parts meet specifications.

Sixth, DOD must broadly assess which spare parts across the inventory would offer economic and operational advantage if shifted to AM. This would enable the prioritization of over 5 million line items across the Defense Department for further investigation, with unity of effort and potential federation across Service channels.[29] Applying data scientists to this effort will help systems engineers prioritize their efforts. Criteria for AM at point of need should include high or intermittent demand, long lag to receipt at supply depot, criticality of readiness impact without component, printing capability to produce a qualified part if required, and accessibility of design specifications in a TDP repository. Adaptive modeling and visualization of which policy adaptations, joint collaboration opportunities, and technical solutions are most useful for increasing capabilities forward, while reducing cost would advise the most beneficial focuses over time across the DOD enterprise.

Finally, it is critical that the most cost-effective methods and processes be determined. The cost calculations for an AM implementation must include the total cost of facilities, training or contracting of operators, unified databases with mechanisms to allow for intellectual property rights of the designs, ongoing fabrication materials costs, software and machine service contracts, and program management over time.[30] As AM is developed, the cost savings that can be realized across DOD if the Services appropriately leverage economies of scale and avoid duplicative efforts cannot be overemphasized. While relatively segregated today across Services, TDP development, database creation and maintenance, contracting methods, safety standards, and AM policy can and must be accomplished jointly.

AM implementation across the Department of Defense is in its early stages. Current experimentation with AM across the Services demonstrates applications for agile operations, emergency situations, and innovative uses. However, there are significant program development hurdles ahead to reach AM's potential. The DOD must identify cross-Service solutions that will generate a distinct operational advantage when factors such as repair time and cost are considered. Some of the most immediate challenges include developing databases of parts that can be printed locally; establishing DOD-wide methods and requirements for safety, parts, and printer certification; and determining which parts are best printed locally and which should

Prototype parts are 3D-printed in new Advanced and Additive Manufacturing Center of Excellence to troubleshoot machines at Joint Manufacturing and Technology Center, Rock Island Arsenal, Illinois, May 15, 2019 (U.S. Army/Debralee Best)

be stocked or supplied through more traditional supply channels. AM is a key enabler for joint agile sustainment, but joint must be part of the design.

The world is changing rapidly, and potential adversaries will aim to rob the United States of all of her advantages. As we envision fighting in austere locations and areas where we are denied access to robust logistics bases, AM, if properly developed, represents a potential advantage for U.S. forces. **JFQ**

Notes

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