AWC Fellows
Strategy Research Project

Additive Manufacturing: Special Operations Forces Capability Production at the Point of Need

by

Colonel Joseph R. Blanton
U.S. Army

Under the Direction of:
Mr. Ted Sturgeon and Mr. Douglas E. Waters

While a Fellow at:
Duke University

United States Army War College
Class of 2019

DISTRIBUTION STATEMENT: A
Approved for Public Release
Distribution is Unlimited

REPORT DOCUMENTATION PAGE	*Form Approved--OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-03-2019	**2. REPORT TYPE** FELLOWS STRATEGY RESEARCH PROJECT	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE

Additive Manufacturing: Special Operations Forces Capability Production at the Point of Need

5a. CONTRACT NUMBER

5b. GRANT NUMBER

6. AUTHOR(S)

Colonel Joseph R. Blanton
U.S. Army

5d. PROJECT NUMBER

5e. TASK NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Faculty Adviser: Mr. Ted Sturgeon
Host Institution: Duke University

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Faculty Mentor: Mr. Douglas E. Waters
U.S. Army War College, 122 Forbes Avenue, Carlisle, PA 17013

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution A: Approved for Public Release. Distribution is Unlimited.

To the best of my knowledge this FSRP accurately depicts USG and/or DoD policy & contains no classified information or aggregation of information that poses an operations security risk. **Author:** ☒ **Mentor:** ☐

13. SUPPLEMENTARY NOTES

Word Count: 6923

14. ABSTRACT

How can additive manufacturing (AM) produce SOF mission essential equipment at the point of need? The 3D printing technology exists to produce equipment in remote locations to support SOF through additive manufacturing. Understanding the SOF core principles and the limited logistical support there is an opportunity to provide flexible materiel solutions in the tactical areas. The DoD is recognizing the benefits of AM. An AM Campaign Plan and policy updates along with a wide variety of initiatives across all military services reinforce this point. The next steps are to implement the policy changes, follow the plans and collaborate with a goal of producing a complete mission essential system via additive manufacturing at the tactical point of need.

15. SUBJECT TERMS

3D Printing, Additive Manufacturing, Materiel Development

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		31	**19b. TELEPHONE NUMBER** *(w/ area code)*
UU	UU	UU	SAR		

Additive Manufacturing: Special Operations Forces Capability Production at the Point of Need

(6923 words)

Abstract

How can additive manufacturing (AM) produce SOF mission essential equipment at the point of need? The 3D printing technology exists to produce equipment in remote locations to support SOF through additive manufacturing. Understanding the SOF core principles and the limited logistical support there is an opportunity to provide flexible materiel solutions in the tactical areas. The DoD is recognizing the benefits of AM. An AM Campaign Plan and policy updates along with a wide variety of initiatives across all military services reinforce this point. The next steps are to implement the policy changes, follow the plans and collaborate with a goal of producing a complete mission essential system via additive manufacturing at the tactical point of need.

Additive Manufacturing: Special Operations Forces Capability Production at the Point of Need

How can additive manufacturing (AM) produce SOF mission essential equipment at the point of need? Additive manufacturing (or 3D printing; the terms are synonymous) has many useful aspects. Supply chain efficiencies and rapid design are two examples. This project looks towards producing an end-product in expeditionary locations, not only repair parts. Additive manufacturing technology exists to manufacture equipment for military use now. However, there are potential legal, security and procedural limitations for the Department of Defense to use these technologies fully. This paper briefly explains some of the technologies; considers some of the benefits and limitations to additive manufacturing as well as constraints on the governmental use of 3D printing; and analyzes current DoD, Army and SOF 3D capabilities. A concept of operation for the use of AM in to support a deployed organization is not used in this project. Rather the goal is to discuss future options to develop finished end-items in distributed operational locations near the tactical point of need for SOF. This scenario would support a wide array of operational scenarios.

Additive Manufacturing

Additive manufacturing is a method of producing a three-dimensional object by adding layers of material. This technique differs from traditional manufacturing methods which reduce material from a solid object in producing a three-dimensional object.[1] An example would be milling or removing excess metal to form a bolt or screw.

The process involves a computer-aided-design of the object to be manufactured. Software slices the design image into thin cross-sections. This design is sent to additive manufacturing equipment. Those cross-sections are produced one at a time, layered upon each other and fused together through various methods.[2]

In the 2010 book, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* Gibson et. al, explained the process in eight steps that, at least to some extent, each AM product passes through. The degree to which a part is refined is determined by the level of precision that is needed. In other words, some parts do not need a high degree of post processing where others may require completion to a higher manufacturing tolerance.

> Step 1: Computer Aided Design (CAD)
>
> All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.
>
> Step 2: Conversion to Standard Tessellation Language (STL)
>
> Nearly every AM machine accepts the STL file format, which has become a de facto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.
>
> Step 3: Transfer to AM Machine and STL File Manipulation
>
> The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.

Step 5: Build

Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.

Step 6: Removal

Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

Step 7: Postprocessing

Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.

Step 8: Application

Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.[3]

There are many AM processes, equipment and materials used today. American Society for Testing and Materials (ASTM) is an organization focused on establishing international standards for AM. In 2010 ASTM grouped the AM processes. Currently, there are seven groupings:

1. Powder Bed Fusion
2. Vat Photopolymerization
3. Binder Jetting
4. Material Extrusion
5. Directed Energy Deposition
6. Material Jetting
7. Sheet Lamination [4][5]

Each of these processes create products with different attributes for a variety of purposes. One application is to print repair parts on demand, thus streamlining supply chain activities like having to anticipate need, process orders, ship or store parts that may in the end not be used. A second benefit is in rapid development in a design process. An engineer can create a design, print out a model and refine the design based on the 3D model. This can be repeated many times inexpensively allowing for low cost rapid design.

Benefits to Additive Manufacturing

Additive manufacturing has other benefits over traditional manufacturing approaches. Additive manufacturing uses less material because an end item is being built by adding needed material. In this process, only the materials needed are added or used. Subtractive manufacturing starts with a larger piece of material, and as the part is created the material being subtracted or milled away is waste. Another benefit of AM is that it can precisely produce a single item or be repeated as needed. More traditional methods require either hand building (which makes it nearly impossible to recreate precisely) or specific tools and manufacturing equipment. Making small quantities is more expensive if produced in a traditional fashion. An additional challenge is transportation and storage costs associated with stocking spare parts. In a traditional sense, parts are either requested when a need arises, or higher demand parts are stored in anticipation of need.

AM can enable customized or tailored products. Essentially, a basic design can be slightly modified to fit unique applications. As an example, NASCAR uses 3D printing in developing parts for race cars. A part is produced, then put on the vehicle and tested in a controlled environment such as aerodynamic testing. Slight adjustments are made to the parts through the software and another part is produced and tested to potentially improve performance.[6] In this instance, 3D printing helps engineers iterate quickly in designing products.

Additive manufacturing has additional benefits compared to traditional manufacturing. According to a Government Accountability Office report in June 2015, AM advantages include “reducing the time to design and produce functional parts, whether the parts are manufactured using additive or conventional processes; producing complex parts with fewer subparts that cannot be made with conventional manufacturing processes; using alternative materials with better performance characteristics; and creating highly customized, low-volume parts—all of which can lead to cost savings”[7]

In a July 2018 article, Carlton A. Doty and Annika Gunderson make the assertion “We are about to enter the most disruptive era in manufacturing since the industrial revolution, and it’s called additive manufacturing. The manufacturing industry is one of the last to face digital disruption at the magnitude that we’ve all seen in other verticals.”[8] 3D printing has been around since the 1980s and used in recent years for rapid prototyping (like the example shared earlier regarding NASCAR). However, changes in the capabilities are “advancing exponentially”, costs are being reduced on a similar scale, advances in materials sciences create the option of printing “metal end-use components at scale” with increasing quality and to higher tolerances.[9] This establishes an environment where industry and other AM users can:

Enable mass-customization. Additive manufacturing has the flexibility to customize parts and do it at an affordable rate. This is expected to be an area of continued maturity across many product ranges. In the automotive industry, customers are enjoying a customized car-buying experience by selecting the “color and texture of a custom effect skin" on the vehicle.[10] The medical, dental and footwear also are an area suited for customization.[11]

Reduce investment and barriers to entry. The costly investment of setting up a traditional facility to manufacture parts is a barrier for smaller startup companies. The affordability of 3D printing systems barrier is all but eliminated. Smaller competitors can compete and scale production to now be competitive and ultimately disrupt the traditional manufacturing companies. The cost of capital for a complete 3D printing system is a fraction of the costs associated with standing up a traditional manufacturing facility. Some metal 3D printers can even be used in an office environment, without special ventilation or waste management requirements. This will allow small new competitors to quickly enter markets and scale. In an environment where "more startups take advantage of additive manufacturing methods; the producers of industrial and consumer products will see heightened competition from smaller disruptors."[12]

Accelerate time-to-market. With the advancements in metal printing end-products can be produced for testing. As before rapidly produced prototypes were manufactured and used for design iteration then the end-product would be produced and assembled using traditional manufacturing methods. While there are design efficiencies with 3D printing prototypes create gain there was loss due to increased cycle time when the develop product was then manufactured via a traditional production process. The traditional method requires unique tools and jigs and that lead to other known inefficiencies associated with historical methods. Now, "companies can upload a new end-product design into a printer and produce it at previously unattainable speeds.

Desktop Metal’s metal production printer prints 100 times faster than any single-laser powder bed printing system”.[13]

Increase part performance and value. Additive manufacturing creates design options the allow parts to be made with increased performance characteristics. General Electric designed a turbine engine blade with sensors. Now during maintenance cycles the blades are scanned and wear is determined per blade. Previously all the blades were replaced on a schedule based on likely or assumed wear. Also, “quality assurance costs are decreased on parts that traditionally have multiple steps to manufacture as well, as 3D printing consolidates and reduces the steps, processes, and costs involved in traditional manufacturing.”[14]

Enable assembly consolidation. 3D printing “will unlock the ability to consolidate parts; designs with multiple different parts can now be printed as one.” Optisys, an aerospace engineering company, was able to build an antenna using additive manufacturing in one part. The original design required 100 individual parts traditionally manufactured. Also, the AM design had a weight reduction greater than 95%, reduced lead time by 9 months (from 11 to 2) and realized production cost savings by 20%.”[15] Plus, AM produced longer-term savings of increased durability and simpler supply chains because of the reduction in parts.[16]

Speed spare part delivery and reduce spare part inventory. With the stated benefits of AM such as combining parts with just-in-time printing the need for high spare parts inventory is reduced. Likewise, forward positioning the 3D printing capability closer to the point of need would reduce downtime for repair parts. There are several service initiatives underway that will be further explained later in the paper that address this approach of experimental labs in tactical locations.[17]

Reduce material waste. As mentioned earlier in this paper additive manufacturing creates the material needed as compared to subtractive which removes it and results in greater waste material. The aviation industry seeks weight savings in several areas and one report indicated a 30% savings through AM processes. It is important to point out the weight savings is for secondary parts not primary stress supporting structures. The limitation there is in the materials currently available. As composite materials are used more reliably the weight savings is expected to continue.[18] 3D printing also “allows more complex, organic shapes to be printed, giving greater design freedom and enabling generative design. Generative design uses AI [artificial intelligence] to create parts with materials only where they are crucial for the parts to meet strength and load parameters. Anywhere a support structure wouldn’t be necessary is left empty, decreasing the amount of material used.”[19]

Challenges with Additive Manufacturing

Intellectual Property. One significant limitation to providing these capabilities are legal restrictions based on intellectual property of the developing defense contractor. Regulations require materiel developers or acquisition professionals to have a plan to manage the intellectual property (IP) of the developer.[20] The U.S military can buy the rights to the IP but it is generally expensive and often considered cost prohibitive. Depending on the complexity of the system or anticipated use it is sometimes more affordable to have the defense contractor maintain the rights and the

U.S. Government pay for upgrades as needed. This is a system by system decision. The challenge with IP and additive manufacturing is the potential legal rights infringement of the US government on the defense contractor if a product is reproduced through AM using proprietary information without compensating the owner or those who are entitled to IP.[21] The acquisition process can account for this, but it is a step historically not taken for all products.

However, on December 7, 2018 the Secretary of the Army issued Army Directive 2018-26 (Managing Modernization Through the Management of Intellectual Property). This is a new precedent for the Department of the Army. This directive mandates the "new approach will ensure flexibility by requiring that we identify early in the process the IP needed in all phases of the Defense business system's or weapon system's life cycle…require transparency…with industry. We will seek tailored access to IP…pursue creative, customized licenses…to meet our needs. Finally, we must aim to negotiate prices for deliverables and associated license rights early in the process when competition exists."[22] This directive further states the acquisition policy and associated technology and sustainment policies reflect this new direction. Lastly, the Assistant Secretary of the Army (Acquisition, Logistics and Technology) [ASA ALT] publish implementation guidance.

On February 5, 2019 the Implementation Guidance was published. In maintaining the intent of the Secretary of the Army this directive highlights that "intellectual property is highly complex and nuanced…and as intellectual property laws and regulations continue to evolve…best practices will be updated".[23]

Materiel Release. Another limitation for fielding end-items is the material release process to field new equipment to military service members. The U.S. Army has four materiel releases: full, conditional, urgent and training. All serve a purpose and have definitive requirements to gain the release to field the system to service members. At a minimum for each release the system must be safe to operate, and the system limitations must be understood. This policy is in place to prevent soldiers from being injured in the operation of a new piece of equipment. To understand if a system is safe to operate and what the system can perform government testing and analysis of test data must occur.[24] While this is different for each system it requires resources (time and money) and cannot be conducted in austere locations where SOF often operate. For simpler developed solutions the Army risk management process is followed and discussed later in this paper related to current capabilities.

Cyber. Cyber vulnerability poses an increasing threat and barrier to additive manufacturing due largely to the reliance on computers for the design and production of 3D printed parts.[25] In a Defense Systems Information Analysis Center (DSIAC) article on the subject, Doyle Motes highlighted in an industry that is experiencing exponential growth each year the likelihood of cyber-attacks is also growing. There was nearly 80% growth in the use of metal-based AM machines in 2017.[26] As AM moves more into the mainstream and with many parts of the U.S. government and all military services looking to increase and improve the use of AM the threat is reaching new levels of concern. As a matter of practice engineers using CAD drawings and uploading as .stl files have shown a vulnerability. One example reported in the DSIAC article related to a drone propeller blade. The .stl file was manipulated to place subtle changes in the blade design that introduced a weakness at a stress point. When the blade was placed on the drone it flew for a short while, but the blade malfunctioned, and the drone crashed. Upon investigation it was found the file was tampered with. This poses concern given the use of AM in the commercial aviation community.[27] While there were several suggested precautions to be taken such as keeping the computers and 3D printing software and machines current with anti-virus there is not a complete solution to this challenge.[28]

Cost. Cost is a challenge for the additive manufacturing community. Cost to operate the types of machines to produce final parts are expensive to purchase and the materials are often proprietary to the machine. Some 3D printers are software enabled to only accept the proprietary build materials.[29]

Quality. Machine variability, certification and quality assurance is not yet comparable to standards of traditional methods. The risk of introducing flawed or substandard parts into the supply inventory or producing an end-item that is different from the tested and approved system is a valid concern. Machines subject to changes in environmental conditions. It’s a challenge with AM machines in a controlled production environment not to mention the challenges facing 3D printers in austere locations. Altitude, heat and humidity have had impacts on successfully replicating an AM produced part using the exact same digital files. It was discovered that some of the build materials are affected by the environment and feed into the 3D printers and perform differently when the atmosphere changes.[30] However, there is an effort “underway since 2009 by ASTM International…primary committee on Additive

Manufacturing" to refine the quality standards to meet those of traditional manufacturing.[31]

Additive Manufacturing as a Growth Industry

The additive manufacturing industry has grown on average 26.6% each year for the last 29 years. The AM market is estimated to be $7.336 billion which includes "all products and services directly associated with AM processes worldwide."[32] This estimate excludes companies internal research and development capital investment to utilize AM in their respective companies.[33]

One company that has benefited from incorporating AM and leading the way into the design and manufacturing of final parts is General Electric. Two successful examples are the CT7 Helicopter Engine and the Advanced Turboprop Engine.

The CT7 Helicopter Engine redesign resulted in 40% of the engine being comprised of AM parts. This reduced the parts from 900 to 16. The engine was 35% lighter and had a 40% cost reduction. The combustion chamber in the engine was designed in six months by one engineer. The new chamber was 30% lighter. The traditional method would required five or six engineers a year.[34]

The Advanced Turboprop engine underwent redesign and had a parts consolidation from 855 to 12, weight savings of 100 pounds, gained 10% more power, and 20% more fuel efficient. The assembly line was streamlined significantly, and the overall maintenance was reduced because of AM.[35]

As additive manufacturing continues to mature companies such as GE are using AM in the production of final parts more each year. In 2017 the percentage of companies using AM in this way was approximately 32.4% which was an increase from 18% the previous year. 3D printing is making a greater impact on manufacturing worldwide and more mainstream each year.

Non-competitive Collaboration

One of the contributors to the continued growth in AM is non-competitive collaboration between academia, private industry and government organizations. These entities come together to advance additive manufacturing practices. In the early stages of these meetings the focus was on improving an AM process but now the focus has expanded to "related processes and technologies, such as equipment for part finishing, 3D scanning, and software tools."[36] There are several of these collaborations that are ongoing one that has relevance to this research project is America Makes.

America Makes is a public-private partnership with over 200 members participating with private investment around $68 million and public investment of $68 million. America Makes serves as a coordinator among the members on "high value, high difficulty, and high impact projects."[37] The project outcome is beneficial to both the project sponsor and the collective AM community by improved techniques and standards.

One example of an America Makes project that has relevance to this research topic is 3D printed grenade launcher. The project is titled RAMBO stands for Rapid Additively Manufactured Ballistics Ordnance. [38]

AM Produced Grenade Launcher[39]

RAMBO took six months and was a teaming arrangement between the US Army Manufacturing Technology (MANTECH), US Army Research, Development and Engineering Command and America Makes. The purpose was to prove a complete weapon system could be additively manufactured to rugged enough to meet military standards.

In addition to the weapon MANTECH wanted to determine if the ammunition could be 3D printed. Army Research Lab and US Army Edgewood Chemical and Biological Center worked on this challenge until a round was successfully developed.

AM Produced Ammunition[40]

US Army Armament Research, Development and Engineering Center conducted the first successful live-fire test of an additively manufactured weapon and ammunition. This demonstrates the ability to 3D print complete systems, not just repair parts, is feasible.

Department of Defense

The Department of Defense is investing in the benefits of additive manufacturing across the services. The Navy is investing in additive manufacturing techniques that enable diagnostic qualities built into parts by combining ceramics and metal together though 3D printing the parts. These parts can help diagnose when a part is nearing breakage. Additive manufacturing of parts onboard a ship without having to take the vessel off line to wait for a part through the service supply system is a readiness gain.[41] The United States Marine Corps uses additive manufacturing to produce repair parts. Recently, the 31st Marine Expeditionary Unit kept an aircraft flying by replacing a rubber bumper on a landing craft door. Traditionally the entire door assembly would be replaced, and the aircraft would not be available for use during that downtime.[42] The Air Force has interest and efforts underway with aircraft such as the F-35. Currently, the Air Force is “3D printing simple plastic replacement parts, such as cable splitters, fasteners, grommets, housing boxes, and wiring harnesses” but maintenance technicians see endless opportunities with different materials, such as aluminum, starting to be used in the additive manufacturing process.[43]

Special Operations Forces Operational Environment

AM could prove advantageous for Special Operations Forces (SOF). SOF operate throughout the world executing broad complex missions often in smaller organizations without a robust presence.

> Special operations forces provide a lethal, unilateral, or collaborative and indigenous counter-network capability against insurgent and terrorist groups, a means to assess and moderate population behavior by addressing local underlying causes, and a means to organize indigenous security and governmental structures. …Special operations forces provide a population-centric, intelligence-enabled capability that works with

> multinational partners and host nations to develop regional stability, enhance global security, and facilitate future operations.[44]

While each service provides common equipment the “demands of special warfare and surgical strike require both standard and nonstandard support in their employment, execution, and sustainment. … [Support organizations] provide capabilities not replicated in the conventional force capabilities that are specifically built to support special operations.[45]

According to Army Doctrine Publication 3-05 (ADP 3-05) “Special Operations,” the special operations forces require core principles of “discreet, precise and scalable operations.”[46] Discreet meaning SOF must maintain a reduced signature; precise meaning specific targeting while limiting unintended damage but with a minimum force on the ground; scalable from small unilateral action to participating in a large conventional operation.[47] These principles reinforce the need for unique equipment and with minimum support to ensure a small signature. Special Operations Forces do not operate with large logistics package. Also, even with detailed pre-mission planning the mission essential equipment required can be unpredictable and dynamic based on changes in the tactical situation.

Ultimately, the SOF operators are a relatively small group of experienced service members charged with a unique mission. Given the size and experience of the force support capabilities can be tailored.

Current SOF Support Capabilities

Mobile Technology & Repair Complex (MTRC) is a SOCOM program that "provides the capabilities and processes to rapidly modify, repair, and fabricate SO-P [Special Operations-Peculiar] equipment and facilities, at the point of need, in order to …adapt to opposition or environment change."[48] The team is comprised of two people to operate and integrate with the operational units. One person is a government engineer overall responsible for the design and initial risk assessment of projects assigned to the team. The second member of the MTRC team is a SOF Technician (SOF Tech), a support contractor. The SOF Tech is usually a former SOF operator and has extensive experience with the SOF culture and organization.[49] The equipment is stored and shipped in two ruggedized containers, the size of a small room, that are about 20 feet each. These types of containers are purpose built for military applications and commonly used for shipping in the Department of Defense.[50] The MTRC team is trained and equipped in engineering, specifically in computer aided drawing, 3D printing, documentation and risk management (critical task in the MTRC mission). Additional capability is in "welding, machining, carpentry, electrical, sewing…limited weapons and C4 [communications] maintenance support".[51] There are 16 teams total. Thirteen are geographically dispersed throughout the world with three remaining in reserve for future operations and training of the teams prior to deployment.[52] As each team works with SOF operators, when a 3D print design is created on (MTRC engineers and SOF operators design and build simple customized niche solutions) the .stl file is uploaded in a SOCOM data repository for future use. [53]

Mobile Technology & Repair Complex teams began in 2009 and added 3D printing capability in 2012.[54] MTRC teams currently use two types of 3D printers. One print technology is Stereolithography (SLA) 3D printing uses a “laser to cure solid isotropic parts from a liquid photopolymer resin”[55] and the other print technology is Fused Deposition Modeling which heats up a plastic filament and when molten is passed through a nozzle in a precise way.[56] These are proving to be effective in limited ways with simple projects but have limitations in strength and durability. To produce an end-item a material made of metal or having the strength of metals would be required for some military products such as a weapon like the RAMBO grenade launcher example.

Earlier in this paper the discussion of a materiel release process must be followed before systems can be employed by Soldiers. This process identifies potential risk with operating the systems. The MTRC engineer has that same responsibility on the designed solutions currently created at the point of need. The capability being built at the point of need currently are simpler with low to negligible risk.

On May 21, 2010, there was an agreement reached by the combatant command and Mobile Technology & Repair Complex through SOCOM that the risk process would be formalized. Mobile Technology & Repair Complex team was directed to follow the Army Composite Risk Matrix (now obsolete). The current process is the updated Army Techniques Publication No. 5-19, *Risk Management* (ATP 5-19).[57]

Army Techniques Publication No. 5-19, *Risk Management* (RM) process is a “systematic way of identifying hazards, assessing them, and managing the associated risks. While safety-related, RM is not contained solely within the protection warfighting function. Commanders, staffs, Army leaders, Soldiers, and Army civilians integrate RM into all planning, preparing, executing, and assessing of operations." [58] The Risk Management process has five steps:

Step 1–Identify the hazards.

Step 2–Assess the hazards.

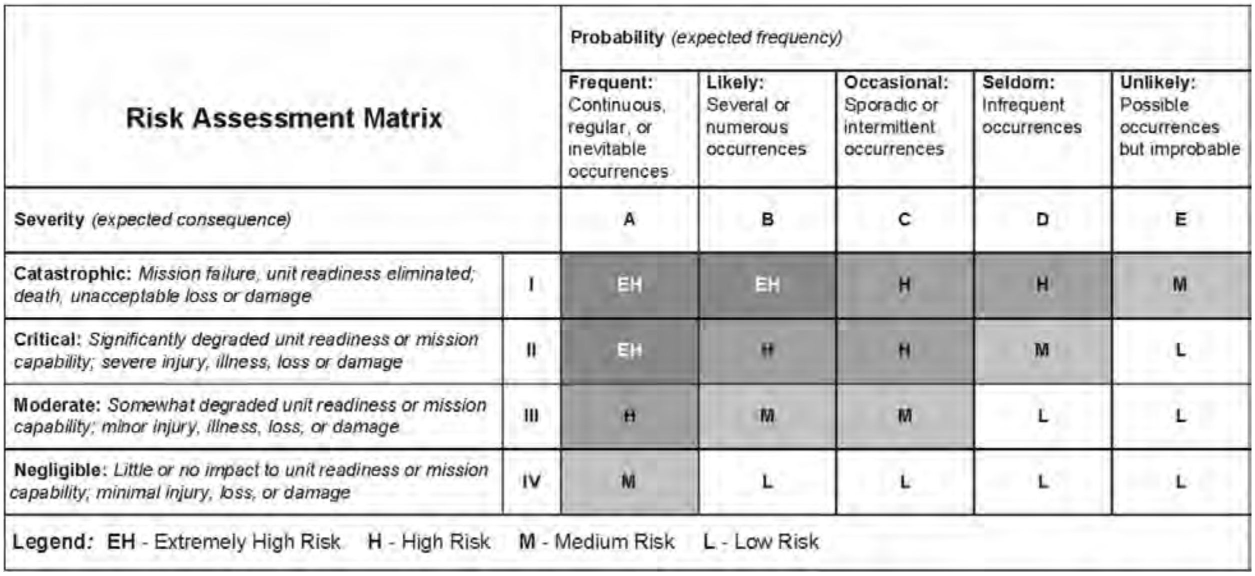
Step 3–Develop controls and make risk decisions.

Step 4–Implement controls.

Step 5–Supervise and evaluate.[59]

The table below is an image of the Risk Assessment Matrix explained in ATP 5-19. The second step, assess the hazards, has two sub-steps of determining the frequency and consequence. The table provides brief definitions of each. The initial risk assessment (extremely high, high, medium or low) is determined from the intersection of the column (probability) and the row (consequence). [60] In keeping with the next step controls are developed and another assessment is conducted to determine the residual risk level. A decision is then requested at the appropriate level. The higher the risk the more senior the approving official. The remainder of the steps are followed through the completion of the event.[61]

Risk Assessment Matrix[62]



Risk Assessment Matrix		**Probability** *(expected frequency)*				
		Frequent: Continuous, regular, or inevitable occurrences	**Likely:** Several or numerous occurrences	**Occasional:** Sporadic or intermittent occurrences	**Seldom:** Infrequent occurrences	**Unlikely:** Possible occurrences but improbable
Severity *(expected consequence)*		A	B	C	D	E
Catastrophic: *Mission failure, unit readiness eliminated; death, unacceptable loss or damage*	I	EH	EH	H	H	M
Critical: *Significantly degraded unit readiness or mission capability; severe injury, illness, loss or damage*	II	EH	H	H	M	L
Moderate: *Somewhat degraded unit readiness or mission capability; minor injury, illness, loss, or damage*	III	H	M	M	L	L
Negligible: *Little or no impact to unit readiness or mission capability; minimal injury, loss, or damage*	IV	M	L	L	L	L

Legend: **EH** - Extremely High Risk **H** - High Risk **M** - Medium Risk **L** - Low Risk

In the case of the MTRC Team the government engineer is responsible for the risk assessment, determining the controls and mitigation measures and then submitted to the operational chain of command for risk decision. This is a rigorous procedure, but as more complex systems are produced at distributed locations there will be a need to following a stricter fielding progression similar to the materiel release process described earlier.

Current Army Support Capabilities

July 28, 2018 the U.S. Army implemented the “Additive Manufacturing Campaign Plan. [63] This plan is the framework for integration of AM capability to “to enhance mission readiness at the tactical point-of-need, improve production, maintenance and sustainment within the organic industrial base (OIB) and support modernization efforts through advanced Science and Technology (S&T) development.”[64] The Secretary of the Army and senior Army leadership guided this plan to synchronize AM across the Army and operationalize it. The Army has conducted limited user evaluations over the past 20-plus years with various AM capabilities trying to best determine tactical uses. The context of this project is consistent with this plan

> AM…has the potential to shorten the design to production cycle timelines, support on-demand manufacturing at the point of need and enable new and innovative designs that are either too costly or impossible to obtain using traditional manufacturing techniques. These developments have been made in separate labs, facilities and fielding of forward deployed units without adequate strategy to focus and guide developmental efforts and with doctrine and policies that need better synchronization and tailoring to address acquisition, fabrication and sustainment issues.[65]

Outlined in the U.S. Army's Additive Manufacturing Plan are "five major Lines of Effort (LOEs) to operationalize AM across the Army enterprise:"[66]

- **LOE 1:** Develop and Implement Coordinated Policy and Doctrine for AM - Develop and implement policies and doctrine that address the development and use of AM across the Army Enterprise and enable tailored Intellectual Property and supporting data rights strategies.
- **LOE 2:** Develop and Implement the Digital Thread for AM - Develop and implement an AM database repository and network system that builds upon existing enterprise solutions and business processes such as the Global Combat Support System-Army (GCSS-A) and the Logistics Modernization Program (LMP).

- **LOE 3:** Develop and Establish Equipment for AM - Develop a plan for identifying, purchasing and implementing the equipment necessary to integrate and synchronize AM into the Army's operational, tactical and organic industrial base.
- **LOE 4:** Develop Comprehensive Training to Support AM - Develop and implement training across the Army Enterprise to inform and enable incorporation of AM into the operational, tactical and organic industrial base.
- **LOE 5:** Execution of the AM Plan to Support Tactical and Operational Environments

  -Enhance Warfighter Capability: Develop AM and related technologies that leverage military, industrial and academic investments in Science and Technology (S&T) to enable enhanced and innovative warfighter capabilities.

  -Increase Tactical and Operational Readiness: Develop AM processes that augment supply chain and maintenance operations and support operation of AM capability in forward deployed forces and ultimately evolve toward Advanced Manufacturing.[67]

In alignment with LOE 5 from there are two expeditionary AM efforts underway: Rapid Fabrication via Additive manufacturing on the Battlefield (R-FAB) and Rapid Equipping Force Experimental Lab (REF Ex Lab).

Rapid Fabrication via Additive manufacturing on the Battlefield is an AM capability currently deployed to South Korea for one year and is "enabling readiness gains through printing battle damage assessment repair (BDAR) and Emergency Repair parts in the field."[68] R-FAB was first used during an Army assessment in Texas in 2016. R-FAB started with four 3D printers and a basic scanner. There were two subsequent assessments in international locations each time with increased additive manufacturing capabilities as well as "reach back" capability via a satellite connection.[69] This satellite connection allows technical subject matter experts to assist Soldiers field expedient ideas and concepts. R-FAB capability is 3D printing of parts from "soft rubber to high strength KEVLAR reinforced Nylon"; and a 3D scanner to support reverse engineering of parts.[70] In support of LOE 2 Digital Repository for AM Parts for Tactical & Operational Readiness (RAPTOR) was established. During the previously mentioned R-FAB assessments RAPTOR database was populated with 3D plans and details. It is now a functioning initial operating capability database.[71]

REF Ex Lab began in 2012 and focuses on rapid prototyping, additive manufacturing and innovative designs for deployed units in overseas locations. The concept is to connect "scientists and engineers with Soldiers at forward-deployed locations."[72] Each lab is self-sufficient to allow the collaboration between soldiers and technicians to work alongside one another to solve individual unit challenges.[73] This is similar to MTRC but on a smaller scale (one deployed team at a forward operating base not dispersed among tactical units) and focus on unique solutions to each soldier problem.

Analysis

The capability gap that exists is the ability to produce an end-item at distributed production locations. The RAMBO grenade launcher is a demonstration that a military end-item can be produced with AM. Currently, the ability to manufacture military finished products at the point of need has limitations outlined throughout this paper. The next steps will be to move specifically towards that goal.

There has been constant growth in 3D printing for almost three decades with a healthy investment by private industry, academia and the US government. The industry has enjoyed collaborative benefits among these segments. AM has not caused a manufacturing revolution as some suggest but it has slowly and dramatically had an impact and will continue to do so in the coming years.

There are tremendous benefits from additive manufacturing, but the impact is just starting to be seen in end-item production. The 3D printed grenade launcher has two benefits. First, the non-competitive collaboration proves to be a beneficial investment to solve hard challenges. Second, producing military purposed end-items was demonstrated and shown to be is feasible.

There are still challenges to the mainstream use of AM. The concern over quality assurances is valid. While the implementation an intellectual property strategy by the US Army is a positive step the effects are yet to be seen. The cost of the machines is still constraining but the industry will continue to move more into the mainstream and will drive the technology to become more affordable. Even with the challenges discussed the Department of Defense is committed and investing in this method of manufacturing. Collaborative partnerships, improving the technical reach back capabilities and materiel developers pressing for the defense industry to design for AM are the areas for future focus. Distributed production through additive manufacturing is possible in the near term.

Recommendations

Here are five recommendations to move toward the goal of producing finished products in austere locations. The first recommendation is to negotiate for intellectual property rights early in the developmental process, so the defense contractor understands the government need and intention for future production through AM. There was a recent policy change in the U.S. Army that will enable this recommendation.

The significance of Army Directive 2018-26 and associated implementation guidance regarding intellectual property encourages material developers to consider IP early in the process with an intent to use it in the support and likely the manufacture of future developed parts and systems. In the past, a defense contractor would design a system and produce it to the required quantities for the Department of Defense. In the future, with the advancement of additive manufacturing, it is feasible that a defense company could simply design up to prototype and the government could test and produce or manufacture the product at distributed locations. An example would be a company designs the system and delivers a prototype. The government project manager would then take the system through testing to determine if the system is safe to use and how effective it is against the stated requirement and if it’s affordable to sustain. Then through government owned additive manufacturing the product could be produced to the required quantities at distributed locations.

Another step forward is to partner with the other initiatives within the U.S. Army. Specifically, within the Army Additive Manufacturing Campaign Plan lines of effort 2 and 5. There are similarities and possibly redundancies in additive manufacturing efforts across DoD. As mentioned earlier, just in the Army, there are similarities between MTRC, R-FAB/RAPTOR and REF Ex Lab. Entering into a partnership to improve communication and foster shared learning will improve the opportunity for capability production at the point on need.

In keeping with the idea of partnership another example is SOCOM aligning with the Army for a better understanding of RAPTOR, design data repository, SOF could possibly be an additional source of data as well as a customer of approved designs across DoD.

The fourth idea is to seek collaborative opportunities with America Makes to leverage the AM community of interest. Present a project to that consortium with a goal of determining quality standards that can apply to a remote production facility. Identify what the optimal process and material blend would best suit repeatable quality production of products. Look to prove that a system can be designed for AM, digital file shared electronically to different locations with ranging environmental conditions and demonstrate the production capability. This could benefit SOF, DoD and the AM community.

Improving communication reach back for MTRC teams is another area to improve. Many of the SOF teams are in remote locations and have limited communication capability. Potentially, satellite reach back like R-FAB and REF Ex Lab for higher level technical support as projects become more complex. Also, this could enable sharing of digital files from larger data repositories as well as promote increased data sharing across the SOF community.

Lastly, adding advanced composite materials reinforced with continuous fiber filament to the inventory of AM capabilities. These advanced materials are advertised to be stronger than aluminum and 40% lighter and suitable for end-item production.[74] This material and needed machines are affordable and show promise for the next generation in deployed 3D printing capability.

Conclusion

This research project suggested a needed solution for Special Operations Forces. When considering capability gaps and potential solutions the Joint Capabilities Integration and Development System considers these areas: Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities and Policy.[75] Since materiel is generally more expensive it is considered independent of the other sections. In terms of this discussion, doctrine and organization are not going to change to alleviate or enable the benefit of having capability production with the tactical units.

Training is always a factor. Training the engineering teams to assess risk and manage the development process is an ongoing effort and critical to the success of 3D printing for capability development. From an operational standpoint the teams should have constant input in the design process for minor modifications but more importantly train with the developed solution to ensure the capabilities and limitations are understood.

Leadership understanding the limitations of AM now and moving forward is important. Leadership making informed risk decisions and not pursuing AM because it's a novel approach but rather the right approach for a given situation.

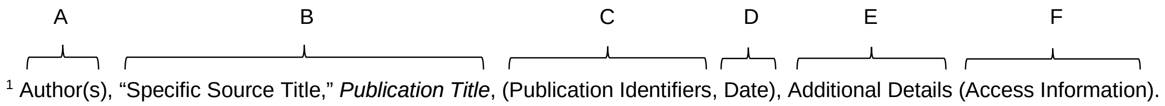
Personnel on the operational teams as well as the engineering teams to understand the capabilities and limitations with each generation of additive manufacturing. It's essential to understand a capability and apply the diligence in employing a capability within the designed limits. Leadership and personnel need to know the challenges of inserting an AM part or system for an original equipment manufacturer (OEM) part until the certification standards catchup to the traditional methods. Acknowledging the process to account for those systems and understanding the limits of the AM procedures will mitigate and manage the potential risk with AM parts.

Facilities apply to anywhere AM is used to produce parts. Whether that is at an OEM facility in a controlled environment like the GE examples or in an austere location with wide ranging environmental fluctuations. Each circumstance poses a unique set of limitations.

The IP policy change is a big step in removing a known obstacle to delivering on demand capability distributed away from the OEM. It is reasonable to expect an increase in momentum towards designing for end-item production with the implementation of the new IP policy.

The 3D printing technology exists to produce equipment in remote locations to support SOF through additive manufacturing. Understanding the SOF core principles and the limited logistical support there is an opportunity to provide flexible materiel solutions in tactical areas. The DoD is recognizing the benefits of AM. An AM Campaign Plan and policy updates along with a wide variety of initiatives across all military services reinforce this point. The next steps are to implement the policy changes, follow the plans and collaborate with a goal of producing a complete mission essential system via additive manufacturing at the tactical point of need.

Endnotes



[1] Additive Manufacturing website, http://additivemanufacturing.com/basics/ (accessed November 1, 2018).

[2] Ibid.

[3] Gibson, I., Rosen, D. W., & Stucker, B., *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing*. New York, NY: Springer (2010), 4-6

[4] General Electric Additive website, https://www.ge.com/additive/additive-manufacturing/information/additive-manufacturing-processes (accessed November 1, 2018).

[5] American Society for Testing and Materials website, https://www.astm.org/ (accessed November 1, 2018).

[6] Additive Manufacturing website, http://additivemanufacturing.com/basics/ (accessed November 1, 2018).

[7] United States Government Accountability Office, "3D Printing Opportunities, Challenges, and Policy Implications of Additive Manufacturing", (2015)

[8] Doty, Carlton A. and Gunderson, Annika "New Tech: 3D Printing, Q3 2018 Forrester's Landscape Overview Of 38 3D Printer Providers", Forrester.com (2018), 2

[9] Ibid.

[10] Ibid.

[11] Wohlers Associates, “Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report”, Fort Collins, CO, (2018), 177-178

[12] Doty, Carlton A. and Gunderson, Annika “New Tech: 3D Printing, Q3 2018 Forrester’s Landscape Overview Of 38 3D Printer Providers”, Forrester.com (2018), 2

[13] Ibid.

[14] Ibid., 3

[15] Mraz, Stephen, “3D Printing Takes Parts Count from 100 to 1 for Antenna”, https://www.machinedesign.com/3d-printing/3d-printing-takes-parts-count-100-1-antenna (accessed March 4, 2019)

[16] Doty, Carlton A. and Gunderson, Annika “New Tech: 3D Printing, Q3 2018 Forrester’s Landscape Overview Of 38 3D Printer Providers”, 3

[17] Ibid.

[18] Smartechanalysis.com, “White Paper: Additive Manufacturing In Aerospace: Strategic Implications”, https://www.smartechanalysis.com/blog/white-paper-am-aerospace/ (accessed March 5, 2019)

[19] Doty, Carlton A. and Gunderson, Annika “New Tech: 3D Printing, Q3 2018 Forrester’s Landscape Overview Of 38 3D Printer Providers”, 3

[20] U.S. Department of the Army, “Acquisition Policy,” Army Regulation 70-1, (2018), 17

[21] Kimberley Kinsley, Gail Brooks, and Tim Owens, “International Legal and Ethical Challenges Related to the Use and Development of 3D Technology in the U.S. And China,” Journal of Knowledge Management, Economics and Information Technology Online IV, no. 3 (June 2014): 1-16, http://www.scientificpapers.org/wp-content/files/1462_KinsleyBrooksOwensInternational_Legal_and_Ethical_Challenges_Related_to_the_Use_and_Development_of_3D_ Technology_in.pdf (accessed September 27, 2018).

[22] U.S. Department of Defense, “Army Directive 2018-26 (Enabling Modernization Through the Management of Intellectual Property)”, (2018), 1

[23] U.S. Department of the Army, “Implementation Guidance for Army Directive 2018-26”, (2019), 1

[24] U.S. Department of the Army, “Type Classification, Materiel Release, Fielding, and Transfer,” Army Regulation 700-142, (2015), 19

[25] Motes, Doyle III, “The State of Cybersecurity in Additive Manufacturing (AM)” Defense Systems Information Analysis Center, https://dsiac.org/resources/news/state-cybersecurity-additive-manufacturing-am (accessed March 1, 2019)

[26] Ibid.

[27] Ibid.

[28] Ibid.

29 Wohlers Report 2018, 185

[30] Technical Lead Engineer for MTRC (February 19, 2019), telephone conversation with author.

[31] Wohlers Report 2018, 188

[32] Ibid., 142

[33] Ibid., 143

[34] Ibid., 184

[35] Ibid., 183

[36] Wohlers Report 2018, 266

[37] Ibid.,267

[38] Saunders, Sarah, “US Army Successfully Tests 3D Printed Grenade Launcher with 3D Printed Grenades” https://3dprint.com/167567/3d-printed-grenade-launcher/ (accessed March 21, 2019)

[39] Ibid.

[40] Ibid.

[41] Saunders, Sarah, “UConn Engineers Develop Ceramic and Metal 3D Printing Solution for US Navy to Manufacture Replacement Parts At Sea” https://3dprint.com/198330/3d-print-replacement-parts-navy/ (accessed March 3, 2019)

[42] Mendoza, Hannah Rose, “Marines Embrace 3D Printing for Production of Replacement Parts”, https://3dprint.com/210788/marines-3dp-replacement-parts/ (accessed March 3, 2019)

[43] Saunders, Sarah, “US Air Force Base in Utah Creating 3D Printed Replacement Parts for F-35 Fighter Jets”, https://3dprint.com/220675/3d-print-replacement-parts-f-35/ (accessed March 3, 2019)

[44] U.S. Department of the Army, “Special Operations,” Army Doctrine Publication 3-05, (2018), 6

[45] Ibid., 7

[46] Ibid., 8

[47] Ibid., 9

[48] U.S. Special Operations Command, “Mobile Technology & Repair Complex (MTRC) Capabilities and Overview”, (2018), 3

[49] Ibid., 4

[50] Ibid., 3

[51] Ibid., 4

[52] Ibid., 6

[53] Technical Lead Engineer for MTRC (February 19, 2019), telephone conversation with author.

[54] Ibid.

[55] Formlabs website, https://formlabs.com/3d-printers/form-2/ (accessed February 28, 2019)

[56] Gibson, I., Rosen, D. W., & Stucker, B., *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing*. 30

[57] U.S. Department of the Army, “Mobile Technology Complex (MTC) Standard Operating Procedure (SOP)”, (2010), 8

[58] U.S. Department of the Army, “Techniques Publication No. 5-19, Risk Management process” (2014), 1-1

[59] Ibid., 1-3

[60] Ibid., 1-9

[61] Ibid., 1-13, 1-14, 1-15

[62] Ibid., 1-7

[63] U.S. Department of the Army, “Army Additive Manufacturing Campaign Plan”, (2018), 5

[64] Ibid., 4

[65] Ibid., 4

[66] Ibid., 4-5

[67] Ibid., 4-5

[68] U.S. Army Combat Capabilities Development Command – Armaments Center, “Rapid Fabrication via Additive manufacturing on the Battlefield (R-FAB) and Digital Repository for AM Parts for Tactical & Operational Readiness (RAPTOR)”, (2019)

[69] Ibid., 4

[70] Ibid., 5

[71] Ibid., 5

[72] U.S. Army Rapid Equipping Force, http://www.ref.army.mil/Projects (accessed March 5, 2019)

[73] Ibid.

[74] Markeforged, https://markforged.com/materials/composites/ (accessed March 29, 2019)

[75] The Joint Staff, “JCIDS Manual”, (August 31, 2018), BGF1-7