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AS THE MARINE CORPS CONTINUES TO MOVE TOWARD ITS FUTURE OPERATING VISION, HIGHLIGHTED BY DISTRIBUTED FORCES, THE STRAIN ON ITS LOGISTICS SYSTEM INTENSIFIES. THE MARINE CORPS MUST CONTINUE TO EXPLORE SOLUTIONS THAT WILL INCREASE THE EFFICIENCY AND RESPONSIVENESS OF ITS SUPPLY CHAIN. ONE SOLUTION TO THIS COMPLEX PROBLEM IS THE EMPLOYMENT OF ADDITIVE MANUFACTURING, COMMONLY REFERRED TO AS 3D PRINTING, TO INFUSE FLEXIBILITY, RESPONSIVENESS AND COST SAVINGS TO ITS SUPPLY CHAIN NETWORK.

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MASTER OF MILITARY STUDIES

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BUILDING SOMETHING FROM NOTHING: WHAT IS ADDITIVE MANUFACTURING AND HOW CAN IT MAXIMIZE A COMPETITIVE ADVANTAGE FOR MARINE CORPS DISTRIBUTED OPERATIONS?

SUBMITTED IN PARTIAL FULFILLMENT
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Executive Summary

Title: Building Something from Nothing: What is Additive Manufacturing and How Can it Maximize a Competitive Advantage for Marine Corps Distributed Operations?

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Thesis: As the Marine Corps continues to move toward its future operating vision, highlighted by distributed forces, the strain on its logistics system intensifies. The Marine Corps must continue to explore solutions that will serve to increase the efficiency and responsiveness of its supply chain within an increasingly complex operational environment that demands distributed operations. One solution to this complex problem is the employment of additive manufacturing, commonly referred to as 3D printing, to infuse flexibility, responsiveness and cost savings to its supply chain network.

Discussion: This research paper will thoroughly define additive manufacturing and explore the Marine Corps's future use of this technology – with a focus on obsolesce management and custom production – and how these new manufacturing methods will help to support an expeditionary force. In addition, several practical and ethical concerns that have arisen since the Department of Defense's (DOD) adoption of the technology will be addressed. In the end, this paper is not designed to provide a roadmap for the Marine Corps to follow. It is, however, intended to expand upon the additive manufacturing conversation, highlight challenges in the years ahead, and provide recommendations for areas where this technology can support a distributed warfighting organization.

Conclusion: The Marine Corps's future fight is anything but certain and requires flexible and adaptable logistics systems that can support distributed operations. Just around the corner – at the intersection of the future and the realm of the possible – lies a technology that will profoundly change Marine Corps logistics and supply chain management. Although the technology is not developed at a level that would allow the complete replacement of legacy logistics networks and systems, its immediate effect as a bridge between hybrid logistics and the future is essential. However, given the long lead times for transitioning new technologies to programs of record, it is critical that steps be taken now to focus efforts.

DISCLAIMER

Preface

I chose additive manufacturing as my research topic due to my interest in technology as an integral part of an organization's process of adapting to the changing conditions of warfare in the 21st century. My research was based on magazine articles, discussions with the Next Generation Logistics Innovation Cell (DC I&L), military publications, and academic journals.

I would like to acknowledge the faculty at the Marine Corps University. The military advisors, professors, and panel discussions provided me a wealth of knowledge to grow personally and professionally. A special thank you to Lieutenant Colonel Good, Lieutenant Colonel Byrne, Dr. Gordon, and Dr. Joyner for your patience and guidance throughout this academic year.

I am forever thankful to my wife and children for their unending support. They have stood by me throughout my career and provided encouragement during the most challenging times. I would not be where I am today without their love and support.

Introduction

Logistics is often looked upon by ground forces as a dull or unglamorous aspect of warfare, but the art and science involved in sustaining armies has proven – since antiquity – a fundamental aspect of successful military operations. Admiral Hyman Rickover, the father of the nuclear Navy, is quoted expressing his opinion over the importance of logistics saying, "bitter experience in war has taught the maxim that the art of war is the art of the logistically feasible."[1] It is this connection – how the feasibility of logistics can more effectively enable warfare – that continues to push military and civilian leaders to strive for greater innovation.

Since the days of Frederick the Great and Napoleon Bonaparte the battlefield has grown increasingly more complex and the required logistical support more extensive and cumbersome. Even with recent advances in technology, the increase in strategic, operational, and tactical dispersion of the last century continues to stress the capabilities of logistics planners. In fact, the United States Military has gleaned quite a few lessons in dispersed sustainment during the wars in Iraq and Afghanistan. In 2014 the RAND Corporation conducted research on the Army logistics framework used during Operation Iraqi Freedom and published its work in a report called "Sustainment of Army Forces in Operation Iraqi Freedom: Battlefield Logistics and Effect on Operations." The study discussed several deficiencies related to the logistics system but more relevant to the Marine Corps, it highlighted a comparatively new method of sustainment described as "distribution based logistics." Distribution based logistics focuses on maintaining a limited inventory that is sufficient to cover small disruptions and consumption between replenishment as opposed to establishing large forward stockpiles, which was the previous best practice of sustainment.[2] This distribution method of sustainment, which was replicated by the Marine Corps, is an essential framework to support a 21st century military organization that will no longer be afforded the option of building "iron mountains."

Per the 2016 Marine Corps Operating Concept, the future operating environment continues to evolve into a multi-dimensional battlefield that is further complicated by the increasingly complex terrain, proliferation of technology, risk imposed by electronic signatures, the use of information as a weapon, and an increasingly contested maritime domain.[3] This complicated environment necessitates a transition from our legacy system to a more agile and distributed Marine Corps that leverages technology to improve performance. So, as the Marine Corps continues to expand small-unit distributed operations in response to the complex future operating environment, the strain on its logistics system intensifies. In response, the Marine Corps must look toward new technologies that enhance our current logistics enterprise through a flattened military supply chain, which pushes the production capability down to the battalion or company level. One possible solution is the incorporation of additive manufacturing (AM), commonly referred to as 3D printing, into our manufacturing process in order to offer flexibility and responsiveness to a support framework that demands increased dispersion and mobility.

This research paper will explore the Marine Corps's future use of AM – with a focus on obsolesce management and custom production – and how this new manufacturing method will help to support an expeditionary and distributed force. In addition, several practical and ethical concerns that have arisen since the Department of Defense's (DOD) adoption of the technology will be addressed. In the end, this paper is not designed to provide a roadmap for the Marine Corps to follow. It is, however, intended to expand upon the AM conversation and provide recommendations for areas where this technology can support a distributed warfighting organization.

Background

To form a baseline from which a deeper discussion about the Marine Corps's adoption of this technology can occur, it is important to provide context through a brief history of AM as well as an overview of the current technology, process, and materials available for use.

AM is a relatively new term for a technology that was born in the late 1980s. When AM was first introduced, it was referred to by many names including rapid prototyping, 3D Printing, and rapid manufacturing. To simplify these varying terms, a Technical Committee within the American Society of Testing and Materials (ASTM) International developed the term AM. AM refers to the production of objects by adding material in layers that are consistent with the input from a three-dimensional computer-aided design (CAD) file.[4] There are numerous types of AM technologies and a variety of materials used in the creation of the different layers, which is discussed in detail in the next section.

Interestingly, AM has been thriving underneath the surface of commercial industry for more than thirty years. Charles W. Hull, considered the founder of AM, invented and patented the first process and machine in 1986 called Stereolithography. Later, Charles Hull founded 3D Systems, which he built around this new technology and produced the first 3D printer in 1988.[5] After the release of Hull's printer, numerous other companies such as Statasys designed and released their own AM processes and printers. Over the years, 3D Printers have gone through a tremendous revolution, growing in their capabilities and available materials. This is largely attributed to the expiration of key patents that paved the way for today's thriving open source 3D printing movement.[6] In addition, the proliferation and adoption of this technology continues to accelerate as industry revenues are projected to increase at an 18.8% annual rate over the next five years. By 2021, the AM industry will surpass $4 billion.[7] These figures highlight a thriving industry, with massive growth potential, that will continue to innovate and that the Marine Corps can leverage to enhance the logistics enterprise.

Additive Manufacturing Process

So, with a common definition and background of this technology as a foundation, the next logical question is how does a 3D printer work? In short, AM refers to a series of processes that varies widely from method to method. However, the various processes can be organized into eight steps: conceptualization and Computer-Aided Design (CAD), conversion to standard tessellation language (STL)/AM file format (AMF), transfer and manipulation of STL file to AM machine, machine setup, build product, part removal and cleanup, post-processing of part, and application of printed part.[8]

To begin the technician must start with a virtual design of the object that he wants to create. The design is generated within a computer aided design file using 3D modeling software, or it can be created using a 3D scan of an existing object. The software that is utilized to create the model can also provide insight into the structural integrity of the product from various scientific data available on the materials used in construction. In addition, the design of the product can be altered by manually changing its dimensions, angles, thickness, etc., until it meets the exact requirements of the desired product.[9] There are several types of CAD: wireframe, surfaced wireframe, and solids. However, to create a viable model for 3D printers, only surfaced wireframe and solid models can be used. Wireframe models only detail the surface of the design and not the interior, which makes it unsuitable for 3D printing.[10]

The second step in the process requires the conversion of the computer aided design into a format that is recognizable by the 3D printer. Legacy 3D printers recognize and use a file format called STL. STL, developed in the 1990s, converts the three-dimensional model into a series of very small triangular facets to approximate the various surfaces of the model.[11] Most CAD software can automatically convert the data into the STL format. Unfortunately, errors in the process of converting to an STL format are possible and often difficult to detect. In accordance with the innovative spirit permeating the AM community, two Cornell University Professors developed a newer file format called AMF. This group of professors designed AMF to overcome some of the challenges with STL conversion. The upgraded format was subsequently adopted by the ASTM and International Organization for Standardization (ISO) as a standard for converting CAD files to a format readable by a 3D printer.[12] In contrast to STL, AMF converts the CAD file into curved triangles and allows the use of multiple materials and colors as well as the manipulation of more complex structures. Although AMF appears to be superior in design and function it has not gained acceptance within the industry due to a strange paradox consisting of industry cost considerations, CAD software interoperability, and printer software.[13]

The third step requires the transfer of the STL/AMF file to the actual printing machine. Once transferred, most printers have the capability to view and manipulate the part's orientation, placement, and size. The orientation of the product will affect the number of support structures needed during production,[14] and since most printers build from the bottom up, parts that are oriented vertically will take longer to build than if they are oriented horizontally.[15] In short, a poorly oriented item could result in increased clean-up during later steps as well as an increase in overall production time.

In addition to orientation, the placement of the part within the machine can also add to or subtract from the build time or quality of the final product. Part placement is a significant factor in some processes, which include stereolithography and laser sintering. If a part is placed correctly, it will allow for the construction of multiple parts at the same time. Machines can build multiple copies of the same part or several different parts if they are all able to fit within the build space of the printer. Some printers can even build parts one on top of the other during the construction step.[16] In addition to the orientation and part placement, the size of the part can be changed at this point. It can either be enlarged or shrunk depending on the desired outcome. This feature is useful when taking into consideration any post-production requirements that could alter the overall dimensions of the part (i.e. adding a protective coating). This step will be incredibly useful during obsolescence management, which will be addressed during the next section.

The fourth step involves the set-up and fine tuning of the 3D Printer to safeguard product quality standards. One of the most significant factors that will require adjustment to the machine's settings stems from the type of raw material used. For printers that are only able to accept one type of material this is not a concern; however, most printers can accept multiple types of raw material. If the printer does accept multiple types of input material, the machine's settings must be adjusted for the type of build material used. Thankfully, most modern printers have easily navigable settings that are pre-configured for the various materials used. Another important setting is the ability to adjust resolution of the printer to coincide with part quality and time available for production. If time is the most important commodity in the production cycle, the resolution can be decreased. On the other hand, if quality is the most important ingredient then the resolution should be increased to pass quality control standards.[17]

The fifth step in the process is the actual manufacture of the item. The method of construction varies with each machine and material, but the basic premise is that the part is built layer by layer through adding and combining raw materials to create a 3D product. The printer will continue to function and provide a finished product until manually halted or it runs out of raw material, similar in nature to a 2D printer.[18] The processes vary greatly and are examined thoroughly in the next section of this paper.

The sixth step occurs after the part is completely built and removed from the machine. This step is most typically accomplished by manual labor rather than automated process. The machine usually has safety precautions integrated to ensure the part's temperature is safe and that there are no moving parts.[19] The final product is either connected to a build platform or laying in excess build material. At this stage, it resembles the final product, but may require additional preparation to meet the intended specifications. The most noteworthy aspect of this step is the removal of support structures that were mentioned in step three. The type and number of support structures will vary depending on the process used and the part constructed.[20] Post-production cleaning methods vary but include post-curing, chemical stripping, bed blasting, or water jetting.[21]

Finally steps seven and eight focus on the final preparation and application of the product. During step seven, the surface of the part must be prepared using methods like sanding or polishing. In some cases, the part is coated with another material such as metal. If the part is designed to be a rough prototype, the time and effort required during this step is minimal, whereas, if the part is designed for installation in a larger component or is part of an aviation platform, this step consumes a considerable amount of time and effort.[22] Similar to the previous step, significant manual labor is required for final application. During this step, the part is either presented for use (in the case of a model or prototype) or installed within a larger system. In some applications, the part is inspected and analyzed prior to installation.[23]

Process Types and Material

AM refers to a wide range of technologies that, are built upon the same foundation, but vary greatly in their specific processes and capabilities. Unfortunately, there are no industry standards for categorizing the various processes. However, for the general purpose of organization, the types of processes are typically separated into three categories, which are based on the type of raw material used. The categories are (1) liquid-based systems, (2) powder-based systems, and (3) solid-based systems.

Liquid-based systems account for some of the earliest AM products produced and use photosensitive liquid polymers that are cured to create a solid material.[24] Stereolithography, jetting systems, and direct light processing technologies all belong to this family of processes. Unfortunately, the liquid properties of these systems tend to be adversely affected by environmental conditions such as sunlight and humidity.[25]

The first of these systems, stereolithography, uses an ultraviolet (UV) laser that is maneuvered according to the CAD file to cure portions of photocurable resin on a platform.[26] The laser, which is usually solid-state powered, is directed by scanning mirrors to specific locations for curing. The first layer that is created is the support base for the product to be built and forms a mechanical bond with the build platform.[27] The platform with the cured resin is dropped a depth equal to one layer and liquid resin is deposited on top. A blade is swept over the surface to ensure that the resin is level.[28] The UV laser cures more of the liquid resin, this time bonding it to the first layer. This process is repeated over and over, layer-by-layer to create a 3D product.[29] During the post-production steps of this process the supports are disconnected and the part is placed in an oven to cure any resin that was not cured by the UV laser. In addition, parts produced using stereolithography may also undergo a chemical stripping process to remove uncured resin.[30] As the oldest of the technologies, stereolithography is considered to have a sound balance between speed, quality, range of materials, and throughput.[31]

Jetting systems use multiple printing heads, which are akin to the typical household ink jet printer. They create parts using photocurable resins like stereolithography, but the resin is deposited by an array of printing heads. After the resin is deposited, a UV lamp passes over to cure it. Once the UV lamp cures the resin, the process is repeated, creating multiple layers. Separate printing heads deposit a second material simultaneously to create the support structures. Direct Light Processing Technologies are similar to jetting systems, but use digital mirror devices (DMDs) to selectively cure the resin instead of the indiscriminate heating lamp.[32] As a result, this process is quicker than either of the jetting systems, but offers lower resolution products.

Powder-based systems use raw materials that are in powder form. The powdered materials include polymers, metals, and ceramics.[33] The first of these systems is Selective Laser Sintering, which is similar to stereolightography with the exception that the raw materials are powder and sintered rather than cured by a laser. The laser scans the entire powder bed, sintering the portions together to form the first layer of the product. A second layer of powder is added directly on top of the first layer and the laser again scans the surface and sinters selected portions of the powder, bonding it to the first layer to create the second layer. The Selective Laser Sintering process uses the un-melted powder to serve the same purpose as the printed support structures in the liquid-based processes. Because the supporting material is not physically attached to the product, the post-production steps are typically less labor intensive.[34] Instead of manually removing the support structures, the excess powder is simply brushed away from the product and removed from any internal compartment.[35]

Selective Laser Sintering for ceramics and metals uses the same basic principles that were described above. To create ceramic products, sand particles are coated with a polymer binder that replaces the polymer powder of the previous process. Likewise, metal powders are coated in a polymer binder to produce metal 3D products. The metal products must undergo an additional finishing process and are placed in a furnace to burn the polymer binder away. The remaining material is sintered and the porous parts are filled with a secondary metal such as bronze.[36] This process is best suited for tooling purposes[37], but is also used to print parts for the aerospace industry.[38]

Direct Metal Laser Sintering is very similar to the selective laser sintering process that is described above except that it does not need the polymer binder coating. The process, however, is limited to a specific metal powder that consists of several components with different melting points. The main advantage of direct metal laser sintering is that it does not require the extra finishing steps that are required for the previous process.[39]

Powder-binder printing was developed at the Massachusetts Institute of Technology (MIT) and was later licensed by commercial entities.[40] Powder-binder printing uses jetting technology to spread a binder on top of a thin layer of powder. The binder solidifies, creating the first layer of the part. The process is repeated for each subsequent layer until the part is completed. Like selective laser sintering, it uses the excess powder to act as the support structure.[41] In addition to the requirement to remove excess powder, this process produces parts that have a subpar surface quality that requires machining to ensure the quality is improved enough to be used for tooling purposes.[42]

The next powder-based system is fused metal deposition. In this process, metal powders are blown onto a melt pool to sinter. A laser is still the primary tool for sintering except in this process it is used to create the melt pool.[43] Compared to other processes, fused metal deposition systems are relatively slow and the products produced have poor surface quality. Its biggest advantage, however, is its ability to build products out of materials with high melting points such as titanium. Another significant advantage is the unique ability to add material to existing products. This capability would allow the user to repair a broken part by adding metal to the area that was broken.[44]

Electron Beam Melting (EBM) is similar to selective laser sintering except that it uses an electron beam instead of a laser to sinter the material. This scanning process is significantly quicker than those processes requiring the use of lasers. Another advantage of this process is that the electron beam produces significantly more power than a laser and is therefore able to melt a wider range of metals within a shorter timeframe. Although these advantages are appealing, this process carries two disadvantages. EBM is limited to conductive materials and it requires a substantial amount of finishing to improve its surface quality to a satisfactory level.[45]

Selective laser melting is almost identical to laser sintering except that it completely melts the material vice merely sintering or fusing the materials together. This process is used to make products out of pure steel and, due to the nature of the melting process, produces parts that are very strong when compared to other processes. In addition, the process allows the creation of relatively small components.[46]

The final power-based system is selective masking sintering, which unlike the previous processes, does not use a laser or a beam to sinter the material together. In place of these typical methods this process relies on a mask of infrared radiation reflecting material on a glass sheet. The mask is then placed on top of the powder bed and an infrared heater placed over top of the mask. Heat then passes through the selected spots in the mask and sinters the powder below. As with the other processes, it is repeated numerous times to create multiple layers. The mask allows the entire layer to be sintered simultaneously versus particle by particle like the laser and electron beam processes. This drastically decreases the build time and makes this process suitable for higher production cycles.[47]

As the name implies, solid based systems use solid raw materials as opposed to the liquid and powders of the previous processes. Although there are only two processes currently used they are relevant to providing a greater understanding and appreciation of AM technology.

The fused deposition modeling (FDM) process was created and produced by Stratasys. The FDM process uses mostly thermoplastic polymers including polycarbonate, polyphenyl-sulfone, and acrylonitrate butadiene styrene (ABS). FDM machines have nozzles that move on the X and Y-axes to deposit polymers in a two-dimensional layer.[48] Prior to reaching the nozzles, the polymer is fed into the system as a solid and is liquefied in a heating chamber. The liquefied polymer is pushed through the nozzle and extruded on the build platform.[49] This process is continually repeated to build the product from the bottom up. Unlike most other processes, the build platform is not lowered to a production level. Instead the nozzles move to the same height as one layer and continue to extrude the semi-molten material layer-by-layer.[50] There is a separate nozzle that follows the first nozzle to deposit a different material to build the support structure.[51]

Given the numerous processes and materials available to the AM industry, the Marine Corps has a range of options for the diffusion of this technology. This plethora of processes offers the Marine Corps numerous advantages during testing and acquisition of this technology. In an email communication with Captain Christopher Wood on February 22, 2017, he stated that FDM is currently the process of choice for unit-level printing in the Marine Corps.[52] This is due to the relatively inexpensive price of the machines, user friendly controls, and the continuous improvements that are made by the industry. The types of FDM printers can be bundled into four categories: entry level, mid-level, expert, and pro. The mid-level machines, priced from $2,000-$5,000, seem to perform to the appropriate standard of reliability that is desirable at the battalion or company level.[53] The mobility of a midlevel desktop printer like LulzBot's TAZ6, will enable a supply chain that gives production capability directly to the warfighter. Instead of registering a repair part requirement with the Battalion S-4 or requesting a traditional fabrication effort to produce an innovative solution, a company commander can simply manufacture those items on site greatly reducing lead time as well as potential danger and strain to a distribution based logistics model.

Raw Materials

The range of materials varies greatly between the four types of processes. Of the four selected processes, stereolithography and powder-binder printing offer the fewest available materials. The materials used for stereolithography are limited to photopolymer materials since they must be cured with UV light. There are approximately twenty-four available raw materials with varying levels of strength, flexibility, and durability. Additionally, the materials are available through multiple suppliers unlike some of the materials for the other processes.[54] The powder-binder printer can only utilize three powdered materials. Two of the materials are cellulose and the third material is plaster.[55] Although these materials are limited, this process allows the finished part to be infused with other materials to change its physical properties and increasing its application. Selective laser sintering and FDM offer the greatest range of raw materials, with selective laser sintering offering the most. Selective laser sintering's range of materials includes extremely strong plastics, stainless steel/bronze alloys, and flexible rubber-like materials. The flexibility provided by the various materials is stifled by the sourcing requirement for these materials. The system manufacturer, 3D Systems, requires printing materials to be purchased through their company.

Although FDM is only capable of supporting polymers, it maintains the second largest range of materials within that base. These materials include several variants of ABS, polycarbonate, rubber-like elastomers, and even wax. The polycarbonate material closely resembles the strength characteristics of injection molded ABS. Similar to selective laser sintering, the printer manufacturer Statasys, is the sole supplier of the raw materials. Unlike the materials for selective laser sintering, the materials for FDM are created from a custom blend of commercially available resins.[56]

Additive Manufacturing Uses and Benefits

In a recent *Marine Corps Gazette* article, Lieutenant General Michael Dana further emphasizes the threats posed in the Marine Corps Operating Concept by highlighting the following challenges that will require innovative solutions to resolve: operating environments characterized by anti-access/area denial threats prevent massing ashore; development of a more lean, responsive and agile logistics system; and the need to maximize a “hybrid logistics” model that takes advantage of new technology to support the legacy system.[57] AM offers a range of benefits that can help resolve the difficulties stemming from these three problem areas and offer a cost-effective method to building the agile system a distributed force requires. In short, AM has the capability to support a 21st century Marine Corps through obsolescence management, creating shorter supply chains, reducing production costs, and enhancing innovation.

The International Institute for Obsolescence Management defines the term as the unavailability of parts, or services, that were previously available. It is prevalent with electronic components but also applies to mechanical components, tooling, and test equipment. The issue of obsolescence is particularly concerning to the Defense Department, which contends with long lead times and maintains major end item programs with decades-long life-cycles. In fact, the US Navy estimates that obsolescence issues cost up to $750 million annually.[58] Moreover, as the Marine Corps continues to utilize commercial off-the-shelf products to fill the needs of defense systems a potential obsolescence trouble spot could emerge as commercial life cycles (typically five years) do meet the 20-year requirement for defense.[59]

Obsolescence management (OM) should be managed by both proactive and reactive measures designed for advanced mitigation and post incident resolution of these issues. To mitigate OM, actions should be taken in three areas of interest: supply chain (life-time buying or partnering agreements), design (multisource components and open system architecture), and planning (OM plan).[60] The Marine Corps currently practices OM in all three of these areas with a focus on planning and partnering agreements. Due to the uncertain nature of commercial industry this piece of OM planning can never be definitively defined. Therefore, it is crucial for units that will operate at the far edges of our current transportation network to possess an organic production capability to reduce the long lead times typically associated with OM issues.

On the other hand, inevitable OM issues will arise and the Marine Corps must have the capability to react effectively where the long process of subtractive fabrication will not suffice. The use of AM offers an innovative avenue to address OM in this context. AM has the capability to support the creation of an equivalent item through a process called form, fit, function (FFF). During FFF, a 3D printed part is designed and printed and the form, fit, and function is tested on the platform before metal fabrication. In fact, 1st Maintenance Battalion recently tested this approach during Exercise Steel Knight 17, where it fabricated unique replacement parts for the Amphibious Assault Vehicle whose long-life cycle has created parts availability issues.[61] Another example of this is provided by the US Navy Reverse Engineering: Science and Technology Obsolescence, Repair, and Evaluation (RESTORE) Lab. RESTORE uses a "SCAN to CAD to FAB" process where it scans an item, creates a CAD solution, and prints a new part. The lab recently produced a positioning mechanism for a radar system that was last produced in 1952.[62] Additionally, AM can support either emulation or a complete redesign of the component to address any issue of obsolescence. Since AM allows the creation of details and forms, with composite or metal materials, that were not previously available to traditional machining, it offers a lower cost option for a low volume production requirement.

In the end, AM has the versatility to support obsolescence issues that create significant lead time hurdles on the battlefield. Given the current fiscally restrained environment, it is likely that commercial off-the-shelf products and legacy systems will continue to be utilized. By utilizing this technology, the Marine Corps can flatten the supply chain and help to support the "hybrid logistics" model suggested by Lieutenant General Dana. However, the Marine Corps must couple these reactive methods with proactive approaches that include partnering agreements with OEMs to facilitate digital file sharing and prevent legal conflicts.

Shortening the supply chain is also necessary to support the Marine Corps' future force. As units become more distributed and A2/AD threats more lethal, the ability to mass supplies will be limited. By providing the capability to produce onsite, AM offers the Marine Corps a useful and cost effective way to reduce the logistics footprint of the Marine Air Ground Task Force.[63] Interestingly, the possibilities of this technology are not limited to the production of repair parts – although this is an important capability for military logisticians. AM experts are experimenting with processes and materials that will support everything from food production to textiles. For an organization whose future force vision is increasingly distributed, the ability for onsite production by small teams (using desktop printers) or a Special Purpose MAGTF outfitted with mobile 3D printing shops (using high grade printers inside recycled twenty foot containers) offers a logistics system that is both responsive and lean. An interesting example of this capability is offered by the Army Research, Development and Engineering Command (RDECOM). A November 2016 Army website article discusses how 3D printed power bars are being tested to ensure their ability to provide the basic nutrients that a 21st century warfighter needs to subsist.[64] Unfortunately, this capability is currently limited; however, once AM advances to a point where highly nutritious food products are made at the point of need, the reduction in volume and weight of supplies needed to support a dispersed unit would decrease rapidly. Additionally, RDECOM is partnering with the Army's Rapid Equipping Force to field expeditionary labs, which are deployable anywhere in the world. These labs are built from 20-foot shipping containers and hold a 3D printer, computer aided design station as well as supporting equipment. It also has traditional tools and equipment to support post form, fit, function test fabrication. This expeditionary lab provides frontline solutions where Marines could describe a need and the lab produces a solution.[65]

Finally, AM provides a cost-effective way to custom design solutions for a myriad of garrison or battlefield supply chain issues. Although current AM technology does not afford mass production capabilities, it does give logisticians the freedom to devise an innumerable amount of unique solutions without the typical transition costs associated with traditional manufacturing. In short, the variable costs and fixed costs associated with 3D printing are not tied to the number of individual projects. Moreover, the unique design possibilities afforded by AM promises custom manufactured parts that are lighter and stronger than their subtractive manufactured counterparts.[66] In fact, 3D printers were used by the Marine Corps in September 2016 to test munitions that were produced by AM. The results, per the Marine Corps's Next-Generation Logistics Office, proved to be more lethal than traditionally manufactured munitions. The co-lead for 3D printing for Deputy Commandant of Installations and Logistics stated that, "One of the benefits of being able to precisely control the way that a munition or warhead is 'grown' through AM is that we think we'll be able to tailor the blast and associated fragmentation to achieve specific effects for particular targets, heights, collateral damage, or even environmental considerations".[67] This method is not intended for mass production but rather to offer tailorable solutions to battlefield problems. This capability offers Marines the time and space to think critically about a problem, devise a solution, produce that solution onsite, and test the product through FFF. In short, AM presents the Marine Corps with low-cost, mass customization solutions for the increasingly complex operational environment outlined in the Marine Operating Concept.

Additive Manufacturing Concerns

There are numerous practical and ethical concerns associated with the diffusion of AM technology in the defense logistics enterprise. Although there are numerous areas of concern, this section of the paper will focus on information security, intellectual property, and process stability. Increased global connectivity provides powerful communication advantages that support US forces. However, it also creates a critical vulnerability that if exploited, could place the lives of Marines in danger. If AM machines are utilized on the battlefield the security of the designs are of the upmost importance. Since the data that supports AM will most likely flow electronically, there is a serious risk to possible system intrusion and disruption. Given the dangers posed by enemy interception or jamming of 3D systems, former President Barack

Obama formed the Digital Manufacturing and Design Innovation Institute (DMDII) in 2014. Based on a public-private partnership, the goal of the DMDII was to study, test, and develop advanced analytics in a secure cyber system to counter potential cyber threats.[68]

In general terms, intellectual property (IP) can be defined as any product of human intellect that the law protects from unauthorized use by others.[69] The nature of AM technology allows almost anyone to recreate an existing design making protecting IP extremely difficult. AM users can modify CAD models, which allow users to produce parts with minor modifications to an original, patent protected part.[70] When printing complex structures, which is happening more and more, becomes commonplace, 3D printing may stress the patent system in the same manner that the digital revolution stressed the music industry. Current DOD acquisition practices allow the purchase of parts outright directly from the original manufactures, thus avoiding IP concerns. However, when AM parts are used the suppliers are removed from the supply chain, which costs them thousands – in some cases millions – of dollars.

To alleviate these concerns, the Marine Corps must come up with a way to pay for the legal right to 3D print proprietary technology. There are a variety of ways that this can be done but the most sensible method would be to create partnering agreements that allow the digital exchange of designs. Since the Marine Corps purchased the CAD file, which allows the printing of an infinite number of parts from that file, it must also develop a licensing agreement associated with that file. When this licensing agreement is included in an overarching contract for the part files, then the Marine Corps agrees to pay a small fee for every part that is printed using the company's CAD file. This strategy is akin to the pay-per-play system developed by the music industry to regulate music sharing.[71]

Another challenge surrounding AM will be the need for standardization of file formats, processes, materials, and terminology. The way in which the industry developed produced desperate funnels that produced a dizzying array of machines and processes. One of the main obstacles that will be faced by the Deputy Commandant for Installation and Logistics and Marine Corps System Command will be reviewing and approving machines and processes that meet Department of Defense standards. Due to the wide range of requirements and many different pieces of equipment, proper quality assessment and control procedure must be developed before AM can be truly effective on a large scale.

An excellent example of the need for sound processes and quality control measures is the recent AM printed parts for an MV-22. In August 2016, the Marine Corps printed and conducted in-flight testing of two mission critical titanium parts. Although the test proved successful, the process was cumbersome and labor-intensive.[72] For these machines to truly make a difference in aviation or ground readiness, the Marine Corps, in conjunction with the Joint Staff and other services, must develop standard processes of production as well as quality control and material standards that will streamline production.

The defense industry uses standards that are promulgated by established organizational requirements based on minimal allowable performance. The requirements established for traditional manufacturing methods often require a long list of complex processes to meet certain performance levels. Some of the factors used to determine performance include smoke and toxicity levels, material strength, flammability characteristics, fatigue resistance, survival temperature, and radiation and chemical sensitivity. These requirements are needed for even the most simplistic parts used by military industries. As previously mentioned, not only are the qualities of parts imperative, but the standardization of those parts is equally important. To accomplish this, the Marine Corps must look no further than the Defense Standardization Program (DSP).

The DSP is the governing body that ensures that the Secretary of Defense maintains a unified standardization program. Per DOD Manual 4120.24-M, this program performs multiple functions in order to maintain unity of effort: standardizing like products and technologies, using a common set of specifications and standards, cooperating with industry in the development of standards, assigning standardization responsibilities in the DOD, resolving disputes between the military departments and defense agencies, and making final decisions on all DSP-related matters.[73] In addition, DOD Manual 4120.24-M states that the standardization affords the warfighter with "equipment that is interoperable, reliable, technologically superior, and affordable." It also contends that several key capabilities are required in order to ensure the success of any standardization effort. These capabilities include the following:

- Interoperability with multi-national partners and among the military departments, which requires standardization of physical, electronic, and functional interfaces and performance requirements;
- Information superiority, which demands standardized data and equipment interfaces and performance requirements to permit information to be shared among systems and personnel;
- Rapid new technology insertion, which requires standard interfaces and performance requirements. Since the DOD must retain existing systems for decades beyond their planned life, affordable technology refreshments will depend in part on the department's ability to define standard solutions across systems based on performance and interface requirements.[74]

To successfully field this technology, the framework for implementation must be tested at the lowest level but defined by the DSP. This means that each service must continue to test this technology by allowing junior and mid-level officers and enlisted to explore innovative techniques that produce results; however, the DSP must be involved and should immediately assign a lead standardization activity (ideally the Department of the Army) and activate a joint standardization board to oversee the development. This is not intended to stifle the initiative of Marine Corps innovation experiments, but rather to ensure lessons learned are captured across the force and that the final solutions for how to incorporate this technology are seamlessly supportable across the entire logistics enterprise.

Conclusion

The Marine Corps' future fight is anything but certain and requires flexible and adaptable logistics systems that can support distributed operations. Just around the corner – at the intersection of the future and the realm of the possible – lies a technology that will profoundly change Marine Corps logistics and supply chain management. Although AM is not developed at a level that would allow the complete replacement of legacy logistics networks and systems, its immediate effect as a supporting effort for a hybrid logistics model will help deliver the Marine Corps into the 21st century. However, given the long lead times for transitioning new technologies to programs of record, it is critical that steps be taken now to focus efforts and ensure unity of effort across the joint force.

The Marine Corps must continue to refine how AM can best support the distributed warfighter by allowing regimental and battalion sized units to acquire and experiment with AM capabilities. These units should interface with the Deputy Commandant for Installation and Logistics and Marine Corps Systems Command to ensure best practices and CAD file libraries are developed and vetted through legal channels. In addition, these experiments should be not be performed in a Marine Corps vacuum. The nature of our future fight will almost certainly be a joint one. It is imperative that the DSP become involved, not to stifle experimentation, but to ensure interoperability of technology that will sustain the program long into the future.

This technology presents a bright future for a Marine Corps working toward the vision of a redesigned logistics system that offers agile and responsive support to distributed forces across a dynamic battlespace. It has the capability to shorten supply chains, help eliminate the need for “iron mountains”, reduce concerns with long defense program life cycles, and add small unit flexibility to improve readiness. The range of possibilities that AM offers are endless, promising to bring about the most opportunity rich disruption to supply chain management since the internet. In short, if this technology is indeed ushering in a third industrial revolution, the Marine Corps must be involved.[75]

Notes

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[1] Beth Scott, James Rainey, and Andrew Hunt. *The Logistics of War: A Historical Perspective* (Maxwell AFB, Air Force Logistics Management Agency, 2000), 24.
[2] Eric Peltz, John Halliday, Marc Robbiens, and Kenneth J. Girandini. Sustainment of Army Forces in Operation Iraqi Freedom: Battlefield Logistics and Effects on Operations. Santa Monica, CA: RAND Corporation, 2005, 13
[3] Headquarters US Marine Corps, *The Marine Corps Operating Concept: How an Expeditionary Force Operates in the 21st Century*. (Washington, DC: Headquarters US Marine Corps, September 2016), 5-6.
[4] Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (New York: Springer Science+Business Media, 2010), 2.
[5] Todd Grimm, *User's Guide to Rapid Prototyping* (Dearborn: Society of Manufacturing Engineers, 2004), 15.
[6] Royal Academy (Great Britain). 2013. Additive Manufacturing: Opportunities and Constraints, Prince Philip House. http://www.raeng.org.uk/publications/reports/additive-manufacturing, 4.
[7] IBISWorld. (2016). *IBISWorld Industry Report. 3D Printer Manufacturing in the US.* Retrieved December 21, 2016 from IBISWorld database.
[8] Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (New York: Springer Science, Business Media, 2010), 4-6.
[9] Ibid, 442.
[10] Grimm, *Rapid Prototyping*, 53.
[11] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 44.
[12] Brent Stucker, Additive Manufacturing: Standards and Other International Trends (Department of Industrial Engineering, University of Louisville, Louisville, KY), PowerPoint Presentation.
[13] Shane Taylor, "AMF Format for 3D Printing Goes Wider – Now Supported by CimatronE," 3D Printing Industry, January 27, 2014. http://3dprintingindustry.com/2014/01/27/amf-format-3d-printinggoes-wider-now-supported-cimatrone/.
[14] Grimm, *Rapid Prototyping*, 63–67.
[15] Ibid, 59.
[16] Ibid, 68.
[17] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 45.
[18] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 46.
[19] Ibid, 5.
[20] Ibid, 46.
[21] Ibid, 46.
[22] Ibid, 47.
[23] Ibid, 47.
[24] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 58.
[25] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 59.
[26] Ibid, 59.
[27] Grimm, *Rapid Prototyping*, 164.
[28] Ibid, 175.
[29] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,*59.
[30] Grimm, *Rapid Prototyping*, 70.
[31] Ibid, 94.
[32] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 60.
[33] Ibid, 61.
[34] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 64.
[35] Grimm, *Rapid Prototyping*, 77.
[36] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing, 65-66.*
[37] Grimm, *Rapid Prototyping*, 97.
[38] Ibid, 98.
[39] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 66.
[40] Grimm, *Rapid Prototyping*, 163.
[41] Ibid, 170.
[42] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 67.

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[43] Ibid, 67.
[44] Ibid, 68.
[45] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 69.
[46] Ibid, 68.
[47] Ibid, 70.
[48] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 68.
[49] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 157.
[50] Grimm, *Rapid Prototyping*, 167
[51] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 75
[52] Captain Christopher Wood, email with the author, February 22, 2017.
[53] Ibid, February 22, 2017.
[54] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 81.
[55] Grimm, *Rapid Prototyping,* 175.
[56] Ibid, 174.
[57] Dana, Michael "Marine Corps Logistics in the 21st Century. Marine Corps Gazette, 8.
[58] Erkoyuncu, John & Rajkumar Roy. 2015. "Obsolesence management". In Through-life Engineering Services, Decision Engineering, edited by Louis Redding and Rajkumar Roy, 287-296. Switzerland: Springer. Doi:10.1007/978-3-319-12111-6_17
[59] Freeman, Jon and Paoli Giacomo. *Additive Manufacturing and Obsolescence Management in the Defense Context*: RAND Corporation, 2015, 7.
[60] Ibid, 7.
[61] Captain Christopher Wood (Co-lead Additive Manufacturing at Next Generation Logistics, DC I&L), discussion with author, January 9, 2017.
[62] Jessica Tozer, "Meet the Scientists: Stephen Cox", *Armed with Science: The Official US Defense Department Science Blog,* November 17, 2014, http://science.dodlive.mil/2014/11/17/meet-the-scientists-stephen-cox/.
[63] Gregory Pace, et al. "When Tomorrow Is Not Fast Enough". Marine Corps Gazette, 22.
[64] Argie Sarantinos-Perrin, "Army Explores 3-D Printing's Future Applications for Soldiers, Force," *Official Army Website,* Novemeber 30, 2016, https://www.army.mil/article/178822/army_explores_3_d_printings_future _ applications_for_soldiers_force.
[65] Ibid.
[66] Thomas Kellner, "World's First Plan to Print Jet Engine Nozzles in Mass Production," *General Electric Reports,* last modified July 15, 2014, http://www.gereports.com/post/91763815095/worlds-first-plant-to-print-jet-engine-nozzles-in/.
[67] Hope H. Seck, "Marines Conducting Tests with 3-D Printed Munitions," Military.com, September 29, 2016, http://www.military.com/daily-news/2016/09/29/marines-conducting-tests-with-3d-printed-munitions.html.
[68] Louis, M. J., Seymour, T., & Joyce, J. (2014). 3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing). Retrieved from http://dupress.com/articles/additivemanufacturing-defense-3d-printing/
[69] Cornell University Legal Law Institute, "Intellectual Property," https://www.law.cornell.edu/wex/intellectual _property.
[70] John Horncik and Daniel Roland, "3D Printing and Intellectual Property: Initial Thoughts," *The Licensing Journal* 33, no. 7 (2013), 12.
[71] Davis Doherty. "Downloading Infringement: Patent Law as a Roadblock to the 3D Printing Revolution, "*Harvard Journal of Law & Technology*, Vol 26, No 1 (2012), 373.
[72] NAVAIR, "NAVAIR Marks First Flight with 3D Printed, Safety Critical Parts," *NAVAIR News,* last modified July 29, 2016, http://www.navair.navy.mil/index.cfm?fuseaction=home.PrintNewsStory&id=6323.
[73] US Department of Defense. *Defense Standardization Program,* Manual 4120.24, September 24, 2014, http://dtic.mil/whs/directives/corres/pdf/412024m.pdf, 15.
[74] US Department of Defense. *Defense Standardization Program,* Manual 4120.24, September 24, 2014, http://dtic.mil/whs/directives/corres/pdf/412024m.pdf, 15.
[75] Economist. (2012). A third industrial revolution. Retrieved from http://www.economist.com/node/21552901.

Bibliography

Beth Scott, James Rainey, and Andrew Hunt. *The Logistics of War: A Historical Perspective* (Maxwell AFB, Air Force Logistics Management Agency, 2000), 24.

Peltz, Eric, John Halliday, Marc Robbins, and Kenneth J. Girardini. *Sustainment of Army Forces in Operation Iraqi Freedom: Battlefield Logistics and Effects on Operations*: RAND Corporation, 2005.

Headquarters US Marine Corps, *The Marine Corps Operating Concept: How an Expeditionary Force Operates in the 21st Century*. (Washington, DC: Headquarters US Marine Corps, September 2016), 5-6.

Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (New York: Springer Science+Business Media, 2010), 2.

Todd Grimm, *User's Guide to Rapid Prototyping* (Dearborn: Society of Manufacturing Engineers, 2004), 15.

Royal Academy (Great Britain). 2013. Additive Manufacturing: Opportunities and Constraints, Prince Philip House. http://www.raeng.org.uk/publications/reports/additive-manufacturing.

IBISWorld. (2016). *IBISWorld Industry Report. 3D Printer Manufacturing in the US.* Retrieved December 21, 2016 from IBISWorld database.

Shane Taylor, "AMF Format for 3D Printing Goes Wider – Now Supported by CimatronE," 3D Printing Industry, January 27, 2014. http://3dprintingindustry.com/2014/01/27/amf-format-3d-printinggoes-wider-now-supported-cimatrone/.

Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* West Sussex, England: John Wiley & Sons, Ltd, 2006.

Dana, Michael G. "Marine Corps Logistics in the 21st Century." *Marine Corps Gazette* 100, no. 10 (2016): 8-11.

Erkoyuncu, John & Rajkumar Roy. 2015. "Obsolesence management". In Through-life Engineering Services, Decision Engineering, edited by Louis Redding and Rajkumar Roy, 287-296. Switzerland: Springer. Doi:10.1007/978-3-319-12111-6_17

Freeman, Jon and Paoli Giacomo. *Additive Manufacturing and Obsolescence Management in the Defense Context*: RAND Corporation, 2015, 7.

Louis, M. J., Seymour, T., & Joyce, J. (2014). 3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing). Retrieved from http://dupress.com/articles/additivemanufacturing-defense-3d-printing/.

Davis Doherty. “Downloading Infringement: Patent Law as a Roadblock to the 3D Printing Revolution, “*Harvard Journal of Law & Technology*, Vol 26, No 1 (2012).

US Department of Defense. *Defense Standardization Program,* Manual 4120.24, September 24, 2014. http://dtic.mil/whs/directives/corres/pdf/412024m.pdf.

"A Third Industrial Revolution." *Economist* 403, no. 8781 (2012).

Pace, Gregory, Matthew Frazier, Ross Hrynewych, and Sean Smith. "When Tomorrow is Not Fast enough!" *Marine Corps Gazette* 100, no. 10 (2016): 22-25.

Stucker, Brent. *Additive Manufacturing: Standards and Other International Trends*. PowerPoint presentation. University of Louisville, Louisville, KY.