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Evaluation of Three-Dimensional (3D) Printing Technology for Coast Guard Applications

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Homeland Security

N O T I C E

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16. Abstract (MAXIMUM 200 WORDS)

This report provides a basic introduction to additive manufacturing technology and its capabilities and limitations with respect to Coast Guard application. It includes a brief summary of the different methods, materials, and design consideration for additive manufacturing. This report includes a review of recent 3D printing efforts within the Coast Guard. It also provides the results of an RDC-sponsored 3D printer evaluation. The evaluation consisted of field units evaluating various types of 3D printers to determine how they can be used to support Coast Guard missions. Recommendations are also made for the wider application of additive manufacturing in the Coast Guard.

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EXECUTIVE SUMMARY

Additive manufacturing (AM) is the process in which a three-dimensional (3D) object is created by sequentially layering materials by a computer controlled device. AM can be used to create an object of almost any geometry using data from a digital representation of that component. AM is an emerging technology that could have a profound impact on the future of manufacturing. There are several variations of the processes encompassing AM. Many processes have been developed for specific material types, others for specific manufacturing methods. Many of the commercially available desktop 3D printers are limited to printing in thermoplastics. Although many components can be made with thermoplastics, fabricating parts with AM processes using metal materials have the widest potential for application in the Coast Guard. Unfortunately, there are a number of limiting factors preventing the wider application of metal AM. These factors include high cost, small build volume, and the requirement for a large supply of inerting gas for operation. Advances in metal AM process and equipment could make it a more viable option in the near future.

The Coast Guard Research and Development Center (RDC) is currently conducting an evaluation of AM to determine if there are applications within the Coast Guard that can improve mission effectiveness or reduce operating cost. As part of this effort, researchers at the RDC are investigating many of the pertinent emerging aspects of AM including new materials, quality assurance methods, and intellectual property rights issues. This project is also providing 3D printers to field units and cutters for six-month evaluation periods. This effort has shown that few personnel have the Computer Aided Drafting skills to make the digital models of the objects before they can be printed. The evaluators have found many unique applications of AM resulting in direct cost savings and innovative new components. In addition to the RDC's research into AM, the Coast Guard Academy and the Aviation Logistics Center are also operating 3D printers and realizing the benefits of in-house manufacturing.

In order to facilitate the wider application of AM, the Coast Guard should formalize the requirements for 3D printing parts by defining material specifications, quality assurance requirements, and the necessary approvals required before a 3D printed part can be used for an operational need. The Coast Guard should also standardize the training requirements and certifications needed to operate AM equipment for operational use. A starting point for the wider implementation of AM in the Coast Guard is the development of a Road Map outlining the steps necessary to move forward with AM integration. This roadmap will identify the actions that need to be taken so the Coast Guard can benefit from this revolutionary technology.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

3D	Three Dimensional
ABS	Acrylonitrile butadiene styrene
AMF	Additive Manufacturing File
ALC	Aviation Logistics Center
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
ATT	Authority to Test
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CDSA	Combat Direction Systems Activity
CG	Coast Guard
CGA	Coast Guard Academy
CLIP	Continuous Liquid Interface Printing
CNC	Computer Numerical Control
COTS	Commercial-Off-the-Shelf
CRREL	Cold Regions Research and Engineering Lab
DED	Direct Energy Deposition
DMCA	Digital Millennium Copyright Act
DoD	Department of Defense
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
LIDAR	Light Detection and Ranging
NDT	Non-Destructive Testing
NGA	National Geospatial Agency
PLA	Polylactic Acid
PVA	Polyvinyl Alcohol
RDC	Research and Development Center
ROV	Remotely Operated Vehicle
SCARA	Selective Compliance Articulated Robot Arm
SFLC	Surface Forces Logistic Center
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
STL	Stereolithography
TRACEN	Training Center
UAM	Ultrasonic Additive Manufacturing
USPTO	US Patent and Trademark Office

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1 BACKGROUND

Additive manufacturing (AM) is the process in which a three-dimensional (3D) object is created by sequentially layering materials by a computer controlled device. AM can be used to create an object of almost any geometry using data from a digital representation of that component. AM is an emerging technology that could have a profound impact on the future of manufacturing. AM can be used to shorten the design cycle by allowing engineers to quickly print prototypes of complex objects for testing and then incorporate design changes and print another prototype in hours as opposed to days or even weeks. Unique items can be made more cost effectively with AM than with traditional manufacturing methods because there is no need for expensive molds or machining equipment. By enabling users to print parts on demand, it is envisioned that AM could result in substantial savings for logistical support activities. On demand printing also opens the door for innovation because users can develop new designs that are tailored to their specific needs. The benefits of AM technology are being realized globally and substantial investments are being made in this new digital manufacturing renaissance.

The first patent for AM technology was granted in 1986 for a sterolithography apparatus (SLA) developed by Charles Hull (Sterolithography, 1986). His original machine was invented in 1983 and was the basis for one of the most prominent AM companies today, 3D Systems. Several other patents were filed in the late 1980s covering various types of AM processes. In 1992, a patent was issued to Scott Crump which covered a process today referred to as Fused Deposition Modeling (FDM) (Apparatus and Methods for Creating Three-Dimensional Objects, 1992). Mr. Crump went on to co-found Stratasys, Ltd., which continues to be a leading manufacturer of AM equipment. Throughout the 1990s and 2000s, several new technologies were introduced, but AM was limited to mainly high-end industrial applications that could afford the expensive equipment. In the late 2000s, several efforts were conceived to develop low cost FDM machines for more general applications. In 2009, both RepRap and MakerBot offered their first open source FDM machines for sale at a considerably lower cost than what AM machines had previously cost. In 2010, the most inexpensive commercially available FDM machine was the Stratasys Mojo priced at approximately $10,000. The new smaller (and arguably, less capable) 'desktop 3D printers' were priced under $2,000. The substantial drop in price made AM accessible to a much larger group of users and made it more economically feasible to use AM for a wider range of objects. Since that time, the price of desktop FDM 3D printers has continued to drop. The reduction in price has changed the cost benefit paradigm and made FDM manufacturing more competitive when compared to more traditional subtractive manufacturing methods.

The Coast Guard Research and Development Center (RDC) is currently conducting an evaluation on AM to determine if there are applications within the Coast Guard that can improve mission effectiveness or reduce operating cost. The RDC initiated Project #7758 in order to evaluate the current state of AM technology. The project has two main objectives. The first is for scientist and engineers at the RDC to research the state of the art in additive manufacturing to better understand the future capabilities and how they may be integrated in the Coast Guard in the future. The second is to facilitate a wide exposure of existing 3D printers on the market to other Coast Guard units to find innovative applications. This has been accomplished by providing different types of 3D printers to field units for their evaluation. By participating in the 3D printer evaluations, personnel at field units can gain a better understanding of the benefits and limitations of additive manufacturing while the RDC receives knowledge on the needs of the users in the field. In total, the RDC plans to gather data from five shore units and five cutters. This report covers some of the results of this research and the lessons learned at this point in the effort.

2 ADDITIVE MANUFACTURING

Throughout this report the terms "Additive Manufacturing (AM)" and "Three Dimensional (3D) Printing" will be used interchangeably. Although the term "3D printing" originally only referred to binder jetting processes similar to inkjet printing, it is now used in the popular vernacular to cover all methods of AM. There are several variations on the processes encompassing AM. Many processes have been developed for specific material types, others for specific manufacturing methods. This section will familiarize the reader with some of the basic definitions and concepts in additive manufacturing, but does not intend on being a treatise on the subject.

2.1 Types of Additive Manufacturing

American Society for Testing Materials (ASTM) International has defined seven unique process categories that are referred to as additive manufacturing (ASTM 52900-15, 2013). They are as follows:

2.1.1 Material Extrusion

One of the most common methods of additive manufacturing is material extrusion. Most of the desktop size printers on the market today use the material extrusion process. ASTM defines material extrusion as any method that extrudes a material through a small nozzle. In most cases the material is introduced in filament form but some machines are fed particulate materials, commonly referred to as pellets. The ASTM defined category includes the methods known as Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM).

There are several different methods of extrusion head control now being employed by FDM 3D printer manufacturers. The most common is a Cartesian system that relies on stepper motors to move a heated nozzle in the X, Y, and Z directions. Depending on the design, the Z-direction movement can be made by moving either the bed or the extrusion nozzle. A more efficient design that is gaining in popularity is the polar 3D printer. A polar printer requires only two stepper motors and can provide substantial energy savings over a Cartesian 3D printer (which usually requires four motors) (Polar 3D, n.d.). There are several more unique FDM machines on the market. One printer is the delta-style machine that relies on three arms to move the extrusion nozzle and another printer is the Selective Compliance Articulated Robotic Arm (SCARA) machine that is based on industrial robot arm design (RepRap Morgan, n.d.).

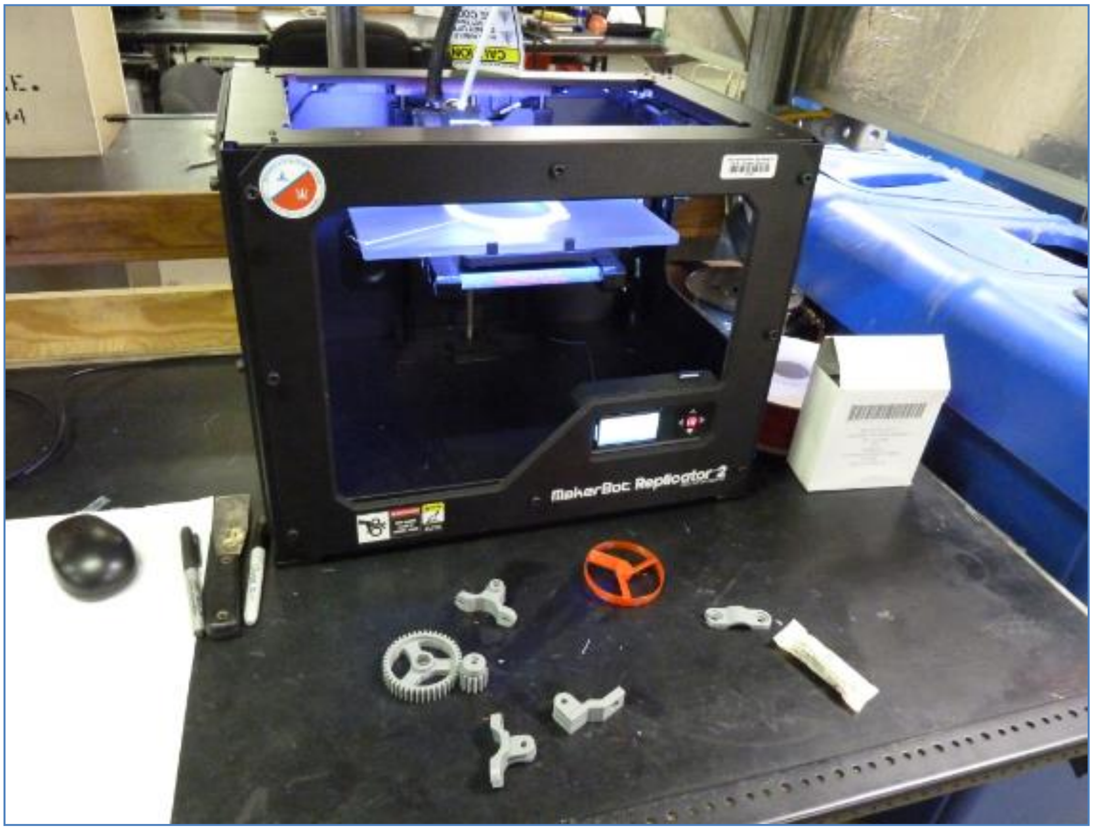

Figure 1. FDM 3D printer on USCGC HEALY in July 2013 (Author Photo).

2.1.2 Powder Bed Fusion

A second very popular method of 3D printing is defined by fusing powder materials together layer by layer. A typical powder bed fusion process involves a method to spread a fine layer of powder on a build surface and then using a heat source to fuse specific parts of the powder layer together. The process is repeated layer by layer until the part is complete. The powder bed fusion method includes Selective Laser Sintering (SLS) used on some metal AM machines.

2.1.3 Material Jetting

Material jetting is an AM process in which small droplets of feedstock are selectively deposited to build up an object. The materials available for this process must have the viscous properties that allow easy formation of drops. Polymers and waxes are most commonly used. Some of the materials used for material jetting can be further solidified by exposure to UV light.

2.1.4 Binder Jetting

Binder jetting is a process in which a liquid bonding agent is selectively deposited to join powder materials. Some binder jetting processes require that the part undergo additional post processing to further bond the powdered material together. Some methods even require the addition of different materials to ‘infiltrate’ the sintered powder materials.

2.1.5 Vat Photopolymerization

This AM method is defined as any process that consists of a pool of photoreactive polymer that is selectively cured by light activated polymerization. This method is known to produce parts very accurately and with smooth surface finishes. One disadvantage of this method is that it is limited to photoreactive materials. Many of the materials available to print are proprietary and specific to the printer's manufacturer. Figure 2 shows a FormLabs Form 2 vat photopolymerization printer at the RDC. The machine consists of a tray with an open pool of photopolymer and a laser device housed in the base. According to the manufacturers information the laser poses no safety risk during operation. The part is built upside down on the platform as it moves vertically away from the resin pool. There is a resin reservoir on the back of the machine that maintains the resin at the correct level. After the object is printed it must be soaked in an alcohol bath to remove the uncured resin from the object. This can be seen in Figure 2, to the left of the printer. In a shipboard environment, open containers of flammable alcohol could pose a safety risk based on ship motions. The printer itself must also be perfectly level during when it is operating which would be difficult onboard a cutter.

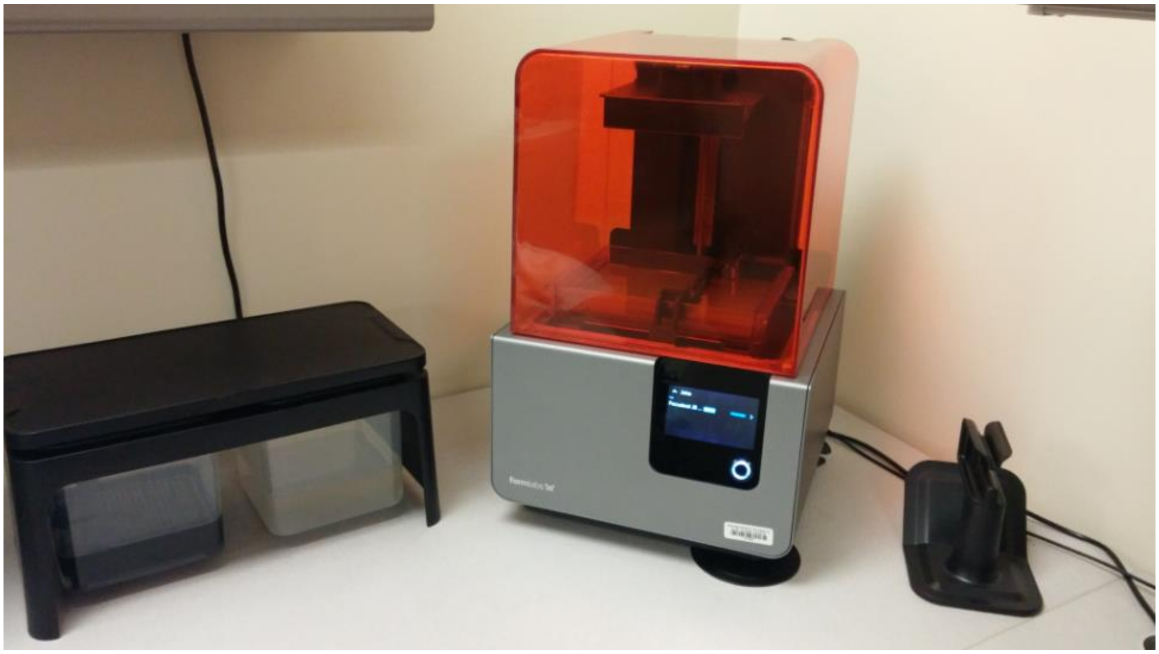

Figure 2. FormLabs vat photopolymerization 3D printer at RDC (Author Photo).

Vat photopolymerization has the potential to vastly increase the speed at which items are printed. A new method being developed continuously projects light to harden an object as it is removed from the resin vat. This method is known as Continuous Liquid Interface Projection (CLIP). Instead of printing one layer at a time, CLIP processes can continuously build the entire level of a part using a light to solidify the object. When compared with traditional AM process that place only small amounts of material on a layer–by-layer basis, this method results in extremely fast printing times.

2.1.6 Sheet Lamination

Sheet lamination process is defined by any AM process that fuses sheets of material together. One of the most common methods is Ultrasonic Additive Manufacturing (UAM). UAM typically involves sheets or ribbons of metal that are bonded together using ultrasonic welding methods. This low temperature method can be used on a wide range of materials. One unique advantage is the ability to develop laminates of different materials to take advantage of their unique properties.

2.1.7 Direct Energy Deposition

Direct Energy Deposition (DED) is a group of processes where focused thermal energy is used to melt feedstock material and deposit it at its final location on the object. The thermal energy can be created by a number of different methods including lasers, ionizing gases, or electron beams. Common applications of DED are for repairing metal parts or adding material to existing metal parts.

2.2 AM Materials

Many of the methods defined in the previous section are effective only when using appropriate materials. The material requirements for a particular part will often dictate the AM process that can be used. Several AM manufactures have developed proprietary materials that are intended to provide benefit to their specific process or equipment (Stratasys Ltd.). This section will identify some common AM material types currently in use.

2.2.1 Thermo Plastics

A typical desktop printer employs a FDM technique that relies on the introduction of a thermoplastic filament feedstock. The most common types of filament commercially available are Polylactic Acid (PLA) and Acrylonitrile butadiene styrene (ABS). In addition to these common filaments, a wide variety of specialty thermoplastics are available. Many of these materials have been developed for specific applications that require distinct material properties. New materials are constantly being developed that allow FDM machines to make parts for broader applications.

PLA is a bio-plastic derived from plant matter. It is a common feedstock for FDM printers due to its relatively low melting point. Another unique property of PLA that makes it a good material for 3D printing is that it has a low amount of thermal expansion. This means that, as the material cools from the extrusion temperature, it does not shrink excessively. This thermal stability makes it a good introductory material because it does not require a heated print surface. Compared to other thermoplastics, PLA does not emit much odor when printing. One drawback of PLA is that its transition temperature is around 140º F. This means that, when exposed to hot water or even left in a car on a sunny day, the mechanical properties will weaken and the printed part could lose its shape.

ABS is another common thermoplastic used in desktop FDM 3D printers. In comparison to PLA, ABS has superior mechanical properties. ABS also has a higher transition temperature than PLA of around 220 º F making it suitable for higher temperature applications. However, it requires a higher printing temperature and a heated printer bed because it shrinks as it cools. The printing area should be ventilated when printing with ABS due to the slight smell and potential for exposure to harmful fumes.

There are several other thermoplastic materials readily available in the commercial marketplace. Polyvinyl Alcohol (PVA) is commonly used to print water soluble support structures. This could be useful as a material in water-activated devices like strobes and buoys. Another AM material--Nylon or Polyamide--provides strength and durability but has the drawback of absorbing moisture from the air before it is printed. This characteristic has a negative impact on its strength and has proven difficult to prevent in a maritime environment.

2.2.2 Continuous Fiber Placement

A recent advancement in FDM is the inclusion of continuous fibrous materials. Fibers are added to the part as the filament is extruded from the nozzle. This combination results in a composite material that can have vastly-improved material properties. Continuous fiber placement methods use materials similar to other thermoset resin-based composite manufacturing including carbon fiber, aramid (Kevlar), and e-glass. One current limitation of this method is that the material can only be placed in plane with the layer. Marrying these methods with advanced printing techniques like SCARA could result in a very capable and low cost automated fiber placement machine that would be capable of making high strength, inexpensive parts.

2.2.3 Metals

Although many components can be made with thermoplastics, fabricating parts with AM processes using metal materials would have the widest application in the Coast Guard. Metal AM would allow the Coast Guard to print high strength, critical parts on demand. This could result in substantial savings and greatly improved logistical support. However, metal manufacturing is much more difficult than thermoplastic manufacturing. Highly specialized equipment is necessary to achieve the temperatures required to bond metal materials. Some materials have unique properties that make them good candidates for metal AM process. The most common metal materials used for AM are titanium alloys and stainless steels.

There are a number of stainless steels alloys available for metal AM. Stainless steel alloy 316L is common in the marine industry due to its corrosion resistance and good weld-ability. Alloy 316L also offers high tensile strength at high temperatures and good ductility making it a candidate for a wide range of applications. Another popular option for stainless steel AM is 17-4 PH. This alloy can undergo heat treatment that can result in a hardness exceeding that of 316L. 17-4 PH is magnetic and can be used for applications that require that distinctive property. 17-4PH is also a common material for medical applications due to its resistance to corrosion.

Titanium alloys are another common option for metal AM. Titanium is known for excellent material strength at relatively low weight when compared to steels (density is around 60% of steel). In addition to being light and strong, titanium provides excellent corrosion resistance in the marine environment. The one disadvantage of titanium is its relative cost when compared to other metals. Many metal AM machines are capable of printing in Ti6Al4V.

In addition to titanium and stainless steel, Inconel is another possible choice for metal AM. Inconel alloys are known for their good resistance to corrosion and are often used in high pressure and heat applications. Cobalt-Chrome (CoCr) is another common material for metal AM. CoCR is commonly used in applications where a high wear material is required. The first Federal Aviation Administration (FAA)-approved 3D printed part for commercial aviation was a compressor inlet housing made from CoCr (Kellner, 2015). There is a substantial amount of research underway to develop new metal alloys that can be more easily 3D printed. Several manufacturers have proprietary alloys that are marketed as having a specific benefit over existing alloys when used in AM processes.

2.3 Shipboard Application of Metal AM

Printing in metals would allow ships to realize one of the greatest potential benefits of AM: printing repair parts on an as-needed basis, while at sea. The current 3D metal printers have several limitations that need to be addressed before they can be utilized on Coast Guard cutters. After discussions with several manufacturers and equipment operators, the project team identified several issues facing shipboard installation of metal AM machines. The following issues were identified:

- **Small Build Volume:** Many of the metal AM machines currently on the market have small build volumes that would limit what objects could be printed on them. The ProX DMP 100 made by 3D Systems (a typical metal 3D printer available for government purchase on General Services Administration (GSA) website) is only capable of printing objects smaller than 3.94"x 3.94" x 3.94". The ProX DMP 200 can only make objects 5.51" x 5.51" x4.91". By comparison, many of the FDM machines typically have a build volume of around a cubic foot (12" x 12" x 12") and often operators are limited by geometry on many of the items they would like to print.
- **High Cost:** The ProX DMP 100 is currently listed on GSA website with a price of $184,800 (GSA Advantage) and the ProX DMP 200 has a list price of $361,900 (GSA Advantage). While this price is expected to trend downwards as metal AM becomes more commonplace, the average price of a cubic foot FDM machine is around $2,500 (GSA Advantage).
- **Inert Gas:** Metal printing requires the build volume be an inert atmosphere, with non-reactive gasses so the metal can cool without being contaminated or oxidized. Typically, this is accomplished with either argon or nitrogen. A large tank for storing this gas will be required to supply the cutter with enough gas for manufacturing while at sea. The tank would need to be located in an area that would allow easy access for pier side gas deliveries. Although the gas itself would not be flammable, it would be under pressure and could pose a significant safety risk. Additionally, pressurized gas lines would need to be installed to deliver the gas to the printer location. These gasses are inert so you can readily breathe them without detecting a smell, but they displace the oxygen in the air. A gas leak of this type will result in personnel losing consciousness without warning and asphyxiation could result if they remain in the space. The manufacturing space and spaces where the gas lines pass will require gas detectors and automatic ventilation systems.
- **Recycling Equipment:** Most metal AM machines consume powder metal materials. Although some machines have integrated powder recycling equipment, the recycling equipment is often sold separately from the 3D printer. Material recycling allows the recovery of the unused metal powder and reduces the cost of manufacturing. Different manufactures have different recycling equipment but the estimated cost of a standard set of equipment is an additional $100,000.
- **Power Requirements:** The electrical power requirements for metal AM equipment can be substantial depending on the AM process being used. The power requirements of each printer and available power (e.g., 440 VAC) on each cutter will need to be carefully evaluated before any 3D printers can be installed.
- **Weight:** The DMP 100 metal printer from 3D Systems weighs approximately 2,200 lbs (3D Systems). The weight increases with the build volume. The DMP 300 weighs approximately 11,000 lbs and has a build volume of approximately 10" by 10" by 13". This weight does not include any of the gas storage, recycling, cleaning equipment, or additional ventilation equipment.

- **Surface Treatment:** After the parts come out of the printer they require a surface treatment by sand blasting. This requires compressed air, a spray cabinet, and various types of fine blasting medium based on the part and its metal composition.
- **Shipboard Environment:** The environment aboard a ship is generally not conducive to metal AM. Most areas of the ship are subjected to high frequency machinery vibrations that can shift powder beds during the fusion process. Motions in a seaway could also have a negative impact on powder beds. The high humidity environment on a ship could also lead to higher maintenance requirements of the non-marinized 3D printer, as well as material contamination.
- **Manpower Requirements:** Metal 3D printing is substantially more complicated then thermoplastic FDM processes. Many AM machines require constant attention by highly trained technicians. Metal AM will require a large investment in crew training and time to maintain the machine while underway.
- **Support of Equipment:** If the equipment malfunctions or is broken, repairing it will most likely be beyond the capability of shipboard or depot level personnel and it will require servicing by a manufacturer's representative. Service contracts will be required to support the equipment, at least initially, while the crew is trained in its operation and maintenance.

Further research and development is required on several of the issues mentioned above before metal AM can be effectively and reliable deployed at sea. In the near term, metal AM could provide material support at land based repair facilities. Installation of metal AM machines at shore based facilities will help the Coast Guard gain a better understanding of the capabilities and limitations of the AM process when using metal materials.

2.4 Materials Science of AM

In traditional thermoset plastics manufacturing processes, all of the material is introduced to the mold and then cooled at the same time. This results in a homogenous material with the same material properties in every direction. A material with the same mechanical properties in every direction is referred to as being isotropic, as compared to an orthotropic material which has different material properties in different directions. Most materials for FDM AM will result in orthotropic material properties. This is because the bond between the subsequent layers of material (in the Z-axis direction) is often not as strong as the continuous filament deposited in the layer (the X- and Y-axis directions). When orienting a part for printing with thermoset materials, it is important to consider the direction the force will be applied on the part. The strength and stiffness of the part will generally be greater parallel to the layers, in the X and Y direction. Figure 3 below shows the common axis orientation used in AM as well as the preferred load direction.

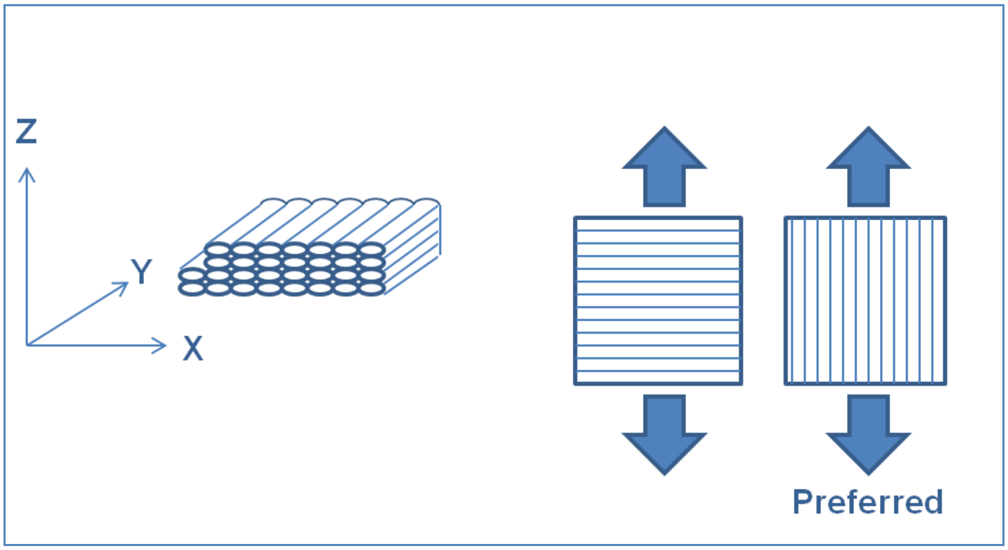

Figure 3. FDM 3D printing material orientation

Although having a different strength in the Z direction could lead to some limitations, it is not an uncommon issue in material science. Both wood and resin-based fiberglass materials are also orthotropic due to their layered construction. In metal AM, the Z direction strength is highly dependent on the material and process being used. Some metals materials will readily accept another layer of material and will have limited, if any, strength degradation in the Z direction. However, some metal materials and processes will not form as strong of a bond between the subsequent layers and will result in an orthotropic material. Whatever the process and material being used, it is important to completely understand the manufacturing process and the resulting material strength of the parts being manufactured. It is recommended that similar parts be subjected to destructive testing; and ensure that the part meets all quality assurance methods for manufacturing.

2.5 Quality Assurance (QA) in AM

In the traditional subtractive manufacturing process, the material is generally sourced from a factory or established industrial material maker. These factories make large quantities of material, often using complex methods and specialized machinery. During the making of the material, it usually must pass several quality assurance tests to ensure that the material being processed meets the required specifications. For example, a common aluminum used in boatbuilding, Aluminum 5083-H32, must meet over 20 different specifications for it to be labeled as such. Each specification must be tested and verified by the material maker. In AM, each print job is a discrete material manufacturing process using the feedstock supplied to the 3D printer. There are numerous environmental conditions that could be different from print to print, that could affect the quality of the part. The quality of the feedstock could also change during the printing process resulting in unexpected material properties. Given the nature of how a part is built up by layers, defects could occur at locations inside the part that would not be apparent under visual inspection techniques.

AM equipment manufacturers and end users are utilizing several methods to help ensure a high quality printed part. Many existing Non Destructive Testing (NDT) methods can be applied to the AM process. The simplest NDT method to incorporate is a visual inspection. Most major defects can be easily detected by unexpected part geometry, part finish, or differing colors of the finished part. Some 3D printers have a camera to record each layer as it is deposited that can be reviewed at a faster frame rate or analyzed by QA software to automatically scan for anomalies. Infrared cameras are sometimes used for this purpose and check for temperature variations during the print that can be an indicator of quality issues in both plastic and metal materials. Another promising NDT method for AM is the use of penetrant testing. The part is coated with a solution that would penetrate any crevices between layers to highlight any areas that are not properly bonded. The solution is then removed and a developer is applied to help identify problem areas. Penetrant testing is a cost-effective way to ensure proper layer adhesion. Potentially one of the most effective NDT methods for detecting voids in AM parts is radiography using gamma or X-ray radiation. Radiography can ensure the internal part integrity by checking for internal voids and anomalies deep inside the part. Unfortunately, radiography usually requires specialized equipment and training and can be cost-prohibitive for widespread implementation. Research in methods to ensure the quality of AM parts is ongoing. There is currently an ASTM working group developing a guide for using NDT procedures for metal manufacturing (ASTM WK47031, 2014). Part verification and QA will become important aspects of AM as it becomes more commonplace.

2.6 Geometric Limitations of AM

Similar to subtractive manufacturing, the AM process has some limitations on what can and cannot be manufactured. There are several factors that will dictate the geometric constraints of the AM process in addition to limitations imposed by the actual build volume of the 3D printer (the most important of which is the AM process being used). By definition, AM processes require a substrate to add to in order to build up an object. For material deposition processes like FDM this usually means that overhangs and angles exceeding 45 degrees from vertical cannot be accurately printed without support. This is because the material being extruded does not have an adequate substrate for building up the next layer. In practice, many FDM printing software has the ability to detect overhangs and automatically add superficial support structures to aid in the printing process. After the print is completed, the support material is designed to be easily removed from the printed object. Figure 4 below shows a removable support structure automatically added to the part in areas that exceeded the 45-degree angle.

Figure 4. 3D printed metal flange showing support structure (Photo: William Bryan, CG-444).

AM processes that build solid objects in fine particles (like powder bed fusion and binder jetting) often do not require material supports. The loose, unbound particles surround the part and support overhangs or other geometry that would otherwise require supports in deposition manufacturing methods. A unique issue with powder processes is that the voids will contain loose powder that cannot be accessed. Often models are designed with orifices to allow the loose powder to drain from the part. When designing parts for AM it is important to fully understand the printing method that will be used so the part can be optimized for that method.

2.7 Typical AM Workflow

It is important to understand the requirements for a complete design cycle, using the AM process. In addition to acquiring the 3D printer, there are additional costs associated with acquiring software, utilizing the resources to develop 3D models, and any post processing required. There are some basic differences in the workflow based on the type of AM being used, but the description below is typical for most machines.

The AM workflow begins by creating a 3D representation of on object using software capable of 3D modeling. This is usually accomplished either by modeling the object using a 3D Computer Aided Design (CAD) program or by 3D scanning an existing object. There are numerous programs commercially available that are capable of this. It is important to consider the type of file that will be created by the software, since many of them use proprietary file types. The cost of a CAD software license varies greatly depending on the program and some programs require annual subscriptions. The software used for this evaluation was SOLIDWORKS Standard version that has a GSA price of approximately $3,000 per license (GSA Advantage).

The next step of the process is importing the 3D model into a different software suite that interprets the 3D model into the required movements for the 3D printer to develop the model. Currently most 3D printing software programs require the 3D model to be saved as a stereolithography (.STL) file type. This file type was originally developed by 3D Systems and is a very common file type available as an output on most 3D CAD programs. In 2011 the International Standards Organization (ISO) and ASTM introduced a new file format specifically for AM known as Additive Manufacturing File Format (.amf) that includes native support for color, materials, and other items specifically for AM (ISO/ASTM 52915:2016, 2016). However, there are very few programs that support this new file format at this time.

After the STL file has been imported, the 3D printing software deconstructs the model into 'slices' that correspond to the deposition layers. There may be incomplete areas if the model has been scanned and the software can usually detect and repair these areas before printing. Using the model slicer, the software then can generate a numerical control programming language, known as G code, to direct the print head during the 3D printing process. Many of the 3D printers commercially available can be controlled by various 3D printing software programs. However, some 3D printers can only receive input from their proprietary software systems. Most Commercial-Off-the-Shelf (COTS) 3D printers come bundled with free or open source 3D printing software. Other manufacturers require users to purchase the required software at an additional cost. Most 3D printers do not provide a method for developing 3D models and third-party CAD software is usually required. The 3D printing software controls several aspects of the finished object. The 3D printing software and its slicing method controls the layer thickness which has a direct relation to the resolution and time it takes to print an object. The 3D printing software typically allows the user to make changes to the process based on material type or lessons learned from previous similar prints.

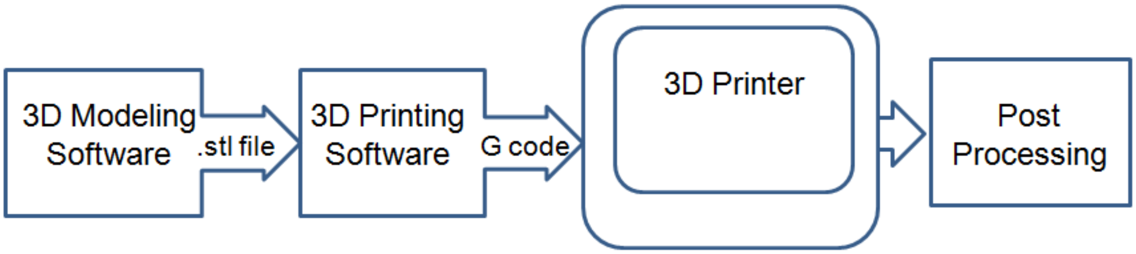

Figure 5. Typical additive manufacturing workflow.

Depending on the AM process used, the part from the 3D printer can require substantial post processing. Typical post processing includes using solvents or sandblasting to improve the surface finish. If rafts or support structures are required during printing then they must be mechanically removed or dissolved. One common technique is to print oversized in high tolerance areas and then remove the excess material using a more precise subtractive method like drilling or planning. If powder based materials are used, substantial cleanup of the build area will be required. Often there is an additional process required for reusing powdered materials. Recovery processes can be specific to the equipment being used and they often require the purchase of specialty reclamation equipment.

2.8 Intellectual Property Rights and Additive Manufacturing

The widespread interest in 3D printing and the distribution of 3D object files could have wide ranging impacts on intellectual property laws. The ability to quickly and inexpensively create exact copies of objects is a core concept of AM. Some equipment like 3D scanners can make exact copies of existing objects that can then be replicated. There are three different types of intellectual property law that cover the use of AM; copyrights, patents, and trademarks. A copyright protects original works of artistic authorship including literary, dramatic, and musical works including computer programs. A copyright does not protect ideas, systems, or methods of operation. A work is automatically covered under copyright the moment it is created. You do not have to register for copyright protection; however, an originator must register the work in order to bring a lawsuit against an infringer (U.S. Copyright Office). The term of a copyright protection has been extended several times. The original term was for 14 years, but currently the term is the life of the author plus 70 years. Copyright law in the digital age can be very complex and is continually evolving to address new and emerging technologies. The methods of copyright observance as outlined by the Digital Millennium Copyright Act (DMCA) could be applied to 3D printing in many instances. This law was developed in response to the digital music sharing phenomenon around the late 1990's that also posed a challenge for copyright law. Under the DMCA, the copyright owner is responsible to identify instances of copyright infringement and issue takedown notices to service providers that facilitate disseminating copyrighted works. While this could limit the liability of service providers, it does not address the liability of individual copyright infringers. It is the responsibility of the user to ensure the objects they are printing are not covered by copyright laws. Unfortunately, this can prove to be very difficult. Since an originator does not have to register the work, there is not a comprehensive way to search for existing similar works. The best way to ensure you are not infringing on a copyright is to have the express consent of the originator to print a copy of the original work.

Patent law is another form of intellectual property rights that apply to AM. A patent is issued by the US Patent and Trademark Office (USPTO) after an inventor has submitted an application describing the useful and functional object. A patent gives the inventor the right to exclude others from making, using, or offering for sale of an invention (U.S. Patent and Trademark Office). In order to infringe on a patent, the object must be made. Having knowledge of a patented object usually does not constitute infringement until the item is actually manufactured. By some interpretations this means having a digital file of a patented object is not infringing until the item it actually printed. This could lead to wide distribution of the digital files of patented objects. It would be extremely difficult for a patent owner to know if the item was printed on a 3D printer in a private residence or business. Another interesting nuance of patent law is that it allows a patent holder to sue persons or businesses that enable patent infringers. Arguably, this could extend to the service providers and even 3D printer manufactures.

Trademarks are another type of intellectual property that can affect printed objects. A trademark is a word, name, symbol, or device that is used to distinguish the source of the goods and to distinguish them from the goods of others. A service mark is similar in that it distinguishes a service rather than a product. Trademarks are also registered with the USPTO. Anyone using a 3D printer to manufacture an item that resembles a trademarked item could be held liable for trademark infringement.

There are some very complicated legal issues surrounding intellectual property rights and how they are applied to AM technology. The easiest way to avoid unknowingly printing objects covered by intellectual property rights is to print objects of original design or objects with expressly released data rights. As the Coast Guard looks to print replacements for existing components, it is important to understand digital data rights and how they apply to AM. As 3D printing becomes more widespread in the Coast Guard, careful consideration must be given to each part before printing to ensure the intellectual property rights of Original Equipment Manufacturers (OEMs) are not violated.

3 ADDITIVE MANUFACTURING IN THE COAST GUARD

This section of the report provides a review of ongoing efforts in AM throughout the Coast Guard. In addition to the RDC's ongoing project, AM is used to meet some unique manufacturing challenges at the Aviation Logistics Center (ALC) and to support the education of some of the Coast Guard's next generation of innovators at the Coast Guard Academy (CGA).

3.1 Coast Guard Academy

The Coast Guard Academy (CGA) has a long history of including AM in their curriculum. Many of the students use 3D printers to make prototype components in support of engineering capstone projects. Currently the CGA operates a Stratasys Dimension 1200 ES, a Stratasys Object 30 Pro, 3D Systems Project 660 Pro, and many desktop 3D printers from various manufactures. The 3D printers are housed in McAllister Hall alongside Computer Numerical Control (CNC) milling machines, manual drill presses, and band saws. The students are encouraged to learn how to use all of the equipment to support a well-rounded education. The faculty at the CGA is also conducting academic research into AM technology that can be directly relevant to applications with the Coast Guard. The RDC and CGA have collaborated on several efforts resulting in mutually beneficial research work for the Coast Guard.

3.2 Aviation Logistics Center

The Coast Guard's Aviation Logistics Center (ALC) also maintains a CAD and computer-aided manufacturing (CAM) shop that incorporates AM equipment. ALC currently produces most of its parts on a Stratasys Fortus 400 MC that uses Insight 3D printing software. This machine allows them to print objects in a rage of various materials including ABS, Nylon, Polycarbonate, and a polyetherimide thermoplastic commonly known as ULTEM. ULTEM can be used to make components that meet FAA FAR 25.853 requirements. ULTEM is a high strength-to-weight material that provides elevated thermal resistance. ALC has developed ALC INST 13020.10B to formalize the workflow when a part needs to be manufactured. Figure 6 below shows a circuit breaker panel that ALC is using their in-house AM capability to manufacture.

Figure 6. ALC's 3D Printed circuit panel (left) and original part (right) (Photo: William Bryan, CG-444).

AM is also used at ALC to support more traditional means of manufacturing. Many drill guides, saw fences, and other specialty components are printed to assist with manual fabrication jobs. One example is the fabrication of a complex Y section of the H-65 fuel tube. The part requires that the fuel tubes are cut at difficult angles and then welded together. ALC has developed a 3D printed jig to hold the pipes at the correct angle while cutting and another jig to hold them in place for welding. Use of this jig allows the cuts to be made easily on a band saw at the correct angle. The welding jig also greatly improves the repeatability of the process to ensure all of the tubes are interchangeable. Figure 7 below shows one of the saw guides for the fuel pipe.

Figure 7. 3D Printed band saw guide for H-65 fuel tube (ALC Photo).

As part of a collaborative effort with the RDC, the Navy's Combat Direction Systems Activity (CDSA) Dam Neck Office offered to provide access to the Navy's metal AM machines. The RDC spoke with ALC about candidate parts for metal manufacturing and decide on three components. The first part was a MH-60T double fuel sump that required strict tolerances be maintained and ALC was interested in the ability of metal AM to meet those tolerance requirements. The second was a MH-65D park control brake relay shaft. The relay shaft was originally manufactured manually on a lathe and required 40 hours of machining time. The manufacturing process is currently done by a CNC lathe and still requires around 10 hours of machining. ALC was interested in how long an AM process would take. The 3D printed version did not result in substantial time savings and the part is currently undergoing quality assurance analysis. The third part was a MH-65D electric pump support that was suggested due to its complex geometry. Figure 8 below shows the metal 3D printed electric pump support at ALC. The 3D printed version did require some support structures but the metal printer was easily able to produce the part within tolerances. Two samples of each part were printed by the Navy. The parts are currently being subjected to a rigorous engineering analysis (to include destructive testing of one of each of the parts).

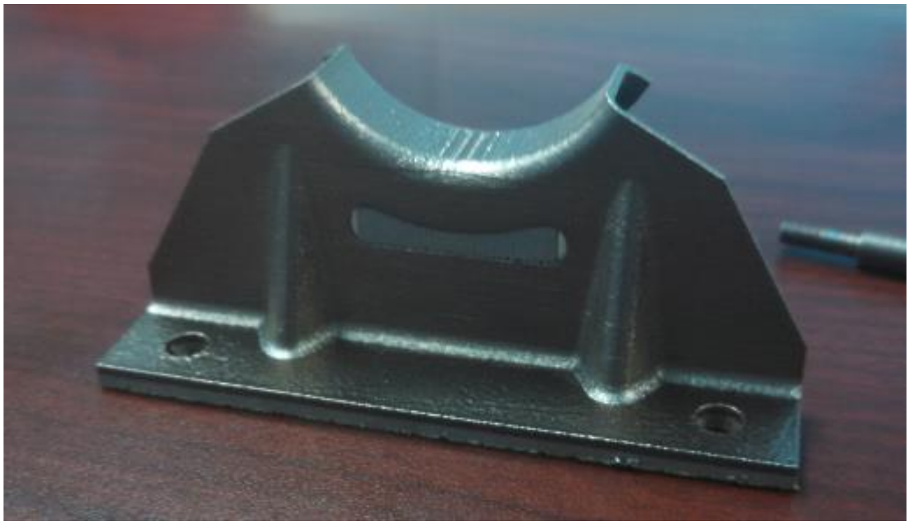

Figure 8. H-65 pump support 3D printed in metal (Photo: William Bryan, CG-444).

3.3 Recent AM activity at the RDC

The RDC has an ongoing project titled "Evaluation of 3D Printing Technology for Coast Guard Applications." The project was initiated in FY16 in response to the growing interest in 3D printing and the realization of the potential impacts it could have on manufacturing in the future. However, AM has been used to support other research objectives at the RDC for some time. Some of the RDC's projects included the purchase of 3D printer prototypes and acquiring access to AM capabilities through contractors. The RDC acquired its first desktop 3D Printer in July 2013 as a less expensive method to manufacturer a scaled model of a waterjet for a collaborative testing effort with the US Army Corps of Engineer's Cold Regions Research and Engineering Lab (CRREL) in their ice test basin. CRREL and the RDC were investigating boat operations in ice covered waters and needed a scaled model of a waterjet propulsion unit to evaluate that propulsion method in ice. The RDC requested an estimate to have the model propulsion system built through traditional means and the cost was $20,000. The RDC purchased a MakerBot Replicator 2 for approximately $2,500 to support this effort. By designing and printing the 3D model in-house, this project was able to save the Coast Guard approximately $10,000 in its first use.

In September 2013, the RDC sent a team to deploy with the Coast Guard Icebreaker HEALY to conduct an oil spill technology demonstration in the Arctic. As a learning opportunity, the research team brought a 3D printer along. During that testing a Remotely Operated Vehicle (ROV) was crushed by ice moving along the hull, resulting in a complete hull breach of the ROV. A cast metal flange was damaged beyond repair and there was not a spare one included in the manufacturer's spares kit. A replacement flange was designed and printed that evening and the ROV was operational again the next morning. Without the 3D printer that equipment would have not been operational for the rest of the deployment. Having the ability to manufacture replacement parts or to prototype custom parts for unforeseen issues is a game changer for supporting field research, especially in extremely remote areas.

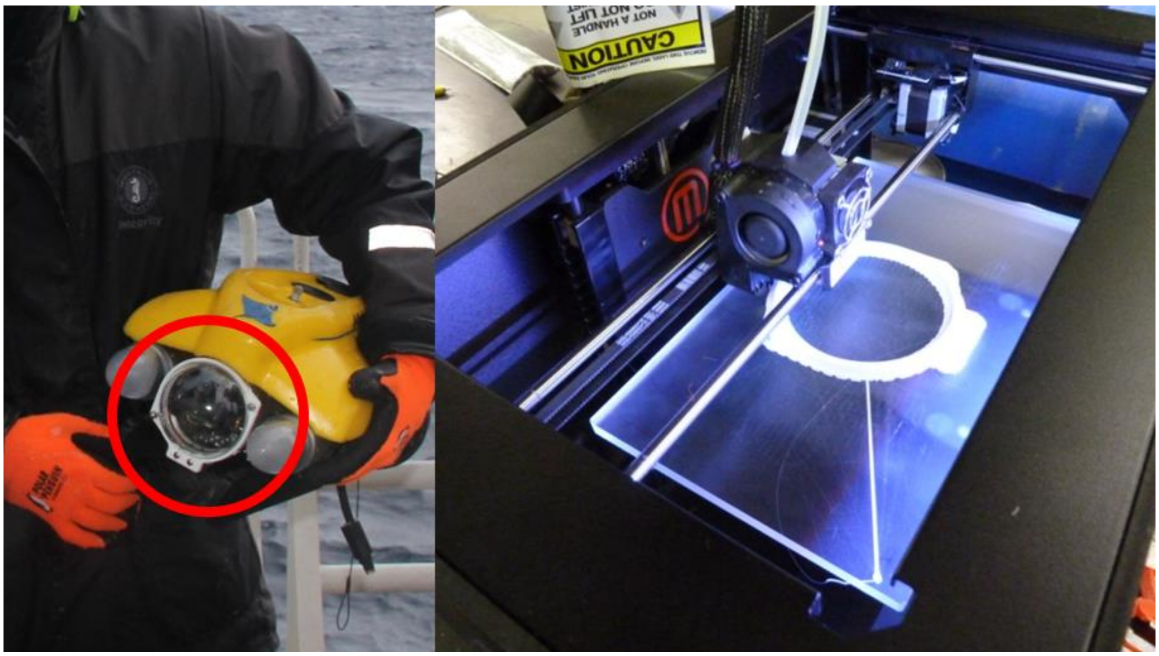

Figure 9. Replacement ROV part printed aboard HEALY (RDC Photo).

In August 2014, the RDC went underway on the HEALY again to conduct an Arctic Technology Evaluation (ATE). The goal of the ATE was to test several new platforms on their ability to assist the Coast Guard in an Arctic environment. During the 2014 ATE the 3D printer was used to manufacture a number of prototype items, including weatherproofing flanges for an Aerostat, modified propeller guards, and various other custom designed parts. The RDC conducted a subsequent ATE in 2015 aboard the HEALY. CGA Professor Ron Adrezin participated on this deployment to conduct AM research as sponsored by Office of Naval Engineering (CG-45). In conjunction with a DHS Science &Technology (S&T) intern, they designed and built several components including an orthopedic insert for a crew member, electric boat control components, and completed an emergency repair on the ship’s dishwasher by making a replacement part not available on the ship. The dishwasher repair translated into direct cost savings by preventing the entire ship’s force from using disposable plates, cups and utensils.

In February 2105, members of the RDC collaborated with National Geospatial Agency (NGA) to build a low cost quadcopter using COTS electronics and 3D printed airframe. The initial quadcopter build time was 10 hours but series construction and application of lessons learned could greatly reduce the amount of time it would take to build the system. After construction, the quadcopter was demonstrated for local Coast Guard members near a lock on the Mississippi River. This system could be used for security missions or for aerial mapping during disaster recovery. NGA personnel also demonstrated the ability of the platform to carry advanced payloads like the Light Detection and Ranging (LIDAR) that can produce more detailed aerial maps. Additive manufacturing can produce many of the lightweight structures needed for small Unmanned Aerial Systems (UAS) at a very low cost. Additionally, the cost of ownership would be reduced because replacement parts for damaged components can be quickly re-printed. AM would also allow the UAS to be easily modified to accept mission specific sensors or advanced payloads.

Figure 10. USCG RDC 3D printed quad copter (Author Photo).

The RDC continues to evaluate new advances in AM. Many of the new materials that are becoming available for FDM machines can increase the scope of objects that can be 3D printed. One area that is of interest is the ability to use conductive materials for part fabrication. This would allow the inexpensive desktop 3D printers to make electronic circuits. Additionally, electrical circuits could be incorporated into the structure of non conductive materials. This could result in potential increases in small UAS performance due to weight savings. Enclosed circuits could help prevent corrosion in marine environments. Unfortunately, the conductive materials currently available for thermoplastic extrusion have high resistance when compared to copper circuits. One of the more conductive material on the market states their material has a volume resistivity of 0.75 ohms/cm which is several orders of magnitude greater than most metallic circuit components. It is assumed that more conductive materials will be available in the future that will allow the construction of efficient electrical circuits.

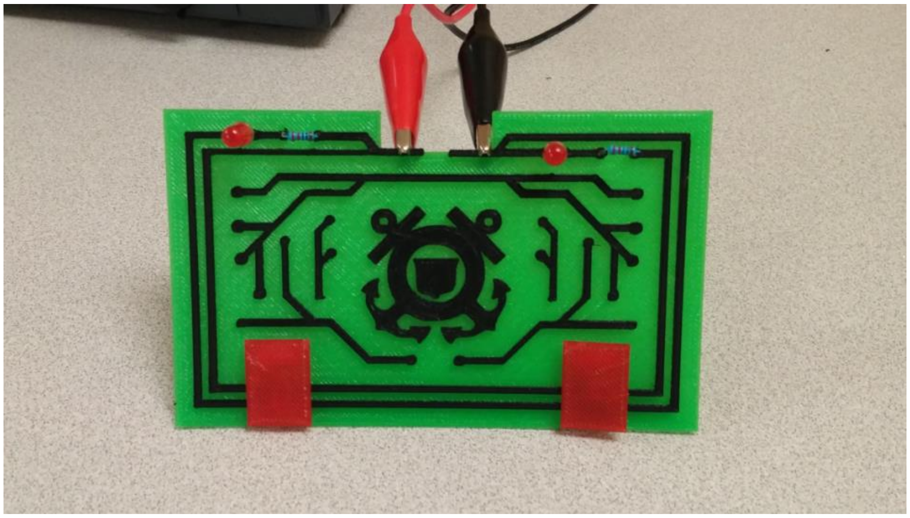

Figure 11. 3D printed circuit (Author Photo).

Another potential application for conductive materials is radio frequency shielding and reception. Electrical enclosures can be specifically designed and printed as needed to ensure the contents are not affected by external RF energy. Antennas could be built on demand and modified for specific reception requirements. The RDC has been testing directional antennas operating around the 915 MHz band with limited success. 3D printing allows for unique antenna shapes to be accurately and quickly printed. Antennas could be incorporated into the structure of object and vehicles. Antennas could be incorporated when the vehicle is designed (instead of installed after the vehicle is completely manufactured). As more conductive materials become available, the performance of 3D printed antennas is expected to increase.

Figure 12. 3D printed Helical Antenna (Author Photo).

FDM 3D printers also have the capability to make objects from more flexible materials than the rigid thermoplastics. Flexible or rubberlike materials can be used for numerous types of items including gaskets, waterproof switch covers, vibration isolators, and helmet inserts. There are currently several types of commercially available, flexible materials offering different hardness and elongation. Most of the materials are proprietary chemical mixtures based on polyurethane. Most of these materials offer good chemical resistance to a wide range of fuel oils. One concern with using flexible materials for gaskets is that usually the gasket will be exposed to some amount of pressure and if there are any defects with a layer of the gasket it could result in an unexpected failure. QA methods need to be carefully considered when making any gaskets. Figure 13 below is an example of a gasket for a waterproof enclosure fabricated at the RDC.

Figure 13. 3D printed gasket (Author Photo).

A relatively new development in FDM is the introduction of continuous fibers into the thermo plastic. This allows the construction of thermoplastic materials with the strength of fiber composites. The MarkForged 3D printer uses a nylon filament material that must be carefully stored to ensure it does not get exposed to humidity as it will absorb the moisture and have reduced material properties. Keeping the nylon filament dry in a high humidity maritime environment could prove challenging. The new software from this manufacturer requires that all print jobs are processed and stored on the cloud which raises security concerns as well as potential connectivity issues if operated at sea. In March 2016 researchers from CDSA deployed on the POLAR STAR with a MarkForged Mark One and designed and printed a number of parts while underway between San Diego and Seattle. One of the items developed while underway was a Kevlar-reinforced bushing for the anti-rotation mechanism of the oil delivery box. There are still ongoing discussions to determine if the printed part can be approved for operational use by the cutter.

The RDC continues to operate several 3D printers in support of various ongoing projects. AM provides the ability to inexpensively design and print prototypes for research purposes. Figure 14 below is an example of an experimental float arrangement on a drift sensor in support of the office of Search and Rescue. 3D printing shortens the design cycle and advances the speed of innovation while reducing cost. AM has become an integral part of rapid prototyping in support of research and development.

Figure 14. RDC manufactured project parts (Photo: Art Allen, CG-SAR-1).

3.4 RDC's Additive Manufacturing Evaluation Project

In 2015, the RDC received a request to conduct research into how AM technology could be used across the Coast Guard. The RDC proposed a project that was segmented into two separate initiatives. The first objective was for personnel at the RDC to research the current state of AM to determine how future AM developments could benefit the Coast Guard. The second objective was to conduct desktop 3D printer evaluations at field units that expressed an interest in the technology. The participants in the evaluation would receive a 3D printer for a six month trial period in accordance with the RDC's Interim Authority to Test (IATT) procedures. By providing 3D printers on a trial basis, the personnel at the unit would have an opportunity to gain a better understanding of the capabilities and limitations of AM. Another benefit of conducting field evaluations is that RDC researchers would have operational level input on potential innovative applications of AM. The RDC documented the challenges faced by new 3D printer users as well as how the 3D printers were used in the field. As part of the evaluation, the RDC hosts a website on the Coast Guard Portal for 3D printing evaluators to communicate about lessons learned and technical issues they may be experiencing. The site also allows for the exchange of models developed at the evaluation sites. The following sections detail some of the experiences of participants in the RDC's 3D printer evaluations.

3.4.1 TRACEN Yorktown

The RDC has a long history of conducting tests and evaluations at the Coast Guards Training Center (TRACEN) in Yorktown, VA. The TRACEN provides training to new Coast Guard members on basic boat operations. Members of RDC staff were at TRACEN Yorktown conducting testing on diesel outboard engines and made contact with the Engineering Systems School. The Engineering Systems School provides training to prospective engineers about the operation and maintenance for cutter propulsion systems and auxiliary machinery. As part of the training, students receive a notebook computer that has most of the information they will need for the class (including detailed 3D models of machinery components). Many of the models are created by the TRACEN staff with CAD programs and 3D laser scanners. The staff also utilizes cutaways and scaled engineering models to help facilitate learning how these complex systems operate. The Engineering Systems School volunteered to participate in the RDC's 3D printer evaluation and print items from their extensive library of 3D-modeled machinery components. They received an Ultimaker 2+ Extended FDM 3D printer and an Ultimaker-specific version of open-source 3D printer slicing application called Cura to print their models. To date they have made several scaled assemblies that are used in the classroom to help students understand the inner workings of the machinery as well as how to assemble and disassemble them. One benefit to the scaled plastic models is that the weight is substantially less than some of the full scale metal parts; they can be easily handled in a classroom environment to educate students before they practice on the real parts. Figure 15 shows a fuel injector for a diesel engine. The picture on the top shows the 3D model as used in the training manual and the pictures below it show the 3D printed parts that make up the fuel injector and the assembled part. Figure 156 is a similar layout of a disk pack filter.

Figure 15. Fuel injector model and 3D printed parts (Photo: Ryan Delbridge, USCG).

Figure 16. Disk pack filter model and 3D printed parts (Photo: Ryan Delbridge, USCG).

Many lessons learned were provided by the evaluation at TRACEN Yorktown. Since most of their prints were scaled models of 3D scanned objects, they had difficulty printing some of the finer details of the larger objects. The evaluators also reported having difficulty with narrow, skinny parts printed upright that would shift and fail during printing. This failure could be caused by a number of factors but was most likely attributable to a loose pulley of the particular machine. The evaluators also noted that many of the larger parts took what they considered an excessive amount of time to print; some of the larger parts required more than a day to print. The TRACEN also reported that on a few prints, power was lost to the machine when it was not attended which resulted in losing the part. Managing print time and part resolution will continue to be an issue with FDM AM process. In accordance with IATT procedures TRACEN Yorktown has extended their initial six month evaluation period and is continuing to print training aides and scaled models.

3.4.2 TRACEN Petaluma

TRACEN Petaluma also received a MakerBot Replicator in the spring of 2016 to conduct a user evaluation. In addition to several small efforts, the evaluators used the 3D printer to develop new equipment for the National Security Cutter (NSC) bridge simulator. The bridge simulator allows Coast Guard personnel to practice the necessary functions of ship operation in a realistic but controlled training environment. The evaluators developed an alidade box that interacts with the simulator and allows the crew to take navigation bearings in conjunction with the larger digital displays used in the simulator. Figure 17 shows the completed alidade box as installed in the bridge simulator. All of the parts shown with the exception of the optical lens were 3D printed. A monocular was also developed that allows the crew to see a small area of the larger display in greater detail. Figure 18 shows the monocular that was developed and the numerous 3D printed parts which comprise it.

Figure 17. 3D printed simulation alidade box (Photo: Brian Dooley, USCG).

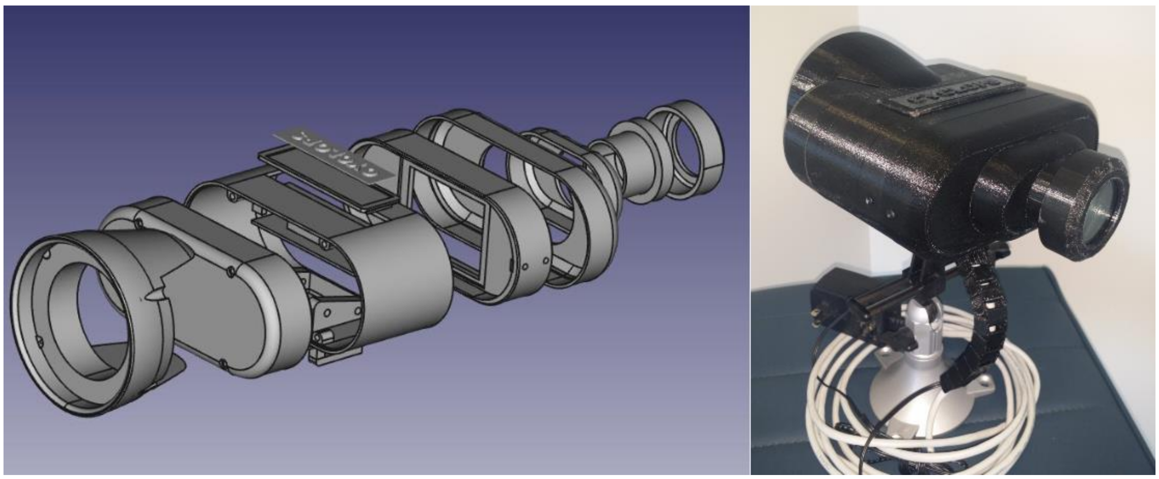

Figure 18. 3D printed simulation monocular (Photo: Brian Dooley, USCG).

In addition to the alidade and monocular, the evaluators designed and printed a multitude of unique items that resulted in savings for the TRACEN. The evaluators designed and printed an alarm door shim to properly align a door with its alarm sensor. By aligning the door themselves, they did not have to call a technician that cost the Coast Guard approximately $1,000 on each of the multiple previous visits needed to align the door. They also printed a "spare" display cabinet key that was no longer available for purchase from the original vendor. Other items printed include electronic device housings, bushings, and spacers as needed.

The evaluators noted that they were limited in the materials they could print because the MakerBot they were using did not have a heated print bed. The evaluators felt that if they had a heated print bed they could use more materials including ABS which would allow them to make a wider variety of objects.

3.4.3 Sector Columbia River

Sector Columbia River was independently researching the capabilities of 3D printing and found RDC personnel contact information in the IT acquisition request database. All Coast Guard IT purchases are logged and tracked; Sector Columbia River noted the RDC had purchased 3D printers and reached out to ask about their capabilities. After some brief discussions, the Damage Control (DC) shop that is responsible for much of the maintenance at the Sector volunteered to participate in the RDC's evaluation. The Sector received a MakerBot Replicator (5th Generation) printer and a laptop that had CAD software and MakerBot's proprietary 3D printer control software installed. The DC shop received the items for a six-month trial period in accordance with the RDC's IATT procedure. RDC personnel traveled to the Sector in the spring of 2016 to help install the printer and provide some basic instruction on its operation. Some of the personnel in the DC shop had CAD experience and one individual even operated a 3D printer at home for hobby purposes. The workload at the Sector can be very cyclical depending on weather and funding and initially the staff did not have enough slack in their schedule to devote to developing 3D models and printing them. During the evaluation, personnel with CAD and 3D printing experience transferred to a different unit and the remaining personnel did not have time available to learn new software due to the maintenance demands on the limited workforce. As a result, the 3D printer saw little use throughout the evaluation period. This evaluation highlighted the need for personnel with CAD experience or the time available for training.

3.4.4 SFLC

The Coast Guard's Surface Forces Logistics Center (SFLC) Engineering Services Division conducted a comparative analysis of three different 3D printers provided by the RDC as part of the evaluation effort. The first printer evaluated was a MakerBot Replicator (5th Generation) MakerBot. SFLC personnel reported having difficulty with the printer and a high percentage of failed builds during the three-month evaluation. The MakerBot was originally sent with a SmartExtruder that is the center of a class action lawsuit claiming the company knowingly sent a defective product on the Replicator (5th Generation) (Zaleski, 2016). A new MakerBot Smart Extruder+ was purchased from MakerBot at a 50 % discounted rate to replace the original Smart Extruder. After replacement the evaluators continued to have issue with the Replicator (5th Generation). Complaints centered on failed print jobs that sometimes resulted in the extruder being dislocated from its magnetic mounts and unexpected errors with the printer software. Another issue noted was with filament jams. Ultimately, the team printed third-party spool holders to better feed filament to the machine. During the evaluation the team printed several objects including scaled propellers, hull models, u-joints, and stern ramp models. The stern ramp models as seen in Figure 19 were used for visualizing the complex interactions between a cutter and a boat during launching and recovery operations.

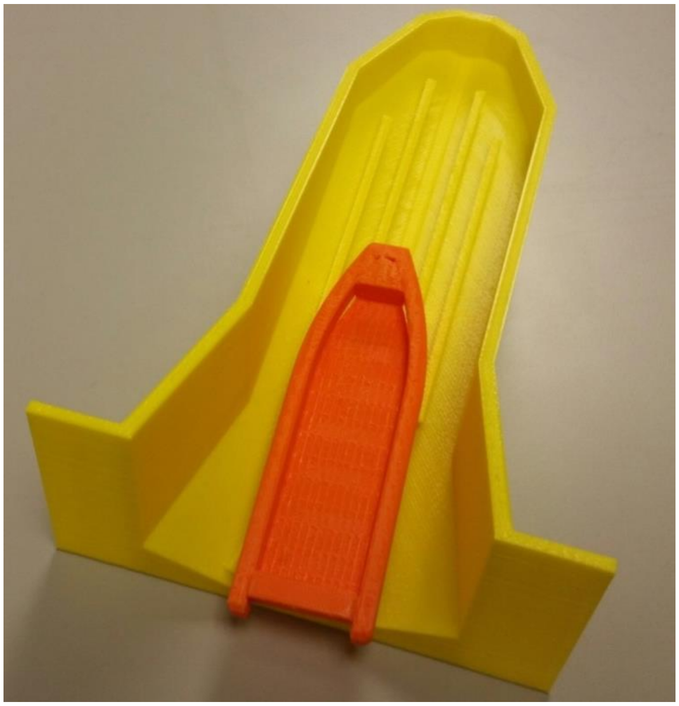

Figure 19. Cutter stern ramp and boat model (Photo: Ryan Roberts, SFLC).

The next 3D printer to be evaluated by SFLC was an Ultimaker 2+ Extended. The Ultimaker has a heated bed and can print a wider range of materials than the MakerBot Replicator (5th Generation). The Ultimaker also has a larger build volume and the evaluators used the increased size to print some relatively large models. One issue the evaluators reported was difficulty with manually leveling the print bed. Another issue they reported was that the printer could not be connected by USB and all prints had to be transferred by SD card which was cumbersome at times. The evaluators reported that the Ultimaker seemed to be more accurate than the MakerBot. Since both machines have various settings that can affect the accuracy, this statement is difficult to quantify. During this evaluation the evaluators printed several objects including a scaled accommodation ladder, adjustable cradle parts, and a crane lifting block assembly. The crane lifting block assembly as seen in Figure 20 was printed full size to help customers visualize a new design.

Figure 20. Full scale crane lifting block subassembly (Photo: Ryan Roberts, SFLC).

The last printer to be evaluated by SFLC was a MarkForged Mark Two. The MarkForged uses a nylon filament and has the capability to add continuous fibers to the filament at the print head. The continuous fibers can be fiberglass, , aramid fiber (commonly known as Kevlar), or carbon fiber. The fibers can increase the strength of a printed part substantially. One limitation is that the fibers can only be placed one layer at a time; this condition limits the orientation of the fibers that could potentially improve the strength of a part. The nylon filament can absorb moisture out of the air before it is used to print so it must be kept in an airtight box with a packet of desiccant. The biggest issue with the Mark Two reported by the evaluators is that the supporting software is web-based. In order to process a file for printing it must be submitted by the internet to the manufacturer’s website and then after processing on their software it is downloaded back to the machine for printing. This software could present some security issues and is difficult to use with existing Coast Guard network protocol.

Several of the same models were printed on all three machines for comparison throughout the evaluation. Although some minor differences were noted, for the most part all the parts were very accurate representations of the models. All of the machines have numerous settings that can dictate the quality of the print. If very thin layers and tight tolerances are required then the print will take a longer time. If a rougher surface finish is acceptable, thicker layers can be used to reduce the amount of time it will take to print. The importance of this paradigm became evident when making objects like the isolation mount gauges developed by the evaluators. The gauges are used for taking very accurate measurements and the 3D printer settings should be set such that the most accurate model will be produced. Figure 21 show the isolation mount gauges developed the SFLC and the high level of detail required for their accurate use.

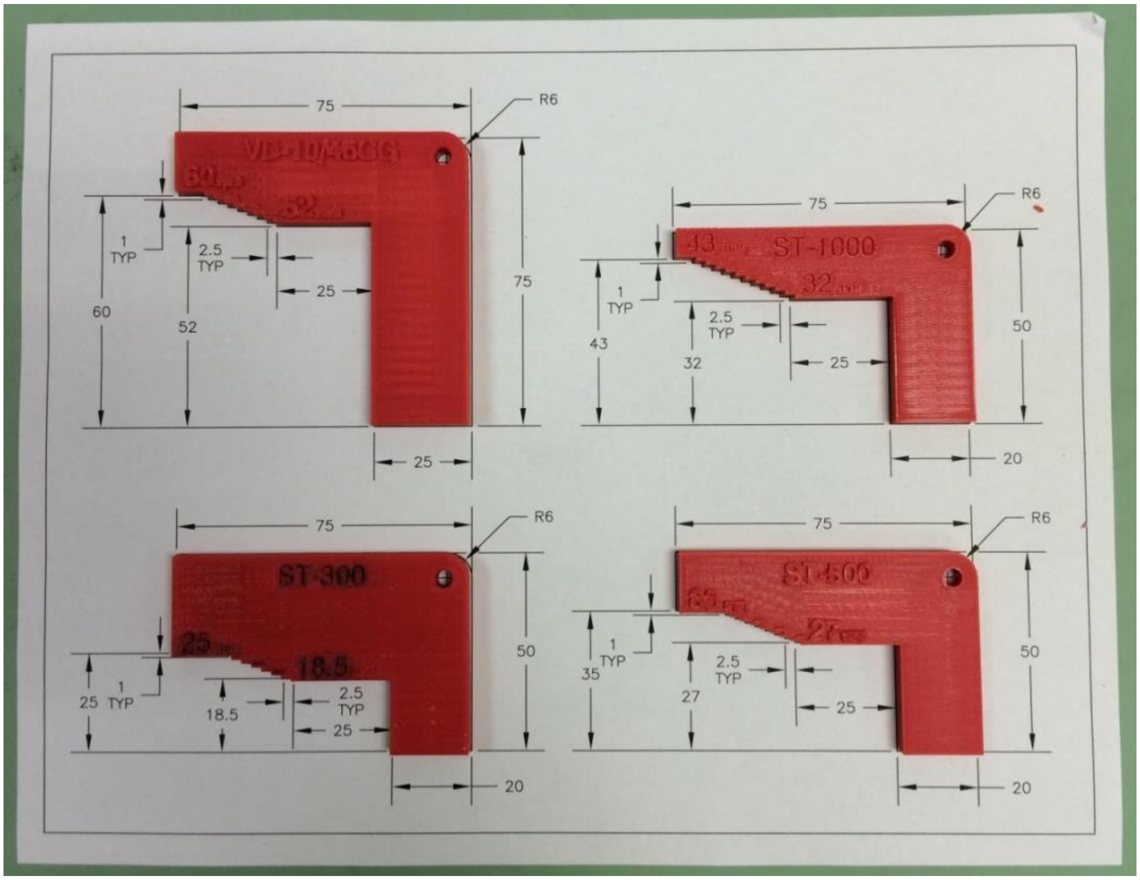

Figure 21. Isolation mount height gauges on top of drawing (Photo: Ryan Roberts, SFLC).

Other feedback provided by the evaluators indicated that self-leveling printer beds on FDM machines resulted in decreased print failures and increased part reliability. The 3D printers that required manual leveling had more failed prints (most likely the result of inaccurate manual leveling). The evaluators also preferred the open source Cura software over the proprietary software required to operate the MakerBot and Markforge. They noted that the software was easier for them to use and provided more intuitive control of the numerous parameters that can be adjusted in the software. The evaluators also experimented with several techniques to manage the first layer's bond with the printer bed. Some personal preference was noted, but no one method seemed to be more reliable than any other. Managing the first layer adhesion on FDM 3D printers continues to be an issue.

3.4.5 Base New Orleans

Base New Orleans received a MakerBot Replicator in late 2016 for evaluation. There were some initial issues with bad adhesion and several techniques were tried to achieve the proper adhesion. The MakerBot does not have a heated bed and managing the first layer adhesion to the bed can be challenging at times. The evaluators tried applying masking tape, washable glue sticks, and cleaning the OEM print bed with isopropyl alcohol. One of the most ambitious projects at Base New Orleans is the DC shop plan to make a large number of customized placards and signage for the entire base using the printer. This effort is expected to reduce cost and allow the evaluators to easily make changes to the placards and print replacement ones on demand. The evaluation is ongoing at Base New Orleans and wider application of 3D printing is expected as the evaluators become more experienced with both the CAD software and the capabilities of the printer.

3.4.6 Coast Guard Cutters

In early 2017, the project began to extend the 3D printer evaluations to afloat units. Project personnel began by working with the CGA to identify Junior Officers (JOs) that gained both 3D modeling experience and AM experience while enrolled at the Academy. The intent on seeking out JOs with relevant experience was to limit the amount of training required in order to accelerate the evaluation effort. Unlike previous temporary installations of 3D printers aboard cutters where RDC personnel operated the equipment, the ship's crew would be responsible for all design and manufacturing. As of April of 2017, four different cutters have 3D printers installed and several others have indicated a willingness to participate. RDC personnel traveled to each cutter to assist with the initial installation and provide some basic lessons learned on shipboard AM. Most of the parts printed to date are either focused on developing new innovations on existing tools or developing replacement parts for legacy items. One of the first items printed onboard the CGC SPENCER was a replacement switch handle for a 440V circuit breaker. The SPENCER has been afloat for 33 years and the shipyard where it was built has been out of business for 25 years. The crew provided many examples of hard-to-get items that could be good candidates for 3D printing while underway. The ability to print these legacy items on demand means the ship will likely realize some cost savings and improved logistical support. Figure 22 below shows a Lulzbot TAZ 6 being operated aboard the CGC SPENCER.

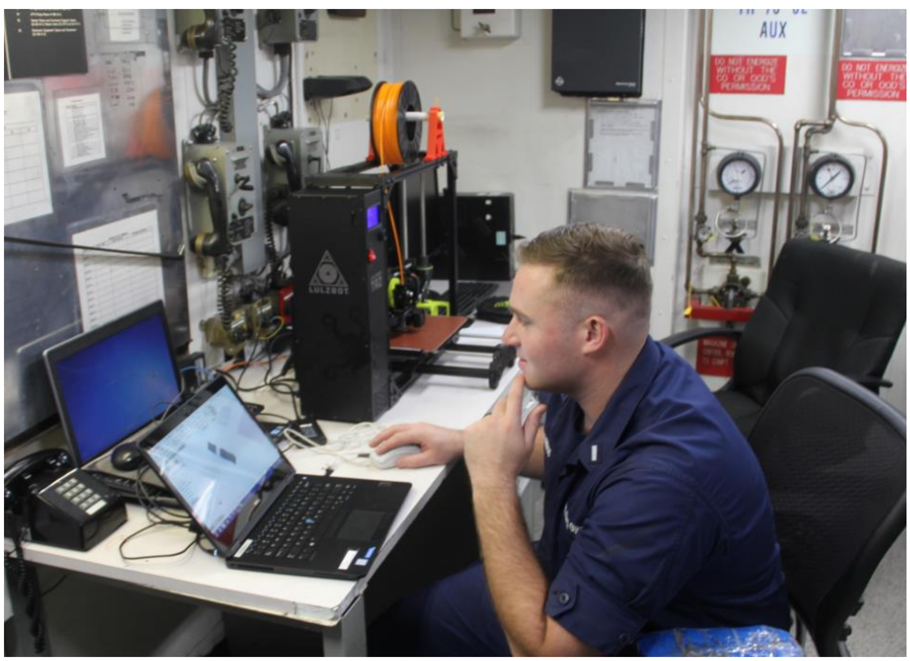

Figure 22. 3D printer aboard the CGC SPENCER (Author Photo).

The RDC research team is continuing to support AM evaluations aboard cutters. The ability to print new items while underway is a good example of how on-demand printing can benefit the Coast Guard. 3D printing parts for new applications or parts needed for repairs is an application that highlights many of the benefits of AM. 3D printers can provide unique solutions to unexpected problems that can happen at any time while underway. The current evaluations are focusing on thermoplastic printers because they are relatively low cost and do not require any modifications to the cutter for installation. The current evaluations are helping to gain knowledge about the capabilities and limitations of AM at sea. The inevitable next step is to extend AM at sea to metal materials. The RDC continues to monitor the constant improvements in the equipment and processes required for metal printing.

4 OTHER GOVERNMENT AM EFFORTS

There are several efforts ongoing to evaluate additive manufacturing. Every Department of Defense (DoD) component is actively pursuing AM capabilities that are applicable to their specific needs. The collective effort of the DoD research in AM is substantial. The Government Accountability Office (GAO) issued a report indicating that the DoD needs to improve collaboration between the components on AM efforts (Merritt, 2015). The GAO report recommended (and the DoD concurred) that they need to better track the activities and better disseminate the results. It is recommended that the Coast Guard continually seek opportunities to collaborate with DoD components on AM initiatives.

The Air Force has several bases with AM capabilities. Robins Air Force Base has been using 3D printing for prototyping parts since December 2014 and has realized up to $15,000 savings per part and saved hundreds of man hours (Gordon, 2015). Beyond prototyping, the Air Force is using AM for manufacturing rocket nozzles, circuit boards, and UAS components (Parker, 2015). The US Army is also very actively pursuing the benefits of AM. Many of the Army efforts focus on moving manufacturing into the field and empowering the soldiers on the ground to develop their own innovative solutions to unique and unforeseen problems encountered on the battlefield.

The Navy has also been investing substantial resources into AM capabilities and researching its application to the fleet. In January of 2106, the Navy issued an AM Implementation Plan that delineates the steps necessary to integrate AM across the Navy (DASN RDT&E, 2016). The implementation plan calls for the formalization of AM process, training, and equipment across several organizations within the Navy. In addition to shoreside applications, the Navy has also been evaluating the applicably of AM while at sea.

The Navy's first "Print the Fleet" was hosted by CDSA Dam Neck in June of 2013 to raise fleet awareness of AM. The first afloat installation of a 3D printer was on the LHD 2 ESSEX during a drydock period. The ESSEX went to sea with the 3D printer in the spring of 2014 for initial testing. Given the success of the initial testing, a 3D printer is permanently installed onboard the ESSEX (Gallagher, 2014). The initial 3D printer installed during the Navy's Print the Fleet demonstration was a Stratasys uPrint SE machine with an acquisition cost of approximately $34,000. In addition to the initial purchase cost, the 3D printer required a $4,000 per year service contract and consumable material usage was estimated to be $12,500 (O'Connor, 2014).

Another AM effort is the mini Fabrication Laboratory known as Fab Lab. A standard Fab Lab consists of two 3D printers, a desktop CNC machine, and large flat screen monitor. The KEARSARGE was the first vessel to receive a Fab Lab in September of 2015 (Wyatt, 2015). Other vessels with AM capability include the aircraft carrier HARRY S. TRUMAN and amphibious assault ship WASP. Figure 23 shows the two 3D printers installed on the TRUMAN as part of their Fab Lab. In July of 2016, NAVAIR marked the first flight of an MV-22B Osprey with a flight critical 3D printed part (NAVAIR, 2016). The part was a titanium link on the engine nacelle. NAVAIR is continuing testing and plans to print at least six other parts on operational aircraft for testing with in the year. The parts will be made out of titanium and stainless steel. Testing of flight critical parts will help identify and standardize the best processes and procedures for QA of 3D printed parts. The RDC worked with CDSA to arrange for the metal printing of three test parts for ALC on their metal 3D printers as part of a collaborative research initiative. As another sea-going service, the

Coast Guard could benefit from the lessons learned by the Navy and should continue to pursue mutually beneficial collaborations and strengthen existing lines of communication between the perspective services.

Figure 23. Fabrication lab aboard HARRY S. TRUMAN (U.S. Navy Photo).

Beyond the DoD there are other government entities that are conducting advanced research into AM technology. The RDC collaborated with DOE's Oakridge National Laboratory (ORNL) to learn more about some of the unique research in AM that is taking place at the facility (ORNL, 2017). Part of this collaborative effort included a personnel exchange where a researcher from ORNL went on a short deployment aboard a Coast Guard Fast Response Cutter (FRC) to better understand the challenges the Coast Guard faces at sea and an RDC engineer was 'embedded' at ORNL for a week to learn more about their AM research. Most of the time was spent at ORNL's Manufacturing Demonstration Facility (MDF) that houses several advanced AM machines. RDC's engineer was able to gain firsthand experience with several different metal AM techniques. ORNL has also pioneered printing large objects using Big Area Manufacturing (BAM) thermoset printers. BAM has been used to manufacture a number of very large items including several vehicles and even an entire house. In the spring of 2016, a CGA professor participated in a similar effort at Lawrence Livermore National Laboratory focusing on new methods in AM. The National Laboratories continue to conduct advanced research into AM as well as other Coast Guard relevant areas and opportunities for collaborations should be continually sought.

There are also opportunities for collaboration within the Department of Homeland Security (DHS). DHS has identified many potential applications for AM to improve the activities of its components. AM can be used to quickly make on-demand solutions for disaster response when time is critical. 3D printers are also being used for prototype development of tools and equipment to improve border security. As part of a strategic framework, DHS S&T seeks to revamp existing programs in AM to facilitate easier partnering with industry (DHS S&T Directorate, 2016). The Coast Guard has fostered good working relationships across the government with respect to AM research. Every effort should be made in the future to continue working with public and private organizations to ensure the Coast Guard will be able to quickly incorporate new technological advances in AM to their benefit.

5 CONCLUSIONS AND RECOMMENDATIONS

Recent developments in AM will have wide ranging implications for the Coast Guard. There continues to be substantial development in all areas of AM. New and improved materials for AM processes are being introduced almost daily. AM methods are continually being improved upon and the cost of AM equipment continues to trend downward. The Coast Guard has the potential to realize numerous benefits from the wider implementation of AM technology.

Wider application of AM technology could improve the operational efficiency of the Coast Guard. The ability to quickly manufacture spare parts means no need to stock as many spares, and a reduction in excess inventory. AM processes could be used to simplify logistical supply chains for low rate production items or for unique items that are not readily available. 3D printing has already been used by the RDC to provide material support for remote demonstrations in the Arctic. The printer was able to manufacture replacement parts that were damaged during testing. As this technology improves it is envisioned that many critical components (including metal) will be able to be manufactured on an as-needed basis in remote locations and aboard cutters at sea. There are currently a number of obstacles preventing the practical operation of metal AM machines on cutters. However, with the constant improvements in 3D printing equipment and additional advances in the processes, metal 3D printers will soon be a more feasible option.

The RDC and their evaluation participants have shown that AM equipment can be used to reduce cost. The ability to quickly manufacturer prototypes and small parts could revolutionize the logistics and translate directly into cost savings. The RDC has previously used a 3D printer to reduce project expenditures by designing and building prototypes in-house. Some of the participants in the 3D printer evaluation have used them to make replacements for parts that are no longer manufactured. 3D printers can be used to help reduce the cost of supporting the Coast Guard's aging cutters, infrastructure, and other equipment.

An important step towards wider acceptance of AM is to develop the process to qualify 3D printed parts for operational use. As discussed in this report, there are several aspects that need to be considered when designing components for AM. ALC has laid the framework for AM part qualification in ALC INST 13020.10B. This document provides a flow chart to assist the manufacturer in the approval requirements for in-house 3D printing. The Coast Guard should formalize the requirements for 3D printing parts defining material specifications, quality assurance requirements, and the necessary approvals required before a 3D printed part can be used for an operational need.

Another important milestone for the further implementation of AM is for Coast Guard personnel to be properly trained in the required skills. The RDC's 3D printer evaluation project has shown that few Coast Guard enlisted personnel have the CAD modeling skills that are need to develop the models of objects before they are printed. One potential solution is introducing AM training curricula at the Coast Guard's TRACENs. The Coast Guard could introduction AM and the CAD training needed for AM model building into the general A School or incorporate it in specific C Schools. Officers receiving an engineering education at the CGA do receive exposure to the AM processes and experience with CAD modeling. The Coast Guard should consider formalizing the training requirements and certifications needed to operate AM equipment for operational use.

A starting point for the wider implementation of AM in the Coast Guard is the development of a roadmap outlining the steps necessary to move forward with AM integration. The roadmap will identify the actions that need to be taken so the Coast Guard can benefit from this revolutionary technology. The roadmap should address such topics as part qualification, management of data rights, quality assurance requirements, and personnel training and certification. Identification of a Program Office be identified - most likely in the Engineering & Logistics Directorate (CG–4) – is recommended to take the lead on the potential adoption of AM technology within the Coast Guard and assist in development of an AM roadmap. The roadmap will help decision makers determine where investments should be made to ensure that the Coast Guard is positioned to realize maximum benefit from new developments in AM.

6 REFERENCES

3D Systems. (n.d.). *3D Systems DMP Spec Sheet*. Retrieved 2017 2017, from www.3dsystems.com

Apparatus and Methods for Creating Three-Dimensional Objects. (1992). *Patent No. 121329 A.* USA.

ASTM 52900-15. (2013, September). *Standard Terminology for Additive Manufacturing – General Principles – Terminology*. Retrieved from ASTM International.

Carbon. (n.d.). Retrieved March 2017, from Carbon 3D : www.carbon3d.com

DASN RDT&E. (2016). *Department of the Navy (DON) Additive Manufacturing (AM) Implementation Plan.* DASN RDT&E.

DHS Science and Technology Directorate. (2016, March). *DHS Science and Technology Directorate Strategic Plan 2015*. Retrieved from Homeland Security: www.dhs.gov

Functionalize. (n.d.). Retrieved January 2017, from Functionalize Personal Industrial Revolution: www.functionalize.com

Gallagher, S. (2014, February). *Essex Leaves an Imprint on Fleet Readiness*. Retrieved January 2017, from America's Navy: www.navy.mil

Gordon, J. (2015, January 30). *3-D printer creates models that save time, money*. Retrieved January 2017, from U.S. Air Force: www.af.mil

GSA Advantage. (n.d.). *ProX 100 Direct Metal 3D Printer, Part No. 3DS-5004721h00, Synnex Corporation,*. Retrieved February 2017, from Contract No. GS-35F-0143R : http://www.gsaadvantage.gov

GSA Advantage. (n.d.). *SOLIDWORKS Standard, Part No. SWX0024, Lyme Computer Systems.* Retrieved February 2017, from Contract No. GS-35F-4754G : http://www.gsaadvantage.gov

ISO/ASTM 52915:2016. (2016). *Specification for additive manufacturing file format (AMF) Version 1.2.*

Kellner, T. (2015, April 14). *The FAA Cleared the First 3D Printed Part to Fly in a Commercial Jet Engine from GE.* Retrieved 2017, from GE Reports: www.gereports.com

Kenney, M. (2013). *Cost Reduction Through the Use of Additive Manufacturing.* Naval Postgraduate School.

Lambeth, J. *USCGC Polar Star Additive Manufacturing At-Sea Experiment.* unpublished.

Merritt, Z. (2015, October 14). *Defense Additive Manufacturing: DoD Needs to Systematically Track Department-wide 3D Printing Efforts*. Retrieved February 2017, from U.S. Government Accountability Office (GAO): www.gao.gov

NAVAIR. (2016, July). *NAVAIR marks first flight with 3-D printed, safety-critical parts*. Retrieved February 2017, from Naval Air Systems Command NAVAIR News: www.navair.navy.mil

Oak Ridge National Laboratory. (2017). *Inovations in Manufacturing.* www.ornl.gov.

O'Connor, C. (2014). *Navy Additive Manufacturing: Policy Analysis for Future DLA Material Support.* Naval Postgraduate School.

Parker, J. (2015, October) *Planning a Larger Role for 3D Printing*, from U.S. Air Force News website, http://www.af.mil/News.aspx

Polar 3D. (Polar 3D). Retrieved Februuary 2017, from www.polar3d.com

RepRap Morgan . (n.d.). Retrieved January 2017, from RepRap Morgan : www.reprap.org

Sterolithography, A. f. (1986). *Patent No. 4575300 A.* USA.

Stratasys Ltd. (n.d.). *FDM Thermoplastics*. Retrieved February 2017, from Stratasys Thermoplastcics : wwwStratasys.com

U.S. Copyright Office . (n.d.). *Copyright in General* . Retrieved March 2017, from U.S. Copyright Office : www.copyright.gov

U.S. Patent and Trademark Office . (n.d.). *General Information Concerning Patents*. Retrieved March 2017, from U.S. Patent and Trademark Office : www.uspto.gov

Wyatt, C. (2015, October). *Kearsarge gets Navy's First Afloat Fab Lab*. Retrieved January 2017, from America's Navy: www.navy.mil

Zaleski, A. (2016, January). MakerBot Replaces Crucial – and Flawed- 3D Printer Part. *Fortune*.