



**UNITED STATES AIR FORCE CIVIL ENGINEERING ADDITIVE
MANUFACTURING APPLICATIONS: TOOLS AND JIGS**

THESIS

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**DEPARTMENT OF THE AIR FORCE
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THESIS

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Captain, USAF

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Abstract

Additive manufacturing is a technology revolutionizing the manufacturing industry. By creating three-dimensional objects from the ground up, the technology does away with the traditional manufacturing methods used to design and create products. This research examines the application of additive manufacturing (AM) to fabricate tools and jigs in United States Air Force civil engineering (CE) operations. Within this research, numerous parts were designed and printed for use within CE operations. After testing of the parts, a usability survey was conducted to validate the need and potential for AM within a CE unit.

The results of the part testing and the resultant survey indicate that AM will definitely impact the daily operations of a CE unit and that a clear need exists for the use of AM. Further, the research determined that AM has reached a point that the integration of AM into strategically coordinated units, along with proper education and training, can be beneficial for the CE career field. Finally, the results indicate that 3D scanning technology will reach a point within the next 5 years where it can help foster the rapid build-up of 3D CE asset designs for printing applications. The overall results push forward the Air Force's 3D printing capability while providing critical information for decision-makers on this up-and-coming technology.

Dedication

“I can do all things through Christ, who strengthens me” – Philippians 4:13

My thesis is dedicated to my bride and newborn son. I could not have done it without the constant support at home and the understanding during the late nights of studying and writing. Also, thanks to my parents for instilling in me a drive to push through tough times and always give my all in everything.

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Bradford L. Shields

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UNITED STATES AIR FORCE ADDITIVE MANUFACTURING APPLICATIONS FOR CIVIL ENGINEER TOOLS AND JIGS

“If we could make a whole car door in less than a minute without any tooling and change it by just changing the computer, I think we would revolutionize the way industry works.”

- Mr. Chuck Hull, 1989 on *Good Morning America*

I. Introduction

An innovative technology rarely influences a drastic change in processes and procedures across numerous industries like that of the potential impact of Additive Manufacturing. Additive manufacturing (AM), more commonly known as three-dimensional (3D) printing, creates a desired product by additively bonding extremely thin, successive layers together. Deemed a disruptive technology, AM contains the potential to displace established technology and eventually shake up or create a completely new industry (Campbell & Ivanova, 2013). AM provides a more flexible and convenient approach to manufacturing, while ignoring the concept of economies of scale. Contrary to traditional manufacturing, which relies heavily upon economies of scale, AM enables customized prints and low-volume production. Historically, traditional manufacturing companies achieve lower unit costs and make higher profits by focusing on the production of larger quantities of one product; however, AM’s flexibility in changing product designs facilitates a consistent unit cost for producing an item. For use in both deployed and home station operations, the United States Air Force (USAF) civil engineering (CE) community intends to harness the transformational characteristics of AM (AFRL, 2011). By gaining a thorough understanding of the potential benefits of

AM, the USAF CE community looks to identify, through this research and other research streams, the potential of AM as a ground-breaking technology capable of solving a number of the paramount problems accompanying a time of aging infrastructure and stricter budgets.

Background

USAF civil engineers stationed on Air Force bases throughout the United States and abroad readily provide the capability for the construction, operation, maintenance, repair, and disposal of base assets and infrastructure systems. Engineers maintain an assorted range of infrastructure including, but not limited to, facilities, roads, runways, water distribution, electrical distribution, and grounds maintenance. Infrastructure systems requiring maintenance by USAF engineers comprise both large primary bases and smaller secondary bases, which are often located in remote and austere areas.

The Air Force civil engineer of today maintains an aging infrastructure, which poses unique and significant challenges. One of the various tests facing Airman Engineers—and the focus of this research—is the ready supply of unique tools and parts required for infrastructure maintenance activities. The Air Force’s need for rapidly deployable engineering units limits accessibility in the event of a unit needing a singular tool or part. The Air Force’s aging infrastructure, as well as companies’ no longer carrying parts for older model items, results in engineers retrofitting resources and affecting the efficiency and reliability of critical assets. Aging infrastructure requires extra maintenance or new replacement systems. The extra time and money spent

repairing degraded assets and purchasing new systems hinders the overall ability of the civil engineering unit.

The vast amount of time and money spent ordering a part and shipping it to any location around the world is a byproduct of the traditional manufacturing process. Traditional manufacturing processes, invented by the likes of John D. Rockefeller, Andrew Carnegie, and Henry Ford in the height of the industrial revolution in the late 1800s and early 1900s, succeeded based on concepts known as the economies of scope and of scale (Audretsch, 2009). Economy of scope establishes the fact that the “cost associated with the producing multiple products simultaneously is often less than the costs associated with producing each product line independently” (Economies of Scope, 2015). For example, Smith Industries produces all the brakes for Car Company XYZ. Based on economies of scope, Smith Industries realizes by manufacturing calipers and rotors, it would cost them less per unit compared to companies solely manufacturing the rotors or solely the calipers. Economies of scale ascertain that it is cheaper per unit to produce one thousand parts compared to the production of only one part. By distributing the overhead costs over all the parts produced, the overall unit cost decreases as the quantity increases.

The overhead costs include the operation and maintenance of all equipment, as well as the development costs of equipment to produce the part and the logistics of shipping the parts around the world. Getting the part to its final location is an entirely separate issue due to the significant time and costs incurred. The resultant amount of time and money spent during the production, shipment, and delivery of a part results in significant losses in efficiency for US Air Force manufacturing needs. The overall

process holds the customer hostage by limiting the types of products available on the market, production capacity of the product, and shipping speed to the customer's location. An onsite technology capable of rapidly producing individual designs for needed parts would greatly reduce the lead time required by the US Air Force for the maintenance of their infrastructure assets.

An up and coming technology capable of quickly manufacturing distinct three dimensional designs is *additive manufacturing*. Additive manufacturing, more commonly known as 3D printing, is defined by Prince (2014) as the creation of physical models through the process of additively constructing objects in three dimensions by bonding material in successive, thin layers. Unlike traditional manufacturing, which mills or cuts down a block of material to form a product or prototype and wastes a majority of the material, AM results in a product that is built "from the ground up." AM allows more precision and flexibility in the design and structure of manufactured parts, resulting in less waste, more-efficient designs, and easy changes to prototypes. A single machine harnesses the capability to print thousands of different tools, parts, and custom designs.

While AM carries the potential to print items already in production through traditional methods, the real potential is in the flexibility of developing new solutions to problems and processes used in situations where parts are hard to find, the location is austere, or where a solution is needed quickly. For example, AM allows for the creation of simple new devices resulting in more-efficient and -expedient work. Devices created for this purpose are referred to as jigs, which are more commonly created with the purpose of holding a tool in an exact location for the user or acting as a guide for a

specific tool when performing a specialized task. The creation of jigs enables a more efficient process for any user. The amount of research conducted within the DoD is minimal in regards to the applications for civil engineers. Based on the proven results from the implementation of 3D printing in other career fields, this technology has the potential to expose the US Air Force civil engineering community to a broad new range of jigs previously too impractical to design and produce. Overall, the realization, understanding, and application of AM will result in the ability to customize and print tools and parts, leading to a more efficient maintenance process for Air Force facilities and infrastructure.

Problem Statement

While the use of 3D printers has been proven in other civilian industry career fields, including automobile maintenance and basic manufacturing, research on possible applications within the CE operational realm has yet to be conducted. Value, as defined by The definitive value of including a 3D printer within a CE unit for the printing of tools, jigs, and parts is still to be determined. The selection of a candidate tool list, based on the product's suitability for more efficient manufacture through AM, is a necessary first step in developing a viable business case analysis for the inclusion of a 3D printer in CE units. Additionally, it is not certain that current technology has reached a point at which 3D printers are suitable for this application. The sponsor for this thesis, the Air Force Civil Engineer Center (AFCEC), determined these problems are valid and warrant further investigation. AFCEC sponsored this research to explore possible applications of 3D printers in building USAF civil engineering tools and jigs.

Research Objective and Investigative Questions

Determining the actual value of AM, which is the overall objective of the research, consists of establishing the need and subsequent usability of AM within USAF CE units for devising tools and jigs. The analysis of four specific investigative questions enables the overall research to provide a more complete analysis.

1. *What added value does 3D printing bring to USAF civil engineering?*

This question explores the benefits and advantages of 3D printing through a detailed exploration of current applications, within both the civilian and military sector, by members who are utilizing additive manufacturing technology and have similar operations to a USAF civil engineering unit.

2. *What attributes make a tool or jig a good candidate to be manufactured using additive manufacturing?*

This question explores the characteristics of a tool or jig that allow more efficient manufacture of it using 3D printing instead of traditional manufacturing methods.

3. *Can questionnaires about a select few printed tools and jigs be used to illustrate the value of 3D printing over traditional manufacturing?*

This question is designed to estimate how applicable the values found within the civilian sector for 3D printing are to USAF operations.

4. *How is usability defined and measured in the context of designing and printing jigs?*

By surveying users of 3D-printed parts and tools, this investigative question weighs the benefit of having a 3D printer for the purpose of designing and printing

custom jigs within the unit. Defining the term *usability* both provides both a method for measuring the term and a validation test for 3D printing within CE units.

Together, the four investigative questions define the goal of the overall thesis effort. The questions shape the direction of the literature review, the methodology, and the final analysis. These questions will be referenced later in this thesis in discussion of the methodology and results.

Research Overview

The organization of the remainder of this thesis follows. Chapter II, the literature review, outlines the state of 3D printing technologies and how those technologies impact traditional manufacturing processes. Current machine types being used in industry, as well as their benefits and limitations, are examined. Additionally, an overview presents literature concerning past and current applications of 3D printers to manufacture tools and jigs. The conclusion of the chapter examines current civilian companies who are comparable to a USAF civil engineering squadron and currently utilize AM. The analysis of the companies identifies the benefits AM currently brings to their operations. The in-depth review of civilian firms using 3D printing provides a breakdown of whether the same benefits and advantages would be experienced within a military CE squadron.

Chapter III lays out the method for measuring the usability and value of AM within an operational CE unit. The design and printing of jigs, previously defined as devices designed to hold a tool in an exact location for the user or act as a guide for a tool when performing a specific task, complements the research on tools. The development of

a jig is normally the result of an experienced technician's realizing that a simple device has the potential to make a process more efficient. This research identifies several processes within CE that a jig could expedite or make more capable. Through a detailed analysis of processes, as well as input from each of the shop leaders within each CE operations shop, three to five separate processes will be identified as candidates to be made more efficient through the design and use of a jig. Following a very specific systems engineering methodology, the designer of each jig works through a process of identifying the requirements, identifying the stakeholder's needs, initial design, development of a prototype, testing of the prototype, and then changes to the initial design. Each jig design procedure continues through the development, testing, and modification progression until the design is perfected.

Chapter III concludes by determining how to appropriately measure the value of a 3D printed product to a CE unit. Through a measure of the product's utility and durability, as well as the flexibility of the design and print process, the added value and usability of the part within an operational CE unit will be determined. The importance of the design and printing of the tools and jigs plays a unique role in proving the usefulness of AM. While tools with common characteristics may prove to be more efficiently manufactured through traditional manufacturing methods, successes within industry and other military organizations proves that additive manufacturing has the potential to solve unique problems facing the Air Force today. The key to unlocking that potential is to collaborate with those in industry who are investing in this new technology and to work diligently to identify every prospective application for additive manufacturing within Air Force CE operations.

If AM is correctly inserted into the right processes, the data looks to prove in Chapter IV that AM has the ability to make processes more efficient and change how operations are carried out. Using the data to analyze cost estimates, material quantities, customizability, and print time for a series of devices generated as examples will determine the added benefit, if any, that 3D printing technologies confer to the USAF civil engineering community.

Chapter V discusses the accuracy of information gathered from the usability survey, as well as performance of the printed tools. Comparison of the data between current processes and AM processes will identify factors signaling circumstances in which 3D printing will contribute added value to operations within a CE unit. These findings illustrate the future possibilities for 3D printing in Air Force civil engineering, as well as other maintenance and construction applications. In conclusion, the research evaluates the extent to which current 3D printing technology can benefit the USAF civil engineering community.

Research Limitations

The strength characteristics and properties of construction materials have been studied and are well established for all engineering designs; however, the material properties of 3D printed resources have not been established. The design of all products within this research is based on the designer's best judgment for strength. No strength tests were carried out on the final products. Additionally, research lacks a concrete decision as to the specific type of 3D printer best suited for the printing of tools.

Many tools in use by USAF engineers within operational settings are governed by occupational safety and health regulations including, but not limited to, the National Electrical Code (NEC®) or the International Fire Code (IFC); therefore, outside approval is needed for the use of certain tools in an operational environment. Due to the newness of the technology, the uncertainty in the material characteristics, and the difficulty in regulating printed parts, neither one of these authorities has reviewed or approved any tools or jigs printed via AM to date. If USAF CE were to use AM for uses other than emergency practices and the printing of prototypes, any tools printed would have to pass the necessary safety inspections and regulations.

II. Literature Review

Chapter Overview

Chapter II outlines all previous research on additive manufacturing with a detailed focus on additive manufacturing for military construction and the civil engineering industry. Based on the methodology for the research, the chapter includes an in-depth review of the methods and processes within traditional manufacturing, as well as the advantages and disadvantages each process brings to the manufacturing industry. After developing an understanding of the advantages and disadvantages of traditional and additive manufacturing, the chapter dives into the systems engineering design process for product development. In order to measure the success of a systems engineering design, the chapter concludes by defining usability and outlining its components. Overall, this chapter covers prior information necessary to fully understand existing research, the research for this thesis, and conclusions discussed in this document.

Traditional Manufacturing

What is Traditional Manufacturing?

The development of traditional manufacturing methods occurred at the turn of the 20th century when the concept of mass production was first being developed. Although technology has improved the efficiency and tools used within each of the processes, the traditional manufacturing process still relies on the original core principles of mass production. The National Academy of Engineering defines manufacturing as “the human transformation of materials from one form to another” (NRC, 1998). The transformation of a material affects both the composition and geometry of the product, depending on the

overall design and material being used. Whether a product is made of synthetic or naturally occurring raw materials, all discrete parts are made using a series of specific steps. Four different categories of manufacturing are defined: casting or molding, forming, machining, and joining (Rhoades, 2005). The four manufacturing groups make up what is commonly known as the traditional manufacturing process.

Casting or Molding

The production of an item through casting or molding requires an object be transformed from a liquid to a solid. Normally a metal or plastic, the material in liquid form is poured or injected into a prefabricated mold and allowed to solidify (Rhoades, 2005). Depending on the material, solidification takes place through heating or cooling the liquid. Once the item is completely solid, it is removed from the mold and post-processed by completing final touch ups and adding aesthetic details (Rhoades, 2005). The mold is normally made from a metal with a higher melting temperature than the liquid being used. Most molds can be used more than once, but some are made to be disposable and destroyed during removal of the solidified object (Rhoades, 2005). Initial molds allow for no flexibility or changes in the product and typically take time to create.

Forming

Forming is the process of “applying a force, and sometimes heat, to reshape and cut a ductile material by stamping, forging, extruding, or rolling” (Rhoades, 2005). The metal or material being used is plastically deformed to shape it into a desired geometry (Metal Forming, 2015). The three main types of material forming are called cold working, warm working, and hot working. The types of forming are based on the temperature at which the forming occurs. Cold working is done at room temperature and

uses the least energy to complete. Higher temperatures change the stress and strain characteristics of the material, especially metals. As a result, warm and hot forming are more common in manufacture of custom construction materials and other specialized manufacturing industries. Each process still uses a vast amount of energy, and the entire progression takes a great deal of time from beginning to end (Metal Forming, 2015).

Machining

Machining is the process of cutting specific features or removing material from a larger, more generic block of material. The process of machining covers numerous different types of machining; however, the most common and traditional types are turning, milling, drilling, and grinding (Machining Processes, 2015). Through the use of a fast-moving cutting tool, usually computer-controlled, the larger block is carved down into a desired shape or geometry. Since the object being cut is normally a metal or hard material, the cutting tool is subject to significant wear and tear. The machine programmer and the designer must take into account the specific “cutting paths” the machine is capable of, and compensate for the wearing down of the tool (Rhoades, 2005). The specific cutting path of the machine limits the possible geometries of the product, and therefore, does not allow for products to be efficiently produced based on shape or material optimization.

Joining

Joining is the process of welding, brazing, and mechanically assembling parts to create a more complex part than would otherwise be possible through the methods of molding, forming, and machining (Rhoades, 2005). Normally, joining requires special tools or programming to ensure adjoining features are correctly assembled. It is also very

common for parts of a product to go through the process of casting, forming, or machining, and then be sent to a specialized worker to join the final product together. Typically, mechanical fasteners, such as bolts, are the cheapest method for assembling parts; but, depending on the product, it is not always feasible and welding, brazing, or soldering must occur (Metal Manufacturing: Joining and Assembly Processes, 2015). No matter the type of assembly required, the process takes time and costs additional money.

How are the Four Types of Manufacturing Limited?

The limited selection of manufacturing processes does not allow for flexible designs or quick, inexpensive production. Each type of manufacturing has its bottleneck process that inevitably takes a lengthy amount of time and requires extremely rigid, geometrically friendly designs that are neither topically optimized nor unique. The significant constraints of time, resources, and cost limit any company's ability to manufacture and provide uniquely designed products to the community. It is due to these constraints that design companies must consider the limited manufacturing processes at every aspect of the design and production life cycle.

Creating a Product from Traditional Manufacturing: Start to Finish

The development of a prototype begins with the identification of the stakeholder's final product requirements. The requirements drive the initial design of the product. After the requirements are identified, the constraints of the equipment and manufacturing process are taken into account. The manufacturing constraints include limited materials available for use, material properties, and flexibility of product and mold design. Furthermore, during the design process, an analysis of the initial requirements is conducted to possibly meet other stakeholder requirements and allow for mass production, which will

bring down the product's unit cost (Rhoades, 2005). Too many stakeholders can sometimes lead to requirements creep and a dilution of the actual requirements from the initial stakeholder. An example of requirements creep can be seen in the design of the F-111 fighter aircraft. Three branches of the US military were tasked to develop one jet for multifunctional use; however, each branch had its own needs. The end result was millions of dollars spent on an aircraft that only partially met the needs of the three military branches and the plane was retired soon after production (Richey, 2005).

Once the initial design is created, a prototype is created using modeling clay or some other easily moldable material. The costs associated with making simple changes to a product after the initial design can be prohibitive; therefore, the initial design is heavily analyzed before any product is created or tested. Even creation of a prototype for testing involves serious manufacturing expenses, which inhibits flexibility in design due to the cost of making small changes prior to production. Once testing has occurred, the product is ready for mass production.

The method of choosing a manufacturing process depends on the product being manufactured and the desired properties of the item. Due to the numerous studies and evaluations conducted on each process using countless materials, the consistency of the processes is extremely reliable (Rhoades, 2005). In the event of casting being the process chosen, molds are developed for the product and assembly techniques are fleshed out. Forming requires that machinery be calibrated to the specific dimensions of the product. Machining operations are programmed and tools are chosen to ensure precise cuts. Each of these processes requires a significant amount of preparation time prior to products actually rolling off the line. The product design and machine setup stages can take many

months or even years but; once complete, the actual product is ready to be produced in mass quantity. Once produced, the products are shipped, sometimes great distances, to customers who are willing to purchase them (Rhoades, 2005).

When analyzing a product to compare manufacturing methods, the whole cost of the product— meaning design, manufacturing, shipping, and storage—must be taken into account. Based on this “whole cost” approach, Rhoades (2005) suggested that the manufacturing definition be changed to “the creation of value through the transformation of materials from one form to another and the delivery of that more valuable product to a buyer.” With traditional manufacturing methods requiring an immense amount of time and cost, what benefit do they actually provide?

What Value Does Traditional Manufacturing Create?

The intent of the research is to measure the value of AM. The Library of Manufacturing defines the value of traditional manufacturing for companies through certain performance criteria. The performance measures for determining the value of all manufacturing processes include (Manufacturing Basics, 2015):

1. Meeting performance requirements (i.e., tolerances, strength, weight, etc.)
2. Meeting cost of production requirements
3. Reproducing constant quality during mass production
4. Uniform material properties throughout manufactured components.

To justify all the up-front overhead costs—including designing, tooling, installing, and calibrating the production lines and equipment—production volumes must be sufficient to produce a reasonable per-unit cost (Rhoades, 2005). Traditional manufacturing

capabilities are perfect for products manufactured in large quantities with little to no changes in design or functionality.

Disadvantages of Traditional Manufacturing?

With the implementation of computers and automation within the manufacturing industry, the processes have become more precise, timelines are accelerated, and lower production costs occur (Rhoades, 2005); however, traditional manufacturing will never be able to affordably produce customized, low-volume products on an individual basis. The inability of traditional manufacturing to efficiently produce low volume, highly customizable products is exactly the reason why new technologies, which have the ability to efficiently produce low volume, highly customizable products, will be able to compete.

These disadvantages are a result of a lack of design flexibility, extreme up-front costs, significant labor wage gaps, and a lack of investment. Products in today's market require customization based on the customer and efficient use of materials. Traditional manufacturing techniques are unable to meet these demands.

High-volume production sometimes has hundreds of steps in the cycle and therefore limits the ability of the manufacturer or designer to make any changes to the design (Rhoades, 2005). Even with the concept of "extended enterprise supply chains," which farms out pieces of a large assembly to smaller factories, the large up-front costs and time lost prohibits any ability to change even a small part. As a result of the changing technology and consumer demand, manufacturers have fought to achieve a balance between scale of production and flexibility. On top of these problems, developed countries are facing an uphill battle against countries with nonindustrial, low labor rates.

The United States, which used to be the manufacturing capital of the world, has lost 2.5 million manufacturing jobs since the year 2000. Countries such as China, India, Indonesia, Brazil, Russia, Bangladesh, and Mexico have worker wages equal to 10% of what a worker in the U.S. would make. Due to this disparity in labor rates, more than half the vehicles sold in the U.S. are produced elsewhere and 2/3 of all machine tools are imported (Bonvillian, 2004). Both of these markets used to be owned by the United States, but are now significantly reliant upon imports. Given all the steps in the traditional manufacturing process, wages play a huge role in determining whether a company can make a profit or not.

Another major cost in the overhead of a traditional manufacturing company is the transportation costs of their product. Data collected by the U.S. Bureau of Transportation during the most recent comprehensive nationwide freight assessment in 2002 estimates that 16 billion tons of raw materials and finished goods were transported yearly throughout the United States at a value of \$11 trillion. With an average annual growth of 1.9% in tonnage, this projected that by 2015 approximately 20 billion tons will be transported on an annual basis. (Statistics, 2015). Based on the data highlights, the cost per ton of a shipment has been on the rise for the last 20 years, thereby prompting manufacturers to reassess their logistics. The cost per ton per day of manufactured goods sitting in port or getting caught in customs becomes extremely costly, especially for manufacturers making high-value goods; therefore, more and more manufacturers are shipping lighter loads and using faster, more expensive modes of travel. The average time to move the equivalent of 1 truckload 1000 miles by air, highway, rail, and water is 2 hours, 2 days, 1 day, and 5 days, respectively (FDOT, 2008). Between 1993 and 2002,

the average shipment doubled in distance, causing the ton-miles transported by air to increase 46% over that time. In contrast, trucking increased 26%, rail 20%, and water transportation decreased 17% (Statistics, 2015). Even with the increase in air freight, it remains 12 to 16 times more expensive than water transportation, as well as 6 to 10 times more expensive than rail or truck. With the increases in transportation tonnage and fuel costs, the cost of transportation per ton steadily increases and continues to climb. In the 2008, the cost per ton-mile for air, highway, rail, and water freight was \$133.23, \$42.38, \$3.70, and \$1.16, respectively (FDOT, 2008). The continual shift toward the production of high-value and light-weight goods requires companies to have a production capability that allows a customizable and flexible design and manufacturing process. With the Internet and a more efficient supply chain, “just in time” deliveries allow companies to keep less storage and product inventory; while, also fostering the ability to send products greater distances in a shorter amount of time.

Overall, the traditional manufacturing process depends on low unit costs. The world is moving toward “just-in-time” manufacturing, which is the production of parts just as the customer needs it (Birtchnell, Urry, Cook, & Curry, 2012). Small volumes, decent wages, and flexible designs do not allow for maximum profit within a manufacturing company. The loss of time and money is the reason why traditional manufacturing tends to deny or overlook any production cycle involving one of the limiting factors.

Additive Manufacturing

What Is Additive Manufacturing?

As described in Chapter I, additive manufacturing is the process of joining thin layers of material to build a three-dimensional (3D) object. While researchers feel the term AM most accurately depicts the overall process, AM is commonly synonymous with 3D printing and rapid prototyping. Originally developed in the mid-1980s by Chuck Hull, who called it stereolithography, the technology was not viewed as a usable technology and especially not one that would become a billion-dollar-plus industry (Birtchnell & Caletrio, 2014). The potential benefits of AM technology over traditional manufacturing methods were not actually realized for well over two decades after the initial conception of the technology.

Unlike traditional manufacturing, which cuts down a block of material to form an object, additive manufacturing creates 3D objects by bonding layer upon layer of liquefied polymer or powdered metal. The main process of printing an object from the “ground up” has stayed the same; however, the materials, print speed, and printer reliability have improved dramatically over the last two decades. The versatility of 3D printing is allowing people to customize objects never considered before. Depending on the printer type, which is covered in depth later in this chapter, products can be printed using materials that include, but are not limited to, polymers, metals, rubber, Kevlar, carbon fiber, and wax. Along with the different types of materials, different colors can be customized, including several printers with the capability to print translucent products (Winnan, 2012). All of this variability has given rise to a growth in the technology and demand for AM machines. Just as when computers were developed, no one could

foresee one in every home. The different types of printers now signify the growing need for 3D printing within businesses and homes.

Categories of 3D Printers

A large variety of 3D printers exist in today's industry. Each type of printer is unique in the way it bonds the material together, the material it uses, the method by which it creates the support structure, and the overall capability. Based on the AM technology classification system from the American Society for Testing and Materials (ASTM International, 2015) (Table 1), a general overview of each type is shown below regarding each of the printers being used within industry.

ASTM divided AM technologies into seven different categories: powder bed fusion, binder jetting, directed energy deposition, vat photopolymerization, material extrusion, material jetting, and sheet lamination (ASTM International, 2015). Table 1 outlines all the different types of additive manufacturing technologies, as well as the materials they utilize. Whereas each type of printer is available on the market and is being used by companies within industry, the main two technologies this research focuses on are vat photopolymerization and binder jetting.

Table 1. Metal/Polymer 3D Printing Categories (ASTM International, 2015)

<i>METAL/POLYMER</i>	
1) Powder Bed Processes	
a. Powder Bed Fusion – An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.	
i. Laser Processes	
1. Selective Laser Melting (SLM) – METAL	
2. Selective Laser Sintering (SLS) – POLYMER	
3. Selective Mask Sintering (SMS) – METAL	
ii. Electron Beam Melting (EBM) – METAL	
2) Binder Jetting – An additive manufacturing process in which droplets of build material are selectively deposited.	
a. Powder Bed Binder Jetting - POLYMER	
3) Directed Energy Deposition – Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.	
a. Coaxial Powder Feed – METAL	
b. Coaxial Wire Feed – METAL	
<i>POLYMER</i>	
4) Vat Photopolymerization – Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization	
a. Stereolithography (SLA)	
b. Flash Curing	
c. Film Transfer Imaging (FTI)	
5) Material Extrusion – Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.	
a. Fused Deposition Modeling (FDM)	
6) Material Jetting – Additive manufacturing process in which droplets of build material are selectively deposited	
a. Drop-on-Demand	
b. Multijet Modeling	
<i>OTHER (typically paper, sometimes metal or polymer)</i>	
7) Sheet Lamination – Additive manufacturing process in which sheets of material are bonded to form an object.	
a. Ultrasonic Consolidation (UC)	
b. Adhesive Bonding	

Vat Photopolymerization

Applied to a thin layer of liquefied polymer, ultraviolet light hardens the polymer by irradiating specified areas of each layer. The liquid resin itself cures as “bullet”

shapes and can result in smooth and rounded objects. In post processing, support structures must be removed and UV curing is required to cure the excess material between the “bullets,” which increases the part’s strength. However, the parts are susceptible to aging problems due to light and heat sensitivity. VP is commonly used for investment casting and the polymer burned off after casting is complete; it also finds common use in hearing aids and Invisalign® braces (Kuhn & Collier, 2014).

The disadvantage of vat polymerization comes with the type of machine being used. Some machines use the exact same material for the print and the support material therefore, post processing becomes more difficult. This can be solved by ensuring the printer uses a soluble or wax support material; which is easily removed by soaking in water or heating in an oven during the post processing phase. All printer types have their advantages and disadvantages based on the type of print being designed and the requirements being printed.

Material Jetting

Material jetting is another AM process that uses polymers in liquid form to create a 3D object. The technology is similar to inkjet document printing. However, instead of jetting drops of ink onto paper, the printer jets liquid photopolymer from multiple print heads to create each layer. UV light is then applied to cure and bond each successive layer (Material Jetting, 2015). These layers build up one at a time in an additive process to create a 3D model. Material jetting is the only type of printer with the capability to use multiple materials within the same print, which speeds up the post-processing procedure. When the main print material is different from the support material, the support material is easily dissolved or melted from the product.

The disadvantage of material jetting is the clogging of the print heads if the printer is not used and maintained properly. The plastic material flowing through the tubes is liquefied using a melting process within the printer; however, if the material is allowed to sit too long in the tubes, it can harden and become more difficult to melt during the next print cycle. Just a few clogged print heads can ruin the entirety of a print.

The Additive Manufacturing Process

Differences among all printers results in a variability of print capability and material being used, but the main process to print a product remains constant across all types. Based on the design and material requirements, the additive manufacturing process will help select the best available method for printing the designed part.

The process to print a product is significantly simpler than the traditional manufacturing methods. The print moves from the designer who developed the digital drawing, to the printer, and then on to the final steps of finishing the item. While small details within each process may be different depending on the material or type of printer, the overall printing process consists of four basic steps: product design, product printing, post-processing, and product testing (Figure 1).

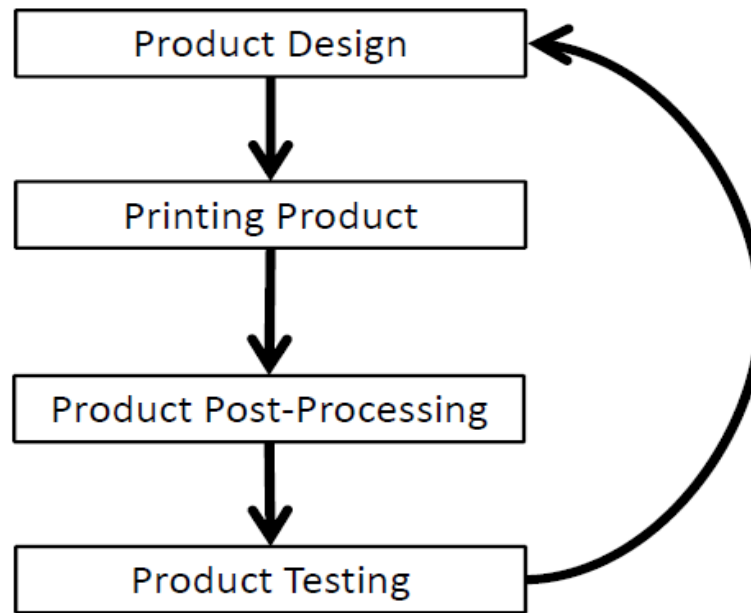


Figure 1. Additive Manufacturing Process

During the product design phase, the designer identifies the requirements of the end user and develops the product based around those needs. Using a systems engineering approach, which is discussed later on in this chapter, a Computer Aided Design (CAD) drawing of the product is created. The digital object is designed typically in solid modeling programs such as Solidworks® or Google SketchUp®. Any program compatible with 3D printers will use the CAD drawing to slice the product into thousands of thin layers for the printer. Once the drawing has been converted into an image well suited for the printer, the printer readies itself for the next phase in the printing process.

In the printing process, the object is built layer by layer on the printer's build space. Some printers print the object upside down by lowering the build platform into a material and then bonding the layer of material to the one above. Other printers complete their print right side up by moving the printer heads upwards as the print builds in the

vertical direction. The type of printer selected will determine the tolerances, reliability, and speed with which the print is created. Normally the speed of a print is determined by the number of layers required or the vertical height of the object; therefore, laying an object on its side sometimes results in a faster print. The rule of thumb for most printers is approximately 1 hour for every vertical inch printed. Some printers have settings that allow for extremely high-definition prints, down to the thousandth of an inch, to get exact measurements on every axis of the print. These printers average approximately 4 hours for every 1 inch in the vertical direction. After the print is complete, it is still not completely ready for its intended purpose, and the object moves on to post processing.

During post processing, the object is cleaned, support structures are removed, and the item is cured. Depending on the type of printer being used, the post processing steps can include different machinery or chemicals necessary to finish the overall product. Post processing for vat photopolymerization printers begins with rinsing the product when it comes out of the printer. During the printing process, the printer leaves an inky residue on the product that must be washed off. The washing procedure is accomplished by rinsing the product in a bath of specialized chemicals, followed by a bath of cold tap water. After rinsing, the item is cured through heat or direct UV light. The final step is breaking away the support material and sanding the piece to finalize the part. Since the support material for some vat photopolymerization printers is the exact same material as the printed product, all the support material must be removed by hand. Breaking the support material is not difficult unless it is inside small areas of the print; to accommodate this, the designer must realize the type of printer being used and may be able to design the part to be printed in multiple pieces and later attached. The final step is

sanding down the rough areas where the support material was attached. Except where precision is critical, this is an aesthetic step to provide a visibly pleasing printed product. Other printers, like those using material jetting, have a less complicated post processing procedure.

Although the material jetting printer uses liquid polymers to create objects, they do not require rinsing. The post-processing procedure for material jetting printers involves heating the object in an oven to melt the support material away from the item. After all the support material melts away and the product is set out to cool, the item is ready for use (Material Jetting, 2015). Some residual support material can be rinsed away using ethanol to completely finalize the product, but it is often not required. As 3D printing technology continues to evolve, the operations to print and post process an item will continue to grow easier and more reliable.

Current State of 3D Printing Industry

Additive manufacturing intends on completely changing the way businesses and society manufactures goods. Described by several researchers as a “disruptive technology” (Campbell & Ivanova, 2013) and said to have the potential to birth the new “industrial revolution” (Prince, 2014), additive manufacturing could change the global market and provide greater benefits for developing countries. Although it was first developed in the 1980s, AM technology saw significant growth and investment in three major industries, automotive, aerospace, and medical, after the year 2000 (Bourell, Campbell, & Gibson, 2012).

The automotive industry was the first major industry to integrate AM as an essential tool in its future operations. Within the automotive industry, AM became a staple technology due to its ability to introduce products into the market in a more expedient and predictable manner (Bourell, Campbell, & Gibson, 2012). Those automotive manufacturers specializing in high-end, low-volume customization of cars saw the most cost savings when printing their parts versus manufacturing them. Larger manufacturers used AM to centralize part production for all their models and reduced the overall overhead costs associated with the production of a vehicle.

The intrigue of AM to the aerospace industry is AM's ability to print lightweight objects using internal honeycomb structures while preserving the overall strength characteristics. With significant funding being poured into the International Space Station mission and the future endeavors to Mars and other planets, the net weight of the vehicle and cargo on a mission is crucial in the use of fuel and resources. The National Academies Press describes the possibilities of AM within the aerospace industry by saying, "Additive Manufacturing has the potential for aerospace use to reduce costs, shorten production schedules, and enable the development of new structures" (Press, 2014). As interest in AM grew within the aerospace field, new carbon composite materials and printable metal have made it possible to incorporate AM into the designs of future aircraft (Bourell, Campbell, & Gibson, 2012). New research into direct metal fabrication offers the most promise for AM within the aeronautical technology industry; however, the additional AM research also unearthed great potential for a variety of biomedical technologies.

Medical technology always has to be on the cutting edge to stay current and offer the greatest quality of life. Due to the increased investment in AM, the medical career field saw the potential for AM's ability to convert 3D medical imaging data into solid objects. This allows for the creation of personal devices customized to suit the exact needs of an individual (Bourell, Campbell, & Gibson, 2012). Just as for the automotive industry, the ability to print high-quality, low-volume objects was extremely cost efficient compared to sending each design off to a manufacturing firm. The quality of life for the individual patient increased as well. Governing bodies who oversee and sign off on new technology within the medical career field are in the process of studying the advances of AM and understanding their success rate within surgical and other medical procedures (Gross, Erkal, Lockwood, Chen, & Spence, 2014). The advancements in biomedical technology due to AM offer great promise to provide comprehensive care for each individual patient, and effective treatments for some of the world's most horrific diseases.

Within all critical fields of study, the fabrication and logistics of designing and manufacturing unique parts and pieces to certain applications has always come at an extremely high cost due to the lack of economy of scale and demand for such custom parts; however, according to Hod Lipson in his book, *Fabricated: The New World of 3D Printing*, "3D printing technologies offer a new path forward by blending aspects of mass and artisan production. They are the metaphorical platypus of the manufacturing world, combining the digital precision and repeatability of a factory floor with an artisan's design freedom" (Lipson & Kurman, 2013). Designs and manufacturing for small business and customized products are now becoming more readily available without

having to be produced in bulk. The original models, typically made from foam or metal and used to form and fabricate items, are becoming a thing of the past and 3D printing will help usher in an era of less waste of resources and better fitting designs and parts that integrate into each of our lives on a daily basis.

In the manufacturing and fabrication of a product, the design and method selection take the bulk of the time as a prototype is being developed. A new technology associated with 3D printing is the implementation and configuration of 3D scanners to scan a desired object and then transfer the object's features into a Computer-Aided Design (CAD) model. This technology has allowed 3D printing technology to transition seamlessly from molds to computer models. The scanning process is, "Scan data is, in my opinion, the bridge that's going to span the gulf between the analog physical world and the binary digital world. Scanned and reproduced physical objects are where the line begins to blur between original and replica, between copyrighted object and derivative work. Scanned data, once captured in a design file, can be edited, replicated, and copied. Someday we will edit the physical world as easily as we edit digital photographs" (Lipson & Kurman, 2013).

Christopher D. Winnan (2012) believes the additive manufacturing impact to third-world countries will be the most drastic. He states that, "The possible potential democratisation of the manufacturing industry is an exciting thought in the context of the West, but in the developing world, this idea could be even more worthwhile. 3D Printing could help countries to 'leapfrog' into new, distributed forms of production that create opportunities for better, environmentally sustainable and more just forms of economic

development, avoiding some of the pitfalls our own economic model has uncovered” (Winnan, 2012).

Based on the potential AM possibilities within the areas of automotive, aeronautical, and medical technologies, as well as the possible economic impacts, military agencies around the world are exploring 3D printing for their own use within their operations (McNulty, Arnas, & Campbell, 2012). The potential for a 3D printer to be used in any location around the world makes the technology well suited for civil engineering operations at home station and deployed locations. As time goes on, the impact of AM on actual military operations will continue to increase. Currently, just like any new technology, AM within the military is very basic and still being used primarily in testing and research and development (R&D); however, some units have realized the potential of AM and are integrating them into everyday operations.

Military Applications of Additive Manufacturing

Although AM is still considered a new technology, its disruptive nature and the potential impact it could have on daily operations has not been overlooked by the United States military (McNulty, Arnas, & Campbell, 2012). All branches are investing R&D funds into developing an understanding of how AM can be used to gain an operational advantage over the enemy or to improve current operations. Each branch, in its own rightful way, has taken steps to integrate 3D printing technology into daily operations.

The US Army used the 1990s to investigate the new technology of AM, referred to then as stereolithography; however, due to the then-primitive technology’s unreliability and minimal utilization in industry, they put little effort into possible applications (Zimmerman & Allen, 2013). As AM technology grew and the availability

of materials increased, the Army realized the impact this technology could have. Due to the expedient growth in AM and other technologies, the Army developed a plan to stay at the forefront of what was being developed. In 2002, the Rapid Equipping Force (REF) was deployed by the Army as a method of “providing rapid engineering solutions to the growing number of capability gaps presented by soldiers” (Rapid Equipping Force, 2015). The REF was developed to be an “on the ground” workshop located at large forward operating bases to provide technical expertise, assistance, and solutions to soldiers complete their mission. In 2012, changes to the REF resulted in the development of two Expeditionary labs (Ex Labs), which are “easily deployable, custom-manufacturing shops equipped with state-of-the-art equipment such as 3D printers, computer numerical control machines, and fabrication tools” (Rapid Equipping Force, 2015).

The development of the Ex Labs represents a rapid integration of 3D printing into US Military operations and has resulted in multiple custom fabrications and product solutions being designed and printed in deployed environments (Asclipiadis, 2014). A faulty wheel design and tire inflation system on the Mine Resistant Ambush Protected Vehicle (MRAP) in theatre was identified, designed, and printed by the Ex Labs and the engineers manning the station. The crucial ability to use the equipment and reach back to engineers at home station locations whose main job is to help with the identification of requirements, the design of prototypes, and provide any technical expertise to those in theatre, have proved pivotal in saving time and money compared to alternate options (Asclipiadis, 2014). Due to the success of the Ex labs, the Army is moving forward to produce more Ex-lab units and provide better capabilities to their units around the world.

The newer assets will include hybrid generators and solar power to help make the Ex-lab units independent to civil infrastructure (Makers on the Front Lines: The Army REF's Ex Labs, 2013). Along with identifying possibilities for 3D printing solutions in deployed environments, the US Army's REF is developing an online tool to give soldiers the ability to submit ideas about problems that can be solved or improved using 3D printing. Army leaders feel the younger generation of soldier will embrace the idea of making an impact on Army operations by identifying areas where 3D printing could improve the way the Army operates (Makers on the Front Lines: The Army REF's Ex Labs, 2013). Altogether, the US Army is moving forward with integrating AM into their operations; as the technology grows, they will continue to identify, test, and incorporate the technology as efficiently as possible. Along with the US Army, the US Marine Corps saw the potential for AM and is working toward identifying areas in which AM could benefit their operations and processes.

Most recently, the US Marine Corps witnessed the initial success of the Ex Labs by the Army and decided to procure their own deployable assets for operational use (Makers on the Front Lines: The Army REF's Ex Labs, 2013). A report issued in 2014 by USMC leadership went in more depth about possible applications for 3D printing use. Several areas for possible cost and time savings due to 3D printing included inventory and warehouse space reduction, logistical transportation and shipping cost reduction, and manufacturing and design costs for training aides (Robert W. Appleton & Company, Inc., 2014). Most recently, 3D Systems® was contracted by the US Marine Corps to incorporate the growing capabilities of Additive Manufacturing technology into their operations. The end goal is to develop quick response teams, which is similar to the

Army's "Ex Labs" and will provide the USMC the skill to "rapidly replace damaged components in the field, especially under critical circumstances" (3D Systems Supports USMC War Game involving 3D Printing and Scanning, 2015). During an upcoming wargame scenario, Marine Corps engineers were expected to use a deployed 3D scanner to model and create a CAD file for a damaged robot. Once the needed parts were printed, the USMC engineers were to repair the robot and complete the assigned operation. By analyzing how quickly a part can be perfected and printed in an operational setting, an evaluation of the technology will be conducted by 3D Systems® and the USMC. Other assets within the USMC inventory are being tested using 3D printing technology as well.

A recent contract between Science Applications International Corporation (SAIC) and the USMC was to upgrade the Marine's amphibious assault vehicles to "serve as prototypes for a program to test the underside of the vehicles against roadside bombs" (Wren, 2015). SAIC won the contract due to their integration of 3D printing into the parts production phase of the process. Most of the parts created by the 3D printing technology are actually stronger, lighter, and more efficient than the original parts being replaced on the vehicle (Wren, 2015). While SAIC has a contract only to create prototypes using USMC vehicles, they hope to utilize their technology and expertise to improve the safety of all military vehicles. Due to the close relationship between the US Navy and US Marine Corps, SAIC also hopes to find potential applications on board the new generation of Naval vessels.

Vice Admiral Philip H. Cullom, Deputy Chief of Naval Operations (CNO) for Fleet Operations and Logistics said at the 2014 US Marine Corps Expeditionary Logistics Wargame (CELW), "It is my strong belief that 3D printing and advanced manufacturing

are breakthrough technologies for our maintenance and logistics functions of the future. We can gain new capabilities to make rapid repairs, print tools and parts where and when they are needed, carry fewer spares and, ultimately transform our maritime maintenance and logistics supply chain” (Halterman, 2014). The Navy and Marine Corps have been working jointly to determine the best way to effectively integrate 3D printing technology into their contingency operations; however, the Navy is developing onboard applications for 3D printing as well. The installation of a printer onboard the USS Essex allowed researchers to test the potential for producing custom made drones specifically designed for individual mission requirements (Williams, 2015).

Files of designs developed and tested on land were e-mailed to the ship and printed within a matter of hours. The concept could significantly reduce the inventory and storage required on board a ship during a tour since the number and types of missions are unknown at the start of a deployment. Because a Naval vessel is the home, hospital, and workplace of so many sailors, the potential for a 3D printer is even further increased with the possibility that medical applications can stem from the same technology. The same printer generating a mission-specific drone could also be a life saving device by printing critical surgical tools (Williams, 2015). In an effort similar to the Army’s REF, the Navy has a group referred to as the Chief of Naval Operations’ Rapid Innovation Cell (CRIC), whose sole purpose is to help identify emerging technologies and find possible applications for research and integration. Based on the success of the printer on the USS Essex and other test prints, the US Navy and the CRIC introduced a concept they call “Print the Fleet,” which intends on introduce all sailors to 3D printing. Naval leadership hopes that introducing all sailors to the technology will lead to development of new ideas

and identification of additional research opportunities (Tadjdeh, 2014). In total, more than twenty possible items were identified within the first year through the “Print the Fleet” program. Those items were then designed using CAD software and printed for testing purposes. In the end, US Navy leadership understands that 3D printing technology is still in its infancy and research still must be completed. Capt. Frank Futch, who is in charge of developing the US Navy’s official additive manufacturing strategy and vision, believes the ability to use a 3D printer for larger projects such as printing an entire helicopter rotor or aircraft wing is not far off (Williams, 2015). He believes the next step for 3D printing within the Department of Defense is all four branches to come together to completely understand the overall possibilities for 3D printing.

For the US Air Force (USAF), the additive manufacturing focus has completely been in the realm of aircraft operations and maintenance technology. Due to the average age of the aircraft in the USAF inventory and the maintenance intensity they require, any time- or cost-saving technology is extremely valuable to the overall operation. In fact, Air Force leadership has identified 3D printing technology as a strategic priority critical to the success of Air Force operations in the future (AFRL, 2011). Within the Air Force Research Laboratory and the Air Force Institute of Technology (AFIT), additive manufacturing is receiving considerable research funding to find additional applications within the Air Force; however, to date, only a minute percentage of operational Air Force units have implemented any sort of additive manufacturing technology within their active processes. The Air Force has focused its research for additive manufacturing on the operational side of the house, since it is made up of the most expensive pieces of

equipment and is the “tip of the spear” for the Air Force mission. That being said, research conducted at AFIT previously identified Unit Type Code deployment kits as a possible application for additive manufacturing.

Air Force Captain Seth Poulsen, a 2015 AFIT graduate, explored the possibility of including AM machines within Unit Type Code (UTC) kits for downrange deployment. During his research, he reached out to Air Force CE leadership and conducted surveys to determine the possible uses for AM within a deployed CE squadron (Poulsen, 2015). While the results of his study suggested substantial opportunities for possible applications within CE’s downrange mission, no specific items to print were identified. The study determined that while it is beneficial to isolate possible areas in which AM could be advantageous within CE, it could only theoretically conclude that the technology would prove to be successful. The final recommendation of the research was to fund a pilot study wherein a 3D printer would be sent downrange in a UTC kit. By getting the technology into an operational environment, the study stated it would educate airmen on the printer’s abilities and lead to the identification of actual uses. In the end, the research provided proof that CE leadership believed there was a unique application for additive manufacturing within their operations; the technology simply needs to be introduced to airmen who have the technical skills to find the specific applications.

Overall, the four branches of the United States military are still understanding the potential of additive manufacturing and what it holds for future operations within their services. Based on the literature review conducted on the current military applications for AM, it seems like the implementation of the technology is being carried out four separate ways by each branch with little cross communication taking place regarding

each branch's implementation successes and failures. To move forward into the new era of technology, the entirety of the U.S. military must come to understand the value that additive manufacturing brings to the unique nature of the mission at hand; additionally each branch must realize that potential value and utilize it best for what that particular service brings to the fight. The foundation has been laid to identify the requirements for each service and to determine how to use additive manufacturing to help solve the problems facing each of the different services.

Systems Engineering Processes

What is Systems Engineering?

Within any design process, implementing a systematic and iterative procedure is paramount to ensure the final system adequately covers all factors of the design needed by the customer. This systematic approach or systems thinking is defined as systems engineering. The most accepted definition of systems engineering comes from the

Systems Engineering Management Guide:

The application of scientific and engineering efforts to (a) transform an operation need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, survivability, human

engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives. (DSMC, 1990)

Within the systems engineering approach, important factors for evaluation during a design include, but are not limited to, user needs, requirements, functionality, design constraints, and the actual design itself. Different methods and approaches have been developed to visualize and conceptualize how to systematically carry out the entire design process of a product. The most applicable and most commonly used systems engineering methods included the waterfall process model, the “Vee” process model, and the spiral process model (Valencia & Shields, 2016).

Waterfall Process Model

Shown in Figure 2, the waterfall process model is one of the original systems engineering models developed. Initially intended for software development, the model varies between having five and eight steps depending on the size and complexity of the project. The five main steps used most often include specification of requirements , system design, implementation, testing, and maintenance (Blanchard & Fabrycky, 2011). Originally, the “Pure Waterfall” model showed each of the stages as completely separate, with no overlap allowed; however, a more updated “Modified Waterfall” model was developed that allows the stages to overlap when needed (Munassar & Govardhan, 2010). The model places strong emphasis on early planning in the beginning stages and help with identifying design flaws in the product prior to production (Munassar & Govardhan, 2010). Where this method differs from other processes is the continuous feedback it provides throughout the process, both up and down the chain of command. When project engineers and developers outside software development began trying to use the model,

they found several problems with the flexibility and amount of required upfront information. A new model, the “Vee” process model, was developed to allow for more flexibility with designs outside software development (Munassar & Govardhan, 2010).

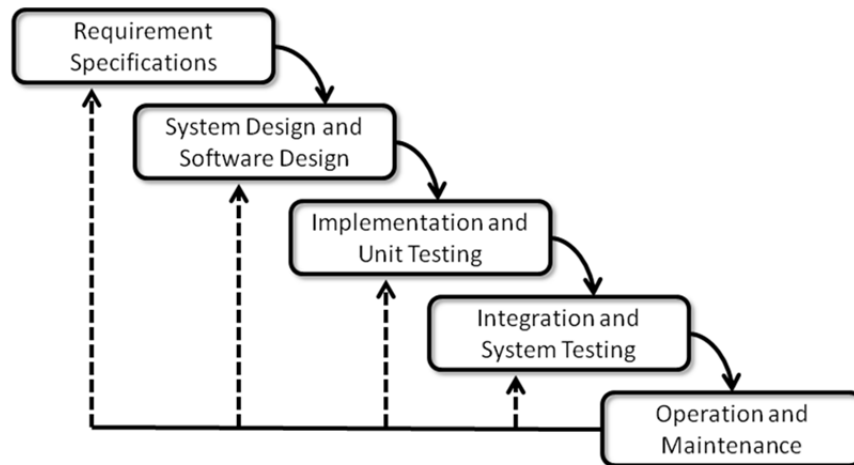


Figure 2. Waterfall Process Model

“Vee” Process Model

Systems engineers developed the “Vee” process model, shown in Figure 3, to provide more clarification and focus on the user’s needs throughout the design and execution process. Like the waterfall model, it is a “sequential path of execution of processes” (Munassar & Govardhan, 2010). By starting the process with the user needs and ending with a user-validated system, the model helps capture the importance of understanding what the user desires from the final system.

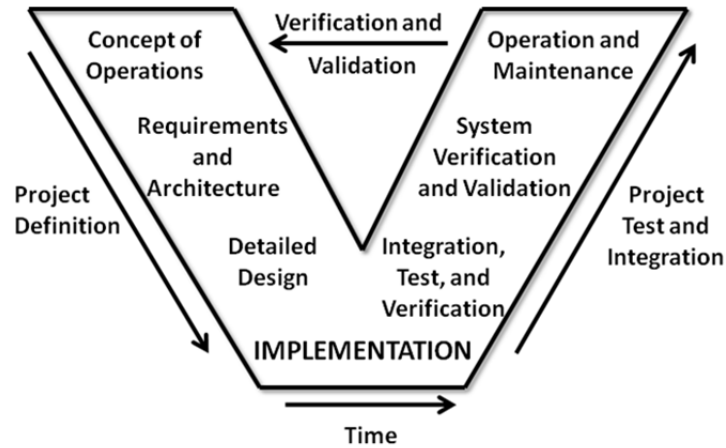
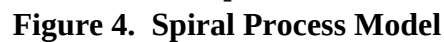


Figure 3. “Vee” Process Model

The process diagram, made up of the typical *V* shape, shows the steps of the process moving from left to right along the *V*. The left side of the *V* shape consists of the “Project Definition” or decomposition and definition activities within the design of the system and its functional requirements. In this part of the process, a systems engineer must understand how to define the requirements and allocate the system functions, and recognize the detailed need of the components within the system. Project integration occurs up the right side, followed by verification of the design. Throughout these steps, constant testing and verification is taking place to ensure the system is designed according to the needs of the user (Blanchard & Fabrycky, 2011). It is crucial that the entire system meet all the specifications laid out in the planning steps of the process.

The advantages of the “Vee” process model include simplicity and ease of understanding. Each phase is defined with specified deliverables and milestones labeled. The model also places a high emphasis on early development of test plans; however, unlike the waterfall method, it works a lot better for smaller projects, for which the requirements and needs of the user are easily understood (Munassar & Govardhan, 2010).

The final model used by systems engineers is the spiral process model, presented in Figure 4. Originally developed in 1968, the model was “intended to introduce a risk-driven approach for the development of products or systems” (Blanchard & Fabrycky, 2011). Using the constant feedback provided by the “Vee” process method, the Spiral model makes the process of requirements, design, and conception cyclical while adding in a factor of risk. The need for risk analysis was the main component lacking from the “Vee” process model and the basis for what drove the design of the spiral model. The



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the desired specifications. Based on the spiral design, the angular component represents the progress of the design, while the radius of the spiral represents cost (Munassar & Govardhan, 2010). At the end of each cycle, prior to moving to the next cycle, the design team is mandated to evaluate their prototypes and alternatives, solicit suggestions and changes from stakeholders, evaluate the inputs, and decide what changes to make.

Software developers and design teams agree the spiral model's focus on risk analysis is an advantage, that it works well for large and mission-critical projects, and that it is iterative and extremely flexible. Disadvantages of the model include that it's costly to use, requires highly specific expertise, is incompatible with smaller projects, and exquisitely dependent on the risk analysis phase (Munassar & Govardhan, 2010). Even with its liabilities, the process quickly became the model of choice for design teams walking through a cradle-to-grave design process (Blanchard & Fabrycky, 2011).

Choosing a Systems Engineering Model

After weighing the options, the design team decides which model best fits the requirements and problem given to them. Each model has a specific set of advantages and disadvantages and is made for certain types of problem sets. While the waterfall model, "Vee" model, and spiral model are the most commonly used models within systems engineering, each can be manipulated to meet the needs of the project specifications and design team. Based on the type of tool and design required with each part of the research described in this document, a specific model was identified and followed until the completion of the design.

Systems Engineering Properties: “-ilities”

At the turn of the 20th century, when automobiles, electricity, and the airplane were all at the forefront of the technological innovations, these inventions were “designed for first use.” This means that the primary aim of the designer was to create an invention that would fulfill its primary function at the time it was first turned on and little thought was given to the indirect consequences of the invention in the future (de Weck, Roos, & Magee, 2011). This time period was referred to as the *epoch of great inventions and artifacts* (de Weck, Roos, & Magee, 2011).

As the innovations and inventions became more common, the focus of the designers began to change, leading to the *epoch of engineering systems*. During this time period, designers placed greater emphasis on understanding the systems engineering properties that affected the long-term utility of their products (de Weck, Roos, & Magee, 2011). The change in thinking was because the customer began to understand the concept of downstream life-cycle outcomes and therefore began placing more responsibility on the designers of the product (Blanchard & Fabrycky, 2011). This increase in responsibility led designers to consider the product’s systems engineering properties, commonly referred to as -ilities, more carefully. A technical definition –of ilities has been stated:

... The desired properties of systems, such as flexibility or maintainability, that often manifest themselves after a system has been put to its initial use. These properties are not the primary functional requirements of a system’s performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements. The -ilities do not

include factors that are always present, including size and weight. (de Weck, Roos, & Magee, 2011)

The properties most commonly analyzed in products today include: quality, reliability, safety, flexibility, robustness, durability, scalability, adaptability, usability, interoperability, sustainability, maintainability, testability, modularity, resilience, extensibility, agility, manufacturability, repairability, and evolvability (de Weck, Roos, & Magee, 2011). Each of these -ilities is specifically defined and can be analyzed through different techniques; however, each -ility's individual definition is highly dependent on other -ilities within the list. The main -ility being discussed and analyzed within this research is usability; however, the definition of usability requires the testing of product quality, flexibility, durability, adaptability, interoperability, maintainability, testability, manufacturability, repairability, and evolvability.

Usability

Usability, slightly different from operability, “deals with an individual’s ability to accomplish specific tasks or achieve broader goals while “using” whatever it is that is being investigated, improved, or designed — including services that don’t even involve a “thing” like a doorknob” (Reiss, 2012). The analysis of usability relies both on the performance of the product, and on the human factors required to operate the product. Human factors are the “properties of human capability and the cognitive needs and limitations of humans” (de Weck, Roos, & Magee, 2011). The usability of a computer program would be zero for a group that had no idea how to use a computer, even if the program is state of the art.

Usability is most commonly analyzed as an -ility for computer interfaces and programs because there is a definite relationship between the program's purpose and the customer's ability to properly use the program. Within computer program design, usability analysis is normally broken into six different objectives or goals. The six measured objectives include the product's being (Preece, Rogers, & Sharp, 2007)

1. Effective to use (effectiveness)
2. Efficient to use (efficiency)
3. Safe to use (safety)
4. Of good utility (utility)
5. Easy to learn (learnability)
6. Easy to remember how to use (memorability).

The goals related to analyzing the usability of a product are normally operationalized as questions to help provide an exact method of assessing the numerous aspects of the interactive product and the customer experience. The more detailed the questions, the more likely the designer is to find unforeseen problems within the design. Having a clear definition and understanding of the different usability objectives helps the designer develop the questions for the analysis.

Usability: Effectiveness

Based on the requirements identified at the beginning of the design process, the effectiveness of the product determines “how good the product is at doing what it was designed to do” (Preece, Rogers, & Sharp, 2007). If the designer correctly identified all the requirements of the user in the beginning and was able to incorporate all those requirements into the design, the effectiveness of the product should be simple to determine.

Usability: Efficiency

The efficiency of the product is determined by the user's level of productivity once the product has been learned (Nielson, 1993). Within the definition of efficiency, other -ilities like quality, flexibility, maintainability, and durability are subsequently tested. This is because a product that is hard to maintain or a product that is of poor quality will result in a lack of efficiency over time for the user.

Usability: Safety

Safety involves multiples tiers of ensuring the product is safe for the customer. The first part of analyzing safety is determining whether the product will place the customer into a hazardous or dangerous environment (Preece, Rogers, & Sharp, 2007). For computer systems that are near hazardous areas like X-rays or chemicals, the program should allow the user to access it remotely.

The second part of the safety analysis is determining whether the product causes the user to carry out unwanted actions accidentally or the ease with which a customer can make an error (Nielson, 1993). This normally occurs due to buttons being too close together, toggles being too sensitive, or a lack of understanding of all the abilities of the product. By ensuring proper safeguards are in place to minimize mistakes and quell any fears by the customer, the safety of the product is addressed (Preece, Rogers, & Sharp, 2007).

Safety can involve analyzing other -ilities including durability, interoperability, repairability, and flexibility. Understanding the dependency on each of the -ilities will make for a better quality product overall.

Usability: Utility

Utility refers to the “extent to which the product provides the right kind of functionality so that users can do what they need or want to do” (Preece, Rogers, & Sharp, 2007). The difference between low utility and high utility is based on the user’s ability to complete everything needed within the task using the tool provided or needing to use other tools and devices to complement the product to solve the problem. By testing utility, one is also looking at flexibility, adaptability, and evolvability.

Usability: Learnability

Learnability is the ease with which the user is able to learn to use the product (Preece, Rogers, & Sharp, 2007). When designers are looking at a program to design, they ensure the system is easy enough for the user to have the ability to begin doing productive work within a reasonable amount of time without extensive, in-depth training (Nielson, 1993). Learnability is ensured through quality assurance practices by the owners and the design companies, as well as iterative testing with those who will use the product.

Usability: Memorability

Finally, memorability deals with the user’s ability to retain the training and skills necessary to still effectively use the product. If a user is able to return to the system after an extended period of time and immediately begin using the product efficiently, then the product is said to have high memorability (Nielson, 1993). A usable system has a higher memorability if continuous training is not required to stay proficient on the system or product. In a way, memorability tests quality, testability, interoperability, and agility. By

testing a product's usability through the given objectives, a researcher is able to analyze how usable a product is for the crowd for whom the product is most intended.

Summary

This literature review provided an overview of the existing literature and current research relating to the key topics of this research effort. The topics described in this chapter included a background on the traditional manufacturing process and a deep dive into the development of additive manufacturing. This led into an introduction of the military applications currently utilizing additive manufacturing. It closed with a discussion of systems engineering methodologies, as well as defining usability when it comes to the value of a manufactured product. The following chapter presents the use of a semantic differential scale survey to measure usability and determine the value of additively manufactured products for use in military operations.

III. Methodology

Chapter Overview

This chapter provides the methodology used in this research effort. The research took place in two steps or phases. The first step was identifying areas within engineering operations that have potential to be made more efficient through the use of a specially designed, additively manufactured part. Utilizing a systems engineering design approach, each part requirement was identified and a prototype was created for the use of the study participants. Once the first phase was finalized, the second phase involved a semantic differential survey designed to measure the actual usability of the printed part. Results from the survey to determine whether measuring usability can act as a proxy for determining the value of additive manufacturing within military operational units are analyzed in Chapter IV.

Systems Engineering Design Methodology

For each part identified and designed during the research, the evaluation of all common systems engineering models allowed for the best process to be chosen specific to the requirements and the desired end-product. In the end, the spiral model, seen in Chapter II and in Figure 5 below, was determined to be the best fit for each of the parts being designed. The model's focus of calculating risk suited the intent of creating a more efficient design for the end user; and allowed for an iterative design-and-testing process to weed out unforeseen flaws within the design or requirements.

As this chapter continues, each step within the spiral model will be discussed. In regard to each specific part designed and printed, Chapter IV will discuss how the design

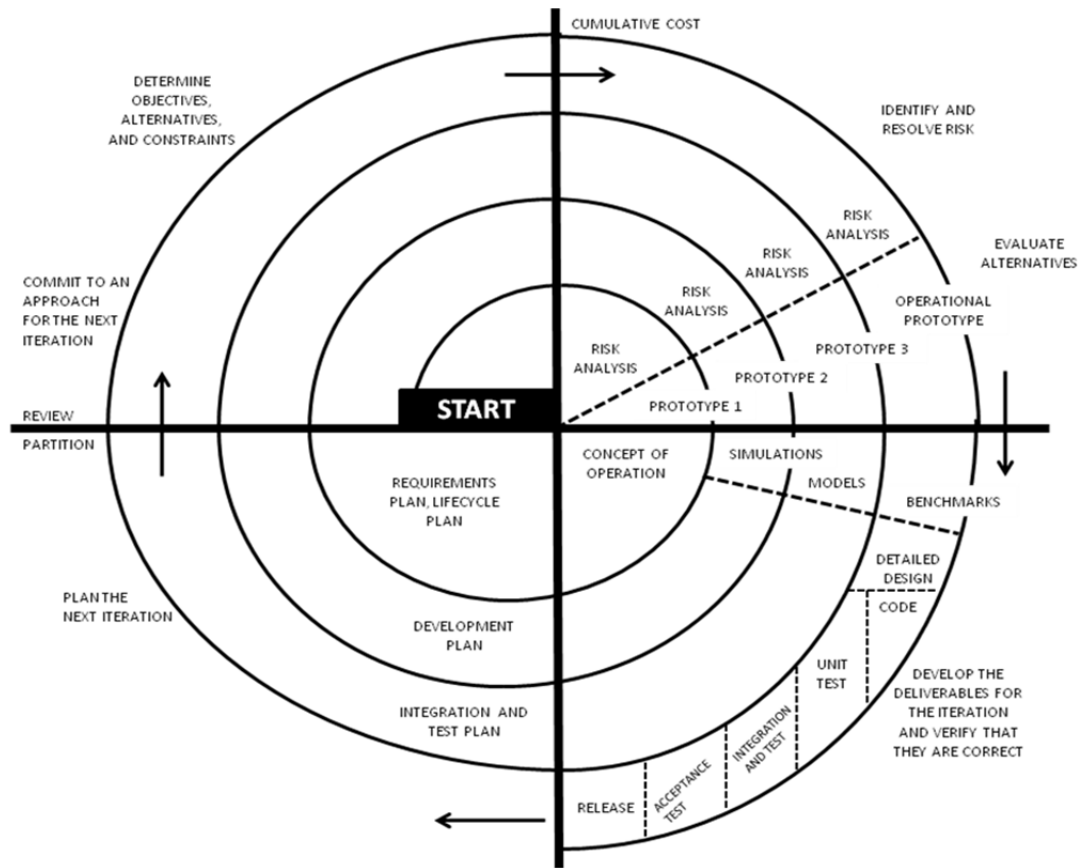


Figure 5. Spiral Process Model

process required stepping through the design drivers, constraints, functionality needs, and different prototype designs multiple times to address unforeseen challenges. One difference between the spiral model and the Vee and waterfall models is that the spiral model dictates the use of prototypes within the iterative design process. The other models do not require prototypes and focus more on the conceptual design phases (Blanchard & Fabrycky, 2011). The ability of the spiral model to identify unforeseen challenges and provide a framework for a work around is a fundamental necessity to enable the performance of this research.

Overall, each of the steps within the systems engineering model, or whole life thinking approach, plays a critical role in incorporating the “life cycle” mindset of all

systems engineering designs. Through the creation of a culture that thinks holistically, designs and problem solving approaches become more adaptable than before, thereby allowing for the improvement of processes and lowering life cycle costs (de Weck, Roos, & Magee, 2011). As this section walks through the different components of the systems engineering model, it is important to realize that while the context of interest for this research is additive manufacturing, the model can be adapted and implemented in many types of design practices and problem-solving approaches. Within this chapter, each design step is discussed in broader terms, to provide a comprehensive understanding of its importance. Chapter IV incorporates the implementation of the design methodology into the identification, design, printing, and testing of the additively manufactured parts and tools. The important thing to remember is that the overall systems engineering model hinges on identifying a majority of the criteria in the beginning, having constant communication throughout the process, and cooperation among the stakeholders through each design iteration to accomplish the goal of providing the best possible product in the end.

Requirements and Design Constraints

The most important step at the beginning of the design process is to ensure it starts out on the right foot. This is done through the development of specific requirements from the user. These requirements identify exactly what the end-product is supposed to do when it comes to solving the problem or meeting the objective. The basics of a requirement include the actual need of the user, what the product to is intending to accomplish for the user, and what initial design constraints may factor into the design of

the problem. Many users can't differentiate between an actual need and a requirement because they are very similar.

To begin, a need or want is simply a broad definition of the overall requirements: the high-level description, “30,000-foot view”, etc, of the problem without identifying any specifics. Examples of a need or want include:

- The football team needs to get better.
- The expanding family wants a house.
- The environmental department at a school needs something to securely hold and shake their glass jars for experiments.

All of these identify an overall goal, but do not address any specifics. This is because the need addresses only the high-level task.

The next level, which is the identification of the requirements, is more specific. Requirements delve into the “what” the product must do to accomplish the need, as in the following examples:

- To get better, the football team must acquire a top 30 recruiting class, state-of-the-art facilities, and depth at key lineman and skill positions.
- The expanding family is in need of at least a 3-bedroom, 2-bathroom home with a 2-car garage and fenced backyard for their dog.
- The agitator has to carry 4 glass bottles, the necks of the bottles are 3 inches in diameter, and the unit will spin at 30 revolutions per minute instead of shaking.

Each of these specifics falls under the broad “need,” and each plays an important role in the overall design of the product by providing specificity. The sooner requirements are agreed upon by the user and designer, the more smoothly the project will go. Some

projects are hindered by requirements that increase during the design's evolution, causing delays and frustrations to both the user and the designer.

Even with specific requirements, every project has design constraints that limit the design in some manner. Clear constraints can be identified quickly and up front in initial meetings; however, more often than not, constraints are found as the design progresses and prototypes are tested. Design constraints can range from material type, color, size, placement, or any other factor that affects the design in some manner. While constraints do limit the design, a thorough identification and consideration of all constraints makes for a better product for the end-user.

The foundation for a smooth design and implementation process starts with a proper analysis of the user's need, all the requirements, and any constraints limiting the design. From there, the designer and builder move on to the project's risk analysis and the design, construction, and testing phases of the process.

Risk Analysis

Risk analysis is done throughout the project, but it is even more important prior to the start of the initial design cycle. Risk is defined as the "potential that something will go wrong as a result of one event or a series of events" (Blanchard & Fabrycky, 2011). Through the use of certain analysis tools, like discrete event simulation (DES) and control theory, certain risks can be investigated and mitigated (de Weck, Roos, & Magee, 2011); however, not all risk can be mitigated within a project. There are four basic types of risks associated with a project (Blanchard & Fabrycky, 2011):

1. **Technical Risk:** This risk is associated with engineering designs and specific performance requirements. When constructed, the owner is taking the risk that

- the contractor is technically capable of providing a usable product. If the designer contracts out certain designs, then the designer is taking the risk that the designs will be technically sound and meet all performance requirements. These risks are ameliorated through design checks, bonding requirements, and experience levels that ensure specific performance and technical requirements are met.
2. **Cost Risk:** For any project, there is always a risk that the costs will exceed the original amount that was bid or estimated. Depending on the type of contract, this risk could be more to the owner or to the contractor. Detailed plans and cost estimates are built prior to the project start to mitigate any possible cost overruns.
 3. **Schedule Risk:** Any deadline runs the risk of exceeding the projected completion date. Contractors can be pressed to not go over their completion date through incentives or delay penalties written into the contract. Detailed schedules with Gantt charts and task lists are created to help a project stay on schedule.
 4. **Programmatic Risk:** In a large organization, this type of risk is much more prevalent. This is the risk of certain events imposed on the project/program, which are a result of external influences. Either from leadership, external supply factors, or any other outside influences, this type of risk can be the most unforeseen and challenging to plan for (Blanchard & Fabrycky, 2011).

In the end, risk analysis is an identification-and-mitigation process for the risks assumed to be the most prevalent surrounding a project. Good project managers, designers, and builders construct Risk Management Plans (RMP) to document the ways they go about mitigating certain risks. Most RMPs also include a broad plan identifying what the project manager would do in the event certain risk events took place on their project site.

Design/Building – Iteration #1, 2, 3...

A project may include numerous design-and-building processes because the spiral model allows for prototypes to be passed across design and testing phases multiple times until a useful product is created and all requirements are satisfied. Within the design-and-building process, requirements and constraints are taken into account and a product is born. The first model may look nothing like the final product, but the iterative process stepping through the design and testing phases allows the designer to create a product and test it for the user and designer to visually inspect. Once the designer makes any changes from the previous testing cycle and finishes the iterative design, it is tested once again.

Testing – Iteration #1, 2, 3...

Following any design-and-building process, the testing phase ensures the product meets the requirements identified within the first step. During this phase, the user and the designer are able to see the prototype of the product in use. Sometimes visualization of the actual designed product can result in additional requirements and constraints on the project due to unforeseen visual or functional problems with the prototype. A part that does not pass the testing phase is sent back to the design-and-building phase for modifications.

Within the testing phase, the viability of the product must also be verified. For this research, the process to accomplish this step will be determining the usability of each product identified and designed. The overall method for verification will be discussed further in this chapter, while the verification results will be outlined in Chapter IV. All of the user's technical and functional specifications must be met for the design to pass the testing phase and move on to the final handoff and integration.

Final Handoff, Integration, and Maintenance

Once through the testing phase, products reach the final handoff and integration phase. This is very different for all products, as some may just be handed to the customer and other products may go to a manufacturer for production. Either way, the customer receives a useable product that must be integrated into his processes. This may involve training and analysis of existing operations, and requires ensuring that procedures are in place for its maintenance and care.

Each of these steps, from the identification of requirements to the implementation and maintenance of the product, is essential to the “life cycle” mindset of systems engineering design. Thinking holistically can cause designs to become more flexible and adaptable than before, allowing for improvement of processes and lowering life cycle costs (de Weck, Roos, & Magee, 2011). This systems engineering design process can be adapted and implemented into the analysis and thinking of all design practices, to provide a more efficient model for product development.

Systems Engineering Application

Within this research, the development of useful products capable of solving the needs within today’s Air Force becomes more streamlined and efficient due to the successful use of the systems engineering design methodology. Through the implementation of the spiral model, the research specifically targets unique applications within the engineering community to provide possible solutions through the use of additive manufacturing. By seeking out applications, identifying the unit’s specific requirements, conducting a comprehensive risk analysis, and then working to design,

print, and test a successful tool, the research looks to validate the ability of additive manufacturing technology to provide solutions to unique challenges in the current resource limited environment. With the systems engineering design methodology described above, the actual tools used within the research design process will now be examined further.

Materials and Equipment

The design process itself requires several different tools and pieces of equipment to ensure an efficient product in the end. For this accounting of this research to be thorough and repeatable, each tool and piece of equipment used within the research is identified and described below.

Solidworks

The design of the tools and jigs during the initial design stages utilized Solidworks® Computer Aided Design (CAD) software. The tutorial within the program is extremely easy to step through and even basic users can design simple shapes and objects after completing the how-to videos. When compared to other design software, the Solidworks® program is easily the simplest to use, especially due to its ability to convert the .SLDWKS file into an .STL file, which is the file type required for each of the AM printers. The file type .STL is used by a majority of 3D printers and is the reason why Solidworks® is one of the main programs used by most additive manufacturing firms. Other types of software include AutoCAD®, Google® Sketchup, and other proprietary programs.

Measuring Tools

For measurements and dimensions during the design process, generic calipers and measuring tools were used. Standard dimensions, rather than the metric system, were used during the design process; however, Solidworks® and all 3D printing software have the ability to switch between U.S. customary/standard units and the metric system units in order to suit the preferences of the user.

Additive Manufacturing Equipment

The 3D Systems® ProJet™ 3500 and ProJet™ 1500 additive manufacturing machines were used as the main printers for the tools and jigs printed during the research. The 1500, seen in Figure 6, is a film transfer photopolymer machine which uses photopolymer plastic material with ultraviolet (UV) curing inside the printer. The printer uses the same plastic material as both the main printing material and the support structure material. Because the support structures were of the same material, they tended to obstruct the intended design of the product and required more-involved post processing. The nominal build area for the printer is 10 in × 7 in × 7 in; however, prints tended to fail approximately 0.5 in from the edge of the print area. While the 1500 did allow for basic AM techniques to be learned, its print unreliability, large tolerances, and outdated technology hindered the speed of data collection in the beginning.

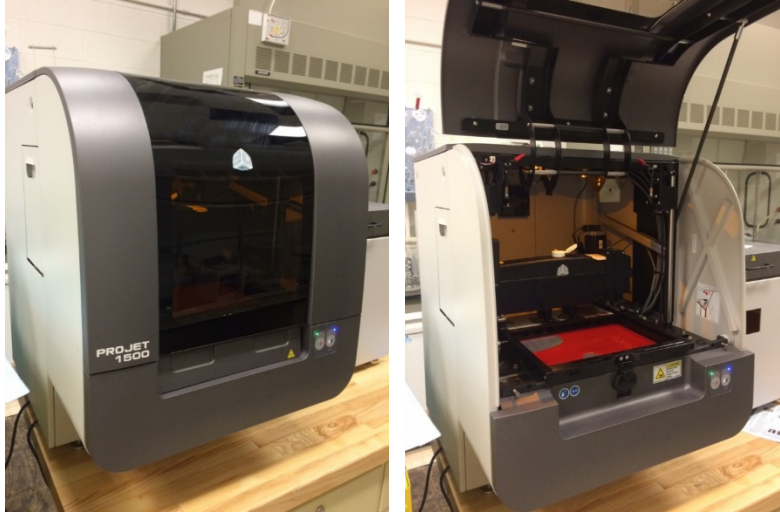


Figure 6. ProJet™ 1500 Printer, Opened to View Printing Bed (right)

The ProJet™ 3500, seen in Figure 7, is a Multijet printer which passes a heated material through multiple print heads to build the object layer by layer. It is a newer printer and much more reliable than the ProJet™ 1500. The 3500 utilizes a clear, liquid polymer as the main print material and a wax-based substance as the support material, which melts off during post processing of the product, allowing for less post processing and more complex designs. The nominal print area for the 3500 is 11 in × 8 in × 8 in.



Figure 7. ProJet™ 3500 HD Max Printer

Post Processing Equipment

Post processing equipment used for prints created in the ProJet™ 1500 is much different from what is used for prints coming from the 3500. The two equipment items used to post process all prints created within the ProJet™ 1500 are the solvent wash bed (Figure 8) and the UV curing lamp cabinet. The only post processing equipment needed for the ProJet™ 3500 is a ProJet™ Finisher oven, seen in Figure 9, which cures the print at ~70° C (~158°F). The oven melts the support material wax from the print, leaving the solidified print behind.

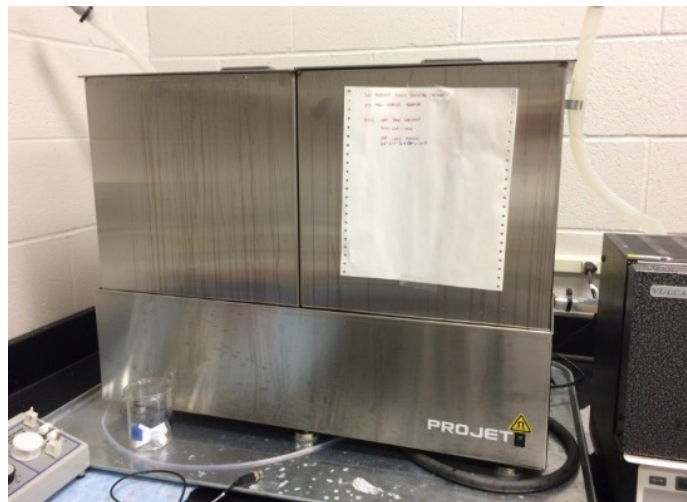


Figure 8. ProJet™ Solvent Washing Basin

Procedures and Processes

Now that the overall systems engineering process has been clearly defined, and the tools and equipment used within this specific research identified, the actual process of this specific research can be discussed. Through the implementation of the systems engineering spiral model and the use of additive manufacturing technology, this research seeks to identify specific applications for the design, printing, and testing of additively manufactured solutions. By meeting the needs of the end-user, the research looks to

provide evidence that additive manufacturing provides a unique tool capable of solving distinctive problems in an efficient and timely manner.



Figure 9. ProJet™ Finisher Oven

During any design or product improvement effort, the communication and interaction between the end-user and designer are paramount to ensure a quality final product. All systems engineering models provide a strategic approach to working through all the steps within a design and ensuring all members are on board; however, the use of more-specific guidelines helps bring the model from conceptual to practical. The spiral model, as well as any modern systems engineering model, utilizes “Interaction Design” to ensure proper communication among all the different stakeholders. Interaction design, which works concurrently with any selected systems engineering model, is a process specifically outlining the required steps to walking through a design

or product improvement. The steps of interaction design include the following (Preece, Rogers, & Sharp, 2007):

- 1) Identify needs and establish requirements for the user experience.
- 2) Develop alternative designs that meet those requirements.
- 3) Build interactive versions of the designs so that they can be communicated and assessed.
- 4) Evaluate what is being built through the process and the user experience it offers

Needs Identification

Certain product attributes make it advantageous for production using AM processes. These include low-volume production numbers, customizability of the product, and flexible designs. Tools and products already within the CE inventory can be rapidly redesigned using AM to reduce material usage, make the tool more efficient overall, and be ready for any “just in time” applications. Additionally, AM can be used to design and print jigs and specialty parts needed to solve current CE frustrations. First one must identify processes within the CE shops that might be made more efficient through the redesign and printing of an original tool. The design process begins by determining exact requirements of the part, possible constraints that limit the design, and the end performance or technical result needed by the user.

Design Process

Once the requirements have been identified, the design process begins. The Solidworks® tutorial gives explicit instructions for creating shapes, cutting holes, and designing any product. After opening the Solidworks® design software, one must select

U.S. standard dimensions or metric system measurements for the design. Once the initial design is completed in Solidworks®, it is saved as a .STL file, the format required for the AM printer. The icon to save a design as a .STL file is located under the “save as” function within Solidworks®.

Product Printing

The saved .STL file is loaded into the printer software on the connected laptop. Based on the printer’s settings, this can also be done remotely if the printer is connected to a network. The diagnostics of the printer and the print polymer levels are tested prior to starting a print. The diagnostic makes a reliable print more likely; checking the levels guards against an interrupted job.

Product Post Processing

When the 3D Systems® ProJet™ 3500 finishes printing a design, the print platform is removed from the printer and placed in a freezer for 5~10 minutes. The freezer separates the build platform from the print and prepares it for the next stage of post processing. The build platform is removed from the freezer and carefully separated from the print, which is placed inside the ProJet™ Finisher oven at ~70° C (~158 °F). The print needs to be rotated every 15~30 minutes until support materials have melted away. Soaking the print in ethanol for ~5 minutes removes final traces of waxy residue from the printed piece. If the printed piece has any moving parts, air tool grease or WD-40® does an excellent job of lubricating the moving parts. Once the waxy residue is gone and parts are sufficiently lubricated, a Dremel® tool can be used to sand down any remaining rough edges.

Product Testing

After printing and post processing, the tool or part is actually tested in a training environment. The test must be conducted thoroughly and designed to test both the utility and the durability of the product—the product must complete its intended task and, unless it is sacrificial by design, survive intact. All initial requirements for the product must be analyzed in a scenario simulating an actual operational setting. If any test is failed or if changes to the design are needed, the product’s design is altered and the process restarts. Only after the final product is handed over to the user can the design be considered complete. Following completion of the design and testing of the tool, a usability survey is given to the user to evaluate the actual usability of the product.

Usability Survey

Usability, as defined by (Reiss, 2012), “deals with an individual’s ability to accomplish specific tasks or achieve broader goals while ‘using’ whatever it is a person is investigating, improving, or designing – including services that don’t even involve a ‘thing’ like a doorknob.” Based on the six specific factors defining usability, a 19-question survey was developed and given to the user after the final printed part was handed over. The survey includes six different objectives or components defining the overall concept of usability. Each goal is operationalized using a semantic differential scale, which utilizes opposite terms along a scale to rate the user’s reaction to the product (Nielson, 1993). Based on the scale and the rating for each question, overall user satisfaction with the product determined its usability. The final rating for subjective satisfaction was calculated from the average overall rating for each objective. The

usability objective title was hidden on the survey given to the users and the questions below were randomized:

1) Quality

a. Overall reaction to the new tool/part

- i. Useless 0 1 2 3 4 5 6 7 Useful
- ii. Difficult 0 1 2 3 4 5 6 7 Easy
- iii. Fragile 0 1 2 3 4 5 6 7 Durable

2) Effective to use (effectiveness)

a. For its desired purpose, the size of the printed part is _____:

- i. A Hindrance 0 1 2 3 4 5 6 7 Optimal

b. The installation of the part is _____:

- i. Easy 0 1 2 3 4 5 6 7 Difficult

c. The printed part could be effectively used in _____:

- i. Training Only 0 1 2 3 4 5 6 7 Fully Operational Uses

d. Iterative testing process _____ additional unforeseen problems

- i. Created 0 1 2 3 4 5 6 7 Solved

3) Efficient to use (efficiency)

a. Compared to original process, the new tool makes the process:

- i. Less efficient 0 1 2 3 4 5 6 7 More efficient

b. Due to the part being printed, _____ specialized tools are needed for installation:

- i. Several 0 1 2 3 4 5 6 7 None

c. Tasks when using the tool can be performed in a straight-forward manner:

i. Never 1 2 3 4 5 6 7 Always

4) Safe to use (safety)

a. Overall safety of product:

i. Dangerous 0 1 2 3 4 5 6 7 Safe to Use

5) Having good utility (utility)

a. Aside from the primary purpose, there are _____ other possible uses for tool:

i. No 0 1 2 3 4 5 6 7 Multiple

b. At home station, _____ other uses within your flight exist for 3D printed solutions to improve operations:

i. None 0 1 2 3 4 5 6 7 Multiple uses exist

c. In deployed environment, _____ other uses within your flight exist for 3D printed solutions to improve operations:

i. None 0 1 2 3 4 5 6 7 Multiple uses exist

6) Easy to learn (learnability)

a. Learning to use the tool was:

i. Difficult 1 2 3 4 5 6 7 Easy

b. Discovering additional uses for the tool is _____:

i. Difficult 1 2 3 4 5 6 7 Easy

c. A _____ amount of Supplemental Reading/Training Required prior to using the tool:

i. Time Intensive 0 1 2 3 4 5 6 7 minimal

7) Easy to remember how to use (memorability)

a. Retraining needs to be done _____ to stay proficient on the tool:

i. Often 0 1 2 3 4 5 6 7 Never

b. Advanced technical skills required to use the tool:

i. Expert 0 1 2 3 4 5 6 7 Basic

The Internal Review board exemption package for the survey can be found in Appendix A.

Data Analysis

To ensure proper evaluation and analysis of the survey results, each designed part must have at least two surveys filled out by different users. The median survey results and standard deviation of the overall results to the questions were then tested to prove the questions consistently garner responses that accurately portray the authentic usability of the product. These calculations are discussed further in Chapter IV.

Summary

In conclusion, the research being conducted with this thesis took part in two phases. Phase 1 determined a need, developed a design, and built and tested a product. This hands-on approach provides a proof of concept for the application of designing and printing tools and jigs within a CE squadron. Phase 2 acquires and interprets more-qualitative data through the use of a semantic differential scale “usability” survey. The intention of the survey, taken by at least two different users for every printed item, is intended to prove the usability of the actual product. By assaying user opinions of the six components of usability, the results of the survey will evaluate examples of AM as a

technology to provide specialized tools capable of providing unique solutions to some unsolved problems facing the Air Force today.

IV. Analysis and Results

The preceding chapter presented the research methodology utilized within this thesis. The methodology primarily outlined the process within Phase 1 for designing a part using a systems engineering methodology and printing the part using additive manufacturing technology. The processes involved in printing an additively manufactured part were described in detail, as was the semantic differential survey used to determine the viability of additive manufacturing within the Air Force civil engineering career field. The design methodology as described in Chapter III was conducted between January and December of 2015. Subsequently, the “Usability” survey was conducted during the months of November and December 2015. The results of each of these phases and an analysis of these results are presented in this chapter.

Additively Manufactured Part Designs

This section covers the AM applications identified within the research. Overall, the identification of six separate parts is discussed, including an in-depth analysis of each design, printing, and testing process. Additionally, the usability results from each corresponding survey are analyzed. Overall, each part proved unique in its challenges and design criteria, and the results acknowledge the general usefulness of the designs and the implementation of the additive manufacturing process within CE operations.

EOD Bracket Design

The design of the Explosive Ordinance Disposal (EOD) bracket evolved from the career field’s need for a piece of equipment to attach specific hazardous material (HAZMAT) sensors to the arm of their main unmanned ground vehicle (UGV). EOD

technicians utilize the Northrop Grumman Remotec[®] UGV, for hazardous duty operations, including field inspection and detonation of explosive devices (Figure 10). The primary focus of the AM applications discussed in this research is localized to the robot arm assembly (Figure 10), which is specified in detail using measurements, drawings, and photographs. *3D Printing Makes Explosive Headway at AFIT* and *3D Printing Handbook: Product Development for the Defense Industry*, both provide details about EOD's mission, the background of the bracket's requirements, and in-depth design analysis of the different prototype iterations.



Figure 10. Northrop Grumman Remotec[®] Unmanned Ground Vehicle (left) (Cooper, 2011). Arm Assembly on the Northrop Grumman Remotec[®] UGV (right)

During the initial requirements meeting, the main purpose and need for the bracket was described as a quick attachment allowing the EOD technicians to switch among three sensors. Each sensor was used for a separate and specific type of chemical, biological, radiological, nuclear, and explosive (CBRNE) threat. EOD technicians at

Wright–Patterson AFB typically utilize four different sensors (Table 2) during their operations.

Table 2. Summary of Sensors

Sensor	Function	Dimensions (in) (width × depth × height)	Weight (lbs)
Victoreen® Fluke® Biomedical 451P	Radiation survey of environment	4 × 8 × 6	2.4
MultiRAE ® PGM® 6248	Multi-threat monitor for radiation and chemical detection	3.8 × 2.6 × 7.6	1.9
identiFINDER® R400	Detects, locates, measures and identifies radionuclides and isotopes	9.8 × 3.7 × 2.9	3.2
Smiths Detection® LCD 3.2E (aka JCAD M40)	Real-time detection of chemical and toxic substances	4.3 × 7.1 × 2.0	1.15

Most EOD operations utilize each sensor on an independent basis, so there was not a specific design requirement to attach more than one sensor to the UGV. Since sensors differ in dimensions, weights, and functions, as shown in Table 2, it was important to understand which sensor characteristics comprise design constraints. The Victoreen® Fluke® Biomedical 451P sensor (Figure 11) was used as the main target during the prototype design—being the largest sensor it had the greatest depth requirement. Weight was not a concerning factor during the initial prototype design. Based on the risk analysis of the requirements and design, the EOD technicians were counting on the bracket to securely hold each sensor on the robot. Any malfunction by the bracket could put EOD personnel in harm’s way to retrieve the failed bracket and sensor; therefore, the two most important requirements for mitigating the analyzed risk were (1) securing the bracket to the robot, and (2) securing the sensor in the bracket.

As the design process kicked off, the initial design was a solid bracket that attached to the robot using a bridge piece to be held by the anchor points and the robot's rotating hook (Figure 12). Walls on the four sides of the bracket would hold the sensors in place on the robot. As this was the initial design, satisfactory attachment of the bracket to the robot was the main consideration. Ensuring each sensor was secure on the bracket would come later in the design. The first iteration did not make it to the printer because it was excessively large and did not meet all requirements mandatory for the design to move forward. In iteration 2, the design team had more experience with the 3D printer and understood better how to design a product to achieve the best results from the print.



Figure 11. Victoreen® Fluke® Biomedical 451P sensor

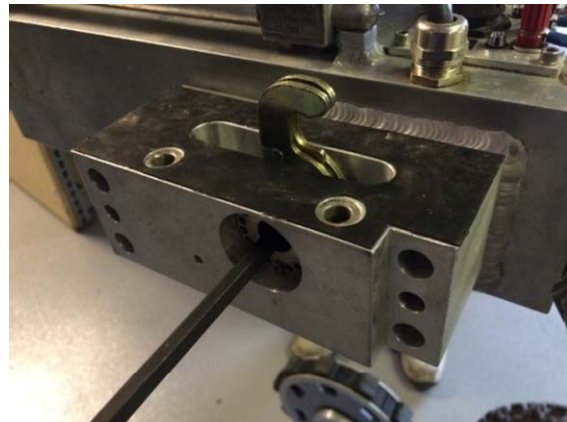


Figure 12. Anchor Points and Hook Attachment for Bracket on the EOD UGV

Iteration 2 evolved with the notion that an additively manufactured product is weakest in the z direction (vertical). Knowing this and also understanding that the bracket had to be built to secure the large sensors, iteration 2 tested the notion of printing multiple parts that would be assembled prior to the printing process. Using squares placed at standardized distances across the bracket, walls were designed to slide into and out of the holes. This conceptually allowed the walls to be moved in and out based on

which sensor was being used in the operation. A large hole was also incorporated into the design for the handle of the largest sensor. As it was the only sensor with a handle, this hole could carry the sensor instead of requiring the bracket to secure the entire sensor on top. The hole for the handle turned out to work and was continued in other iterations. On the other hand, the concept of assembly turned out to be flawed due to tolerances of the printer, which caused the walls to not fit correctly and not securely attach the sensor to the bracket; thus, iteration 2 made it past only the printing phase.

Iteration 3 was an assembly in greater depth, based on the design of clips found on suitcases and backpacks. The design tested the print material's ability to bend before locking the piece in place. The elasticity of the material proved to be too little—each print snapped during assembly. Iteration 3 was scrapped prior to field testing. Failures based on the assembly design, inspired a new concept that was discussed and integrated into iteration 4.

The iteration 4 design recognized that additive manufacturing's potential to quickly and efficiently print parts and tools for unique situations did not exclude fabricated components. Elastic bands, available at any retail or home improvement store, were incorporated into the design of iteration 4. Using a base to attach the bracket to the robot, 3 connection points were added on either side of the bracket to attach the elastic bands and secure the sensors on the bracket. Only one piece had to be printed and the elastic bands allowed for EOD technicians to quickly detach and switch sensors in a matter of seconds. Iteration 4 was the first prototype taken to EOD for field testing. The design was successful in that it secured the sensors to the bracket; however, the hook put

too much force on the bridge and cracked the bracket. Iterations 5 and 6 retained the elastic bands and focused on strengthening the bridge for the attachment of the part to the robot.

Iteration 5 moved the bridge slightly lower and added material underneath it to provide more resistance to the hook. Additionally, the design was refined to decrease use of material. Unneeded sections of the bracket were cut out, thus requiring less material for printing. The bridge again failed during the testing of iteration 5. For iteration 6 the design team explored alternative methods for securing the bracket to the robot.

The method of securing the bracket to the robot had not changed since the beginning of the initial design. This method was based on how the other EOD attachments were connected to the robot; however, they were made of steel and had far superior shear strength than the additively manufactured parts. The printed bracket was much lighter than any of the other attachments, so the full force of the hook was unnecessary to hold the bracket down. Using the same elastic bands being utilized to secure the sensors, the new design called for attached tightly stretched band within the interior of the bracket, ran it through a hole where the bridge used to be, and then attached it to one of the connection points on the opposite side of the bracket. The tightness of the band provided the needed strength to hold the bracket down, but also was flexible enough to withstand the force of the hook on the elastic strap. This prototype included a few other small modifications based on last-second needs from EOD. This print tested successfully in the field and passed an operational test within a controlled training scenario. Figure 13 shows the bracket being tested with the identiFINDER® R400 successfully attached to the robot. A look at the progression from iteration 1 to

iteration 6 can be seen in Figure 14. Following testing, the bracket was handed over to the EOD shop for use.

Multiple brackets were printed and given to the EOD shop for use in training and operations. The design was also sent to multiple other EOD units across the country for printing and use. EOD technicians quickly reported finding other uses for the bracket within their training, and are continuing to look for ways to leverage their new tool and

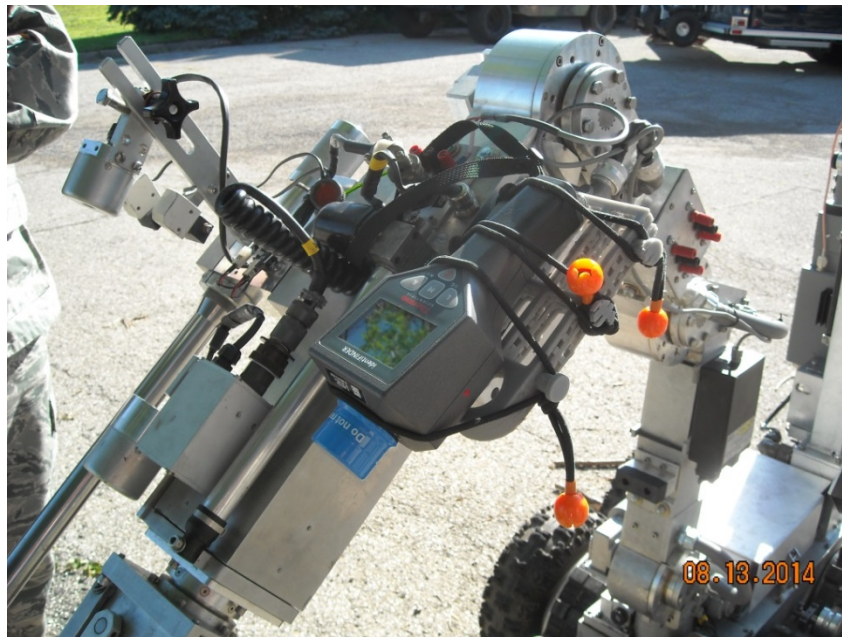


Figure 13. EOD Bracket with IdentiFINDER® R400 Attached

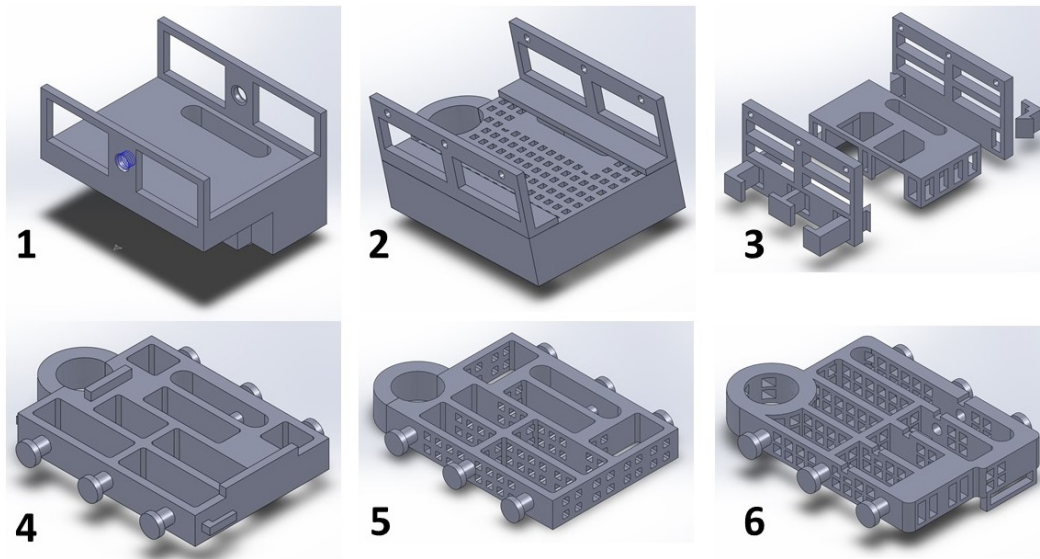


Figure 14. EOD Bracket Design Progression (Six Iterations)

3D printing technology within their shop. In Figure , the bracket was set up to carry one of the unit's backpack sensors that is normally used to inspect Conex boxes for explosives. This is important because the weight of the sensor was driving normal EOD operations and requiring an EOD operator to carry the sensor in to inspect those units. Other units



Figure 15. EOD Bracket with Backpack Sensor Attached

found that they could attach multiple sensors to the bracket at the same time, as seen in Figure 16. In the end, the overall design went through six major iterations and multiple tests. The first prototype tested (iteration 2) required 551g of material and was extremely bulky and heavy. In contrast, the iteration 6 design required 240g of material and proved to be light and efficient. The design of the robot bracket took 10 months, mainly due to logistics within the research; however, multiple iterations and designs were turned around in less than 24 hours when the resources and time were available.



Figure 16. EOD Bracket with Two Sensors Attached

EOD Bracket Survey Results

The usability survey was given to the three EOD technicians who had the most experience using the robot within the Wright–Patterson EOD shop. Their time in service ranged from 4 to 8 years, and their ranks included airmen and non-commissioned officers (NCOs). Each technician understood that the survey measured the usability of the specific EOD bracket and was not based on any other experiences with 3D printing. The

results of the usability survey, shown in Table 3, are broken down by each component and then aggregated into an overall score.

Table 3. EOD Bracket Usability Survey Results (*n* = 3 Responses)

Objective	# of Questions	Evaluator Scores			
		High	Low	Mean	Standard Deviation
Quality	3	7	5	6.44	0.88
Efficiency	3	7	7	7.00	0.00
Effectiveness	4	7	3	6.50	2.82
Utility	3	7	3	5.78	1.86
Learnability	3	7	3	6.11	1.76
Safety	1	7	7	7.00	0.00
Memorability	2	7	5	6.67	0.82
Aggregate	19			6.44	1.28
90% CI Limits		7.00	4.80		

As discussed in the methodology chapter, each survey question measured a certain usability objective and the range of scores was 0 to 7. The EOD bracket received a perfect score (7.0) for objectives dealing with efficiency and safety. Scores for the aspects of usability, memorability and effectiveness were also close to perfect, averaging 6.67 and 6.5, respectively. The 6.67 memorability score echoes that the bracket might require minimal retraining for members after an extended time away from the tool, and the 6.5 effectiveness score mirrors one technician's belief that the bracket is a bit more useful in a training role than in an operational role. The two younger technician's viewpoints were not aligned with the more-experienced NCO, who scored the bracket well for the memorability and effectiveness objectives.

The numerous iterations required to perfect the cracking bridge piece within the part resulted in a lower quality component score of 6.44. The only quality question receiving less than optimal scores was the durability component of the bracket. The final

design fixed the cracking of the bridge; however, tests still showed that a 5-ft drop caused the plastic material to break. Quality scores were near the average among overall scores of the usability components.

The two lowest-scoring components were learnability and utility, having a mean result of 6.11 and 5.78. The lower scores for learnability and utility of the bracket were inferred from questions about additional uses for the bracket. Within the usability construct, a product's ability to accomplish multiple tasks other than the original requirement increases its utility. It is not a negative thing for a part to only be able to accomplish one task; however, its utility score will remain low. During initial testing, additional sensors, not incorporated into the original design, were successfully tested on the bracket, and camera attachments were discussed as ideas for future designs. Other than those few additional uses, the technicians considered it difficult to find other uses for the tool. It successfully completed the job it was intended to do, but the overall feeling from the technicians was that the utility and learnability was a little less than ideal.

Based on the aggregate results from the survey, the 90% CI range from all the questions was 4.80 to 7.0. A score of 0.0 is complete usability failure, and 3.5 indicates no improvement over current practice. The results from the EOD bracket indicate that certain areas can be improved upon, but the overall usability of the part was a success; therefore, the bracket is determined to be a useful tool.

Computer Engineering Microchip Jig Design

Even though this research focuses on civil engineering applications for additive manufacturing, potential uses for the technology far outreach the boundaries of the CE career field. Students in computer engineering, another graduate degree focus at AFIT,

use a specially made jig to hold their microchips in place to make modifications and repairs. The jig, which is difficult to order and bulky in size, does not fit every model of microchip used in their research. The need is for a jig that securely holds various microchips and that fastens to the bed of the testing equipment. Microchips of multiple sizes are used by the engineers and one jig did not have to fit all. The engineers required a jig that fits the chips currently being used; however, they also wanted a saved design that could easily and quickly be changed and printed when needed. As the engineers had been using a jig, which is where iteration 1 began.

As before, the original jig was large, bulky, and inefficient. The area required to hold a microchip accounted for only 10~15% of the overall material area, so building that jig was wasteful of material. Iteration 1 designed around the required microchip area and the location of the bolts for the bed of the equipment. These were the only areas where material was required. Once the microchip area was outlined and the straightest path to the bolts was built, iteration 1 was complete. The part was printed and went into the testing phase. Within this phase, a new requirement surfaced that was incorporated into iteration 2.

During the modification and repair of the microchips, sensors are placed on the microchip to monitor certain functions. These sensors are delicately connected to the chip and rest on the jig during the repair process. The “excessive” area removed from the design of the old jig left nowhere for the sensors to rest, which resulted in their falling off the jig and disconnecting from the microchip. The second design, seen in Figure 17, provides an adequate area for the sensors to rest adjacent to the microchip. The second prototype passed all tests and is now in use within the computer engineering department.

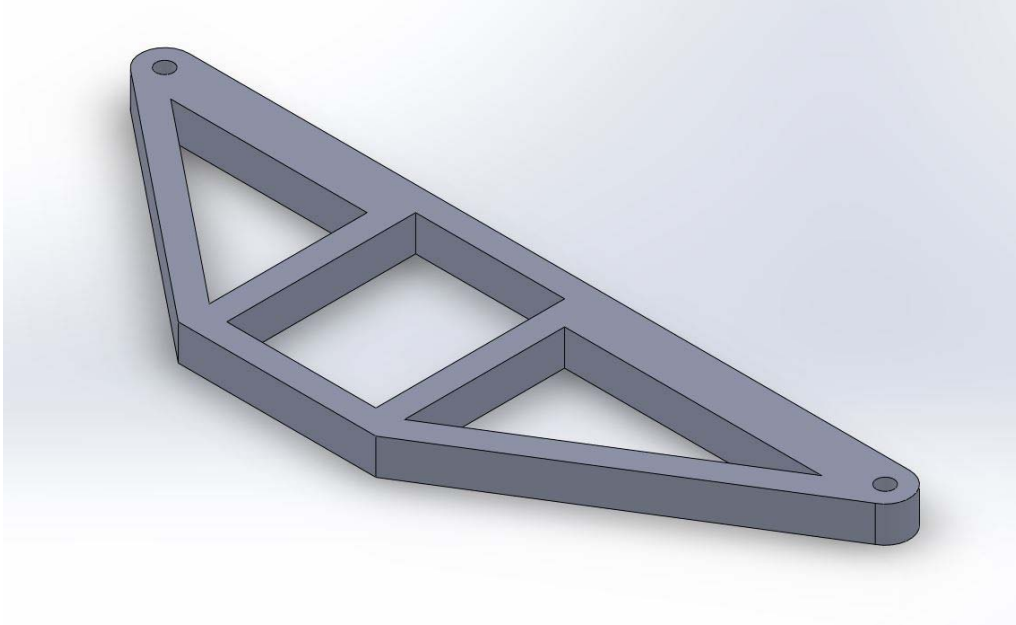


Figure 17. Computer Engineering Jig, Iteration 2 Design

The printed jig and the CAD design, were handed over following final testing. According to the requirements identified at the beginning of the design, the user is now able to quickly change the needed dimensions of the jig and reprint the tool. The time table for the actual tool, seen in Figure 18, from the identification of requirements to handing off the part, was approximately 1 month. The next section discusses the results of the usability survey evaluating the computer engineering jig.

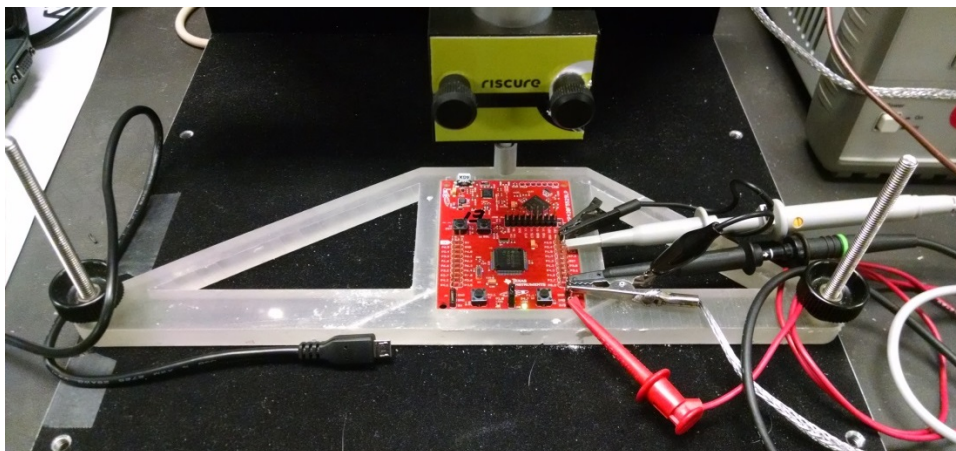


Figure 18. Computer Engineering Jig in Operational Use

Computer Engineering Microchip Jig Survey Results

The computer engineering jig was used by only two members in the department; both US Air Force Majors, and both took the usability survey. Their time in service ranged from 13 to 15 years. The results, seen in Table 4, and discussion are found below.

Table 4. Computer Engineering Jig Overall Usability Results ($n = 2$ Responses)

Objective	# of Questions	Evaluator Scores		
		High	Low	Mean
Quality	3	7	5	6.33
Efficiency	3	7	0	4.50
Effectiveness	4	7	5	6.50
Utility	3	4	0	2.67
Learnability	3	7	3	5.83
Safety	1	7	7	7.00
Memorability	2	7	7	7.00
Aggregate	19			5.53
90% CI Limits		7.00	2.80	

The results from the usability survey for this jig appear to be anomalous when compared to the results from the other printed parts. At first look, it is difficult to understand the extreme variation in scores; however, when analyzing relevance of the questions to the job description of the personnel using the part and taking part in the survey, a clearer picture emerges of why the results are so significantly different.

Engineers with an Air Force Specialty Code (AFSC) designation of 62E are referred to as developmental engineers, and job descriptions in the developmental engineering career field differ completely from those within civil engineering. Developmental engineers typically work in research and development areas and are not subject to many deployments or operational taskings. Thus, several questions within the usability survey that were

directed toward deployments or operational job duties are not relevant to the experience and duties performed by those taking the survey for the computer engineering jig.

The specific objectives most affected by the difference in job duties include efficiency, utility, and learnability. Since the part is used within a larger machine for microchips, the installation of the printed tool still requires the use of other equipment to ensure proper placement. This resulted in the efficiency metric being skewed by low answers for the one question.

The utility and learnability of the part were both low due to the specific questions being asked. The tool was printed for a specific purpose and could not be used for anything else. Furthermore, because the tool was designed for a research and development-based career field, applications within their job for 3D printing were not applicable at home station or within a deployed environment. When the participant was asked about giving the score of a 4, they answered based on the assumption that 4 would be interpreted as “Not Applicable” or “not good or bad.” Based on the findings, the specific questions led to low scores for utility and learnability. AM’s ability to design a product specifically for one purpose resulted in a decrease in the utility of a part. This decrease, while it does not mean a poor product, it does skew the actual usability results as a whole. A lesson here is that future surveys should include a “Not Applicable (N/A)” choice to allow a person taking the survey can answer in a more reliable manner without skewing the overall results.

As the objectives with skewed results can be disregarded, the other four usability components scored well. Markdowns for effectiveness came from the user who regarded the size of the part not optimal and thought the design process should have identified the

unforeseen problem in the first design. When interviewed about the scores, the user did not answer how the jig was imperfect, but did concede that the problem was an additional requirement that was not identified during the initial design process. Regarding the size of the part being a hindrance, the amount of material used in the final design was 60% less than for the original part, and product weighed almost 43% less. The design team could find no way to meet all the requirements and shrink the part any further.

Even with the mismatched questions, the jig's mean score was 5.53, which identifies an improvement in usability. Due to the small sample size, the variance and other statistical measures are greatly multiplied and end up skewing the end results. The 90% CI range for the overall usability score is 2.8 to 7.0. This is a larger gap than any other printed part within the research, so the research concludes that while the literal result implies a slightly better of "neither usable nor nonusable" product, a more-qualitative interpretation of the overall results clearly identifies a "completely usable product." In the end, the product was deemed extremely useful based on the stakeholder being pleased with the design and they are currently using it for their computer engineering operations.

Utility Pipe Inspection Autonomous Vehicle Bracket Design

Among the numerous innovations being researched at AFIT, another researcher is looking into the possibility of being able to conduct underground utility infrastructure inspections through the use of completely autonomous vehicles is intriguing for many aspects within civil engineering. Similar to the current condition of aboveground infrastructure, much of the infrastructure below the surface is just as degraded and well beyond its useful life. The ability to conduct accurate inspections and then pinpoint

where the next failure will occur has the potential to mitigate millions of dollars in contingency spending for broken water mains and utility lines. Due to the nature of this research, the researcher designed a vehicle, seen in Figure 19, to be placed inside utility pipes and carry out inspections based on specific inspection parameters. Several pieces of equipment designed to go on the robot were more difficult to attach than originally expected. The lightweight and customizable benefits provided by additive manufacturing enabled the researcher to continue their research without compromising their vehicle due to the equipment limitations. The parts designed and printed for the autonomous vehicle project are discussed in the following sections. An overview and interpretation of the usability survey results follow the discussion of the design for the autonomous vehicle parts.

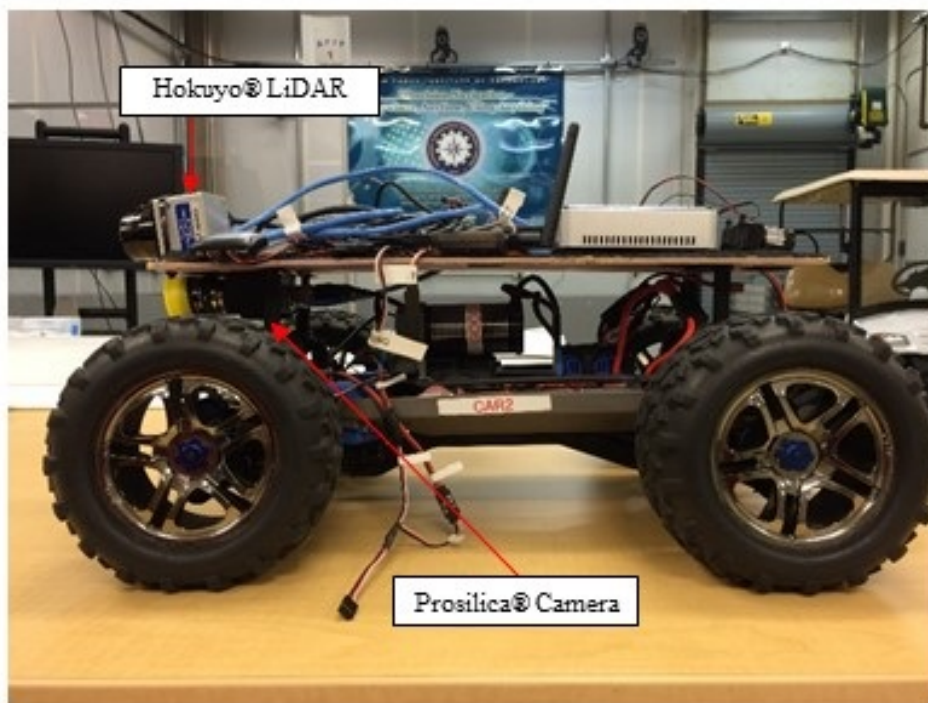


Figure 19. Autonomous Utility Inspection Vehicle

Front Camera Bracket Design

The first piece of equipment designed for the autonomous utility inspection vehicle was a dual bracket intended to go on the front of the vehicle and hold both a light, detection, and radar (LIDAR) sensor and a digital video camcorder. The Hokuyo® URG-04X-UG01 LIDAR sensor, conducts a 270° scan of the pipe and its programmed algorithm detects any anomalies. Prior to the additive manufacturing bracket design, attaching the front LIDAR sensor required running a plastic cord (cable tie) through holes in the base plate of the vehicle, seen in Figure 19; however, the geometry of the sensor caused it not to sit exactly level, which made it difficult to orient the sensor perfectly level with the vehicle and limited the reliability and range of the sensor, which is critical to accuracy of data it generates. The sensor must also be far enough forward of the vehicle so that its sensor can freely perform the perpendicular 270° scan around the diameter of the pipe. The digital camcorder, pictured in Figure 19 and Figure 20, provides both light and a video feed to the inspector. The required tilt of the camera was exactly 39° based on the focus specifications and the inspector's need to see approximately 10 inches in front of the vehicle. The camera has to sit up high for a good picture, but must not block the scan from the LIDAR sensor below it. These requirements were taken into account as the additive manufacturing design began taking shape.

From the start of the design, due to the conditions of the inspection, the most important risk analysis factor was the difficulty of retrieving any item that fell off the vehicle if the printed bracket failed during an inspection. Based on this, the connection of the bracket to the vehicle was rated equally important as securing the equipment to the

printed part. The main design constraint was the limited number of areas available for attaching the part to the robot.



Figure 20 – Prosilica GC1290C Camera (AVT, (n.d.))

From a distance, the LIDAR sensor looks like a cube with a lens on the front; however, the rear of the unit is larger than the front, so it points slightly down when set on a level surface. The original design, seen in Figure 21, developed a box slightly sloped from front to back to hold the LIDAR sensor completely level. The rest of the box surrounded the sensor and fit snug. The design placed the camera on top of the LIDAR sensor sloped at the required 39° and provided a hole for the camera lens to slide through. The approximate size of the camera lens was equal to the height and width of the other parts of the camera; therefore, the design intended the attachment of the lens to take place prior to placing it into the bracket. This actually held the camera in place and did not require any other constraints to fasten the camera to the bracket. Iteration 1 worked well during testing; however, the researcher needed the camera height increased and an area cut out for cabling to be connected to ports on the right side of the LIDAR sensor. Iteration #2 took into account those design changes.

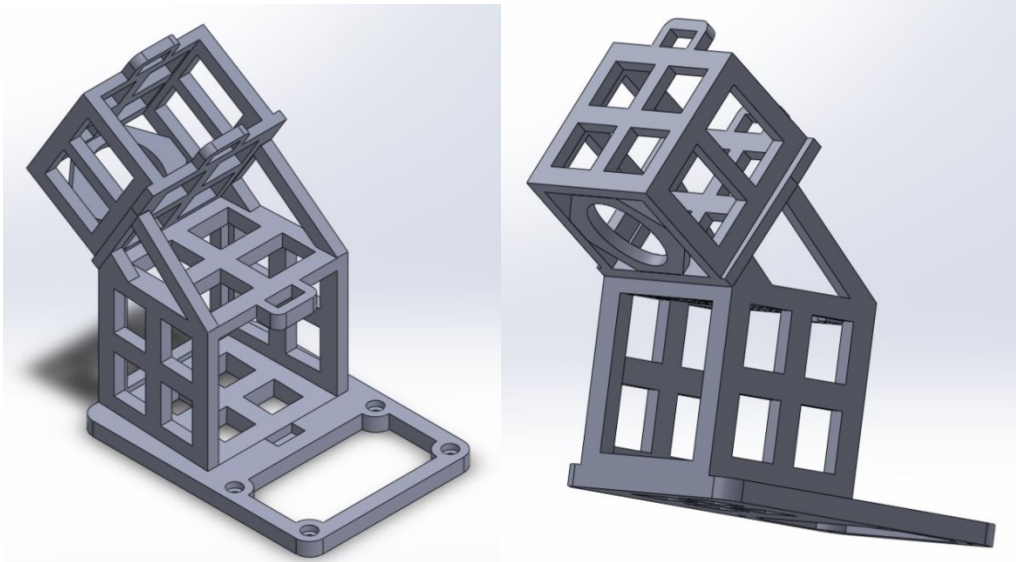


Figure 21. Autonomous Vehicle Front LIDAR and Camera Bracket Iteration #1

The second iteration of the design for the front LIDAR and camera bracket elevated the camera and the port connection area on the right side of the LIDAR sensor. The designed part, seen in Figure 22, has four connection points rearward of the LIDAR area. These points will bolt to the frame of the autonomous vehicle and hold the entire bracket in place. Testing of the bracket proved successful, and it and a spare, were handed over to advance the civil engineering autonomous vehicle research. Pictures showing the testing of the bracket can be seen in figure 23. The total time for the identification of requirements, design of the part, printing, and testing took approximately 2 weeks. The survey results for this part are discussed in a later section.

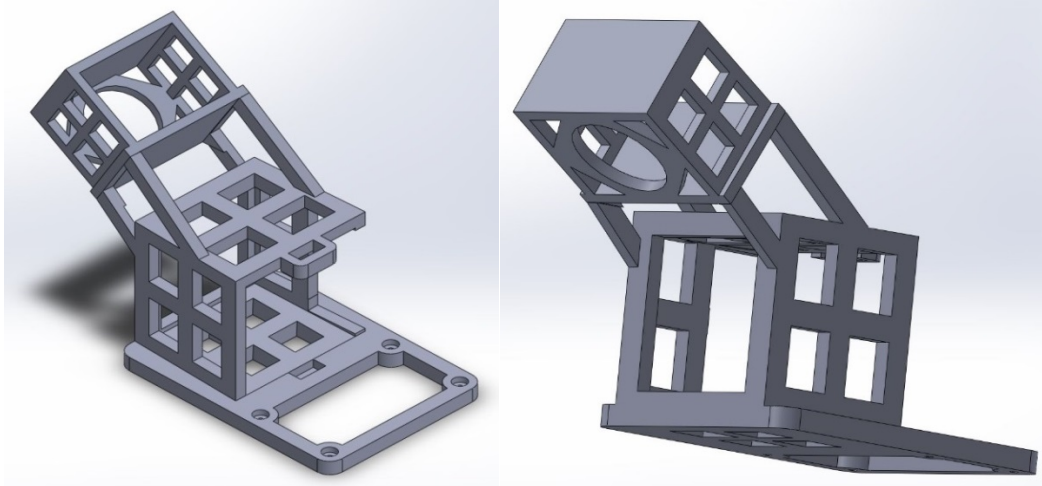


Figure 22. Autonomous Vehicle Front LIDAR and Camera Bracket Iteration #2

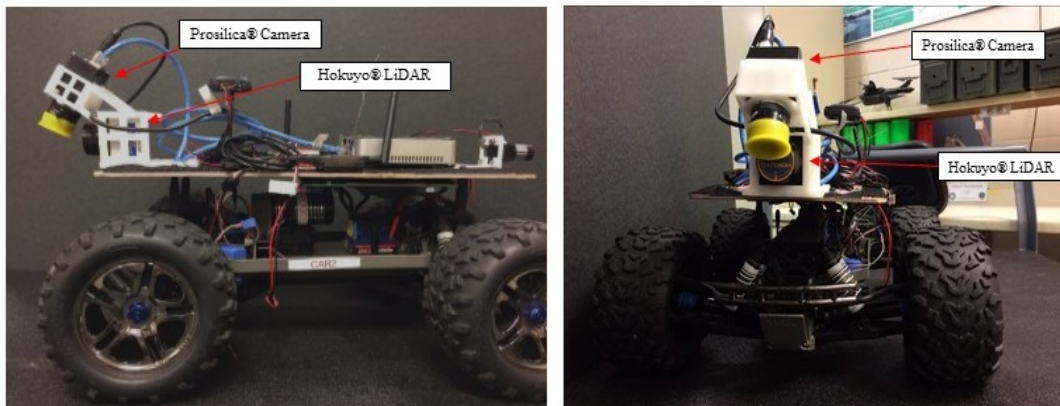


Figure 23. Front LIDAR and Camera Bracket Testing

Rear LIDAR Bracket Design

The autonomous vehicle required a separate LIDAR sensor, the Pulsed Light, Inc® LIDAR Lite™ unidirectional laser range finder, on the rear of the vehicle for the purpose of determining specific distance and location measurement. The sensor, seen in Figure 24, shows four separate connection points; however they are perpendicular to the base to the vehicle. Again, prior to an additive manufacturing solution, this LIDAR sensor was cable tied to the base near the rear of the vehicle. Due to the sensor's having

zero requirements for placement on the vehicle, the original location unnecessarily took up valuable space on the base plate. The design of the LIDAR bracket aimed to free space for on the robot by strategically removing the sensor from the footprint of the base plate and hanging it from the rear of the vehicle.



Figure 24. LiDAR Lite™ Range Finder (RobotShop, n.d.)

This component required a single design iteration (Figure 25) and included four connection points for attaching the bracket to the vehicle and four connection points for attaching the sensor to the bracket. The testing of the rear LIDAR bracket proved extremely successful and provided more reliable results from the LIDAR sensor than in previous tests. Since this design allowed the connection of the sensor to the vehicle without taking up critical space, the researcher was able to improve the location of certain other pieces of equipment on the vehicle. The design process for the rear LIDAR camera

took approximately 1 week. The bracket, successfully attached to the robot, is seen on the far right hand side of Figure 26. Following the completion the bracket, those taking part in the autonomous vehicle research took part in the usability survey. Their results solely described their feelings regarding the process surrounding the design and printing of the rear LIDAR bracket and are discussed in a later section.

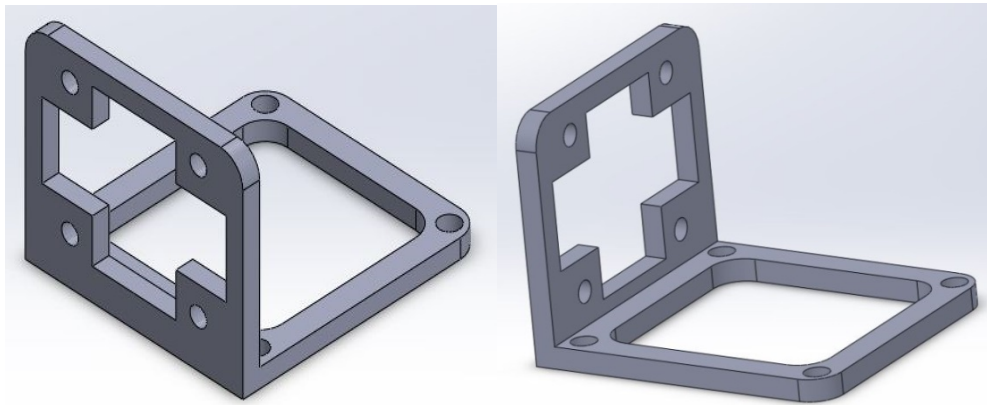


Figure 25 – Autonomous Vehicle Rear LIDAR Camera Design

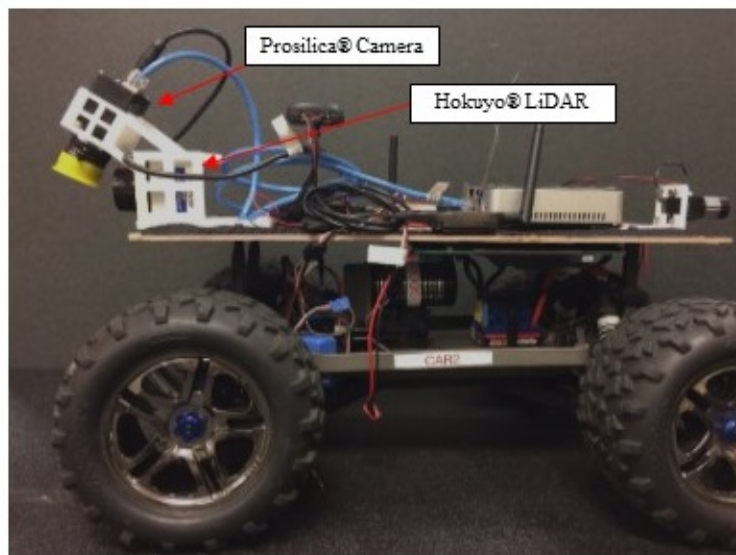


Figure 26. Autonomous Utility Inspection Vehicle Rear LIDAR Test

Large and Small Battery Receptacle Design

The autonomous vehicle and all the equipment it carries is powered by numerous batteries of different shapes and sizes. The two batteries powering all the equipment and causing limitations for the vehicle have dimensions of 7 in $\times$ 3 in $\times$ 1.5 in and the other 5 in $\times$ 2.5 in $\times$ 1.25 in. Prior to an additively manufactured solution, no practical method of securing the batteries to the vehicle was available. During test runs with the vehicle, the batteries were simply placed on top without any constraints; however, the batteries tended to fall off when the vehicle was subjected to rough terrain. The design of the battery imposed minimal requirements about the placement, except that they be spread out as widely as possible to distribute their weight. This was taken into account during the initial design process.

Two long connection pieces beneath the base plate of the autonomous vehicle snap into place to hold other vehicle pieces in place. The design from that connection piece was adapted to place two additional battery receptacles on top, the larger one on the left side of the vehicle and the smaller one on the right. The design, seen in Figure 27, created a box wherein the batteries are securely held and easily connect to the vehicle. The orientation of the two designs was due to how each side of vehicle connected to the long piece of the bracket.

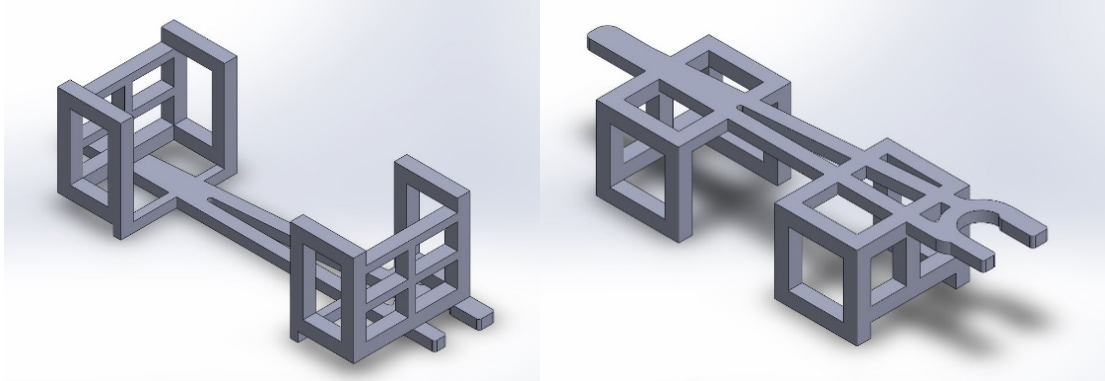


Figure 27. Autonomous Vehicle Large Battery Receptacle Design (left), Small Battery Design (right)

Additional design iterations did not change the design, only strengthened the walls for more support. Testing of the printed pieces resulted in successful prints and the two brackets were handed to the student for her research. The design and printing of each bracket, including the different iterations, took approximately 2 weeks. Following the design process, those close to the research took part in the usability survey for the two brackets. While the two brackets were discussed concurrently due to their similar requirements, each had its own design process; therefore, two separate surveys were conducted to provide the most accurate results. The attached brackets are seen in Figure 28 and Figure 29.

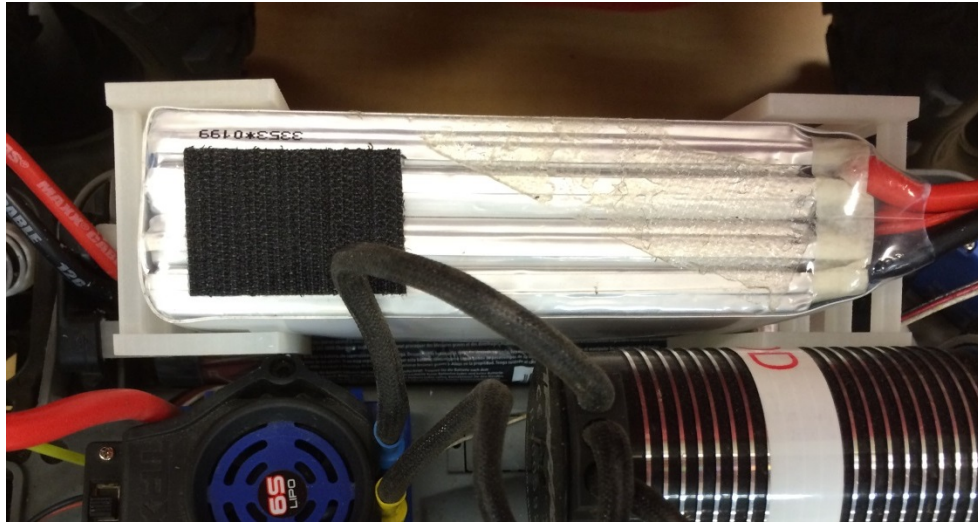


Figure 28. Autonomous Vehicle Battery Receptacle during Testing



Figure 29. Autonomous Vehicle Battery Receptacle Attached to Robot

Utility Pipe Inspection Autonomous Vehicle Bracket Survey Results

Those working on the autonomous vehicle research took part in the usability survey regarding the design and printing of the four brackets designed specifically for the autonomous vehicle. Both researchers have at least 14 years' of experience within the engineering career field. They both understood that each survey is completely based on the design and printing of only the specific bracket in question for the autonomous vehicle, and

they were instructed to not allow prior experience with 3D printing to influence their answers.

The results of all four autonomous vehicle bracket usability surveys, shown in Table 5, Table 6, Table 7, and Table 8 below, break down the resultant scores from each of the different usability objectives. An aggregate score for the usability of the each bracket is also included in Table 9.

Table 5. Autonomous Vehicle Front Camera Overall Usability Results ($n = 2$)

Objective	# of Questions	Evaluator Scores		
		High	Low	Mean
Quality	3	7	7	7.00
Efficiency	3	7	7	7.00
Effectiveness	4	7	7	7.00
Utility	3	7	3	5.67
Learnability	3	7	7	7.00
Safety	1	7	7	7.00
Memorability	2	7	7	7.00
Aggregate	19			6.79
90% CI Range		7.00	5.63	

Table 6. Autonomous Vehicle Rear LIDAR Bracket Overall Usability Results ($n = 2$)

Objective	# of Questions	Evaluator Scores		
		High	Low	Mean
Quality	3	7	7	7.00
Efficiency	3	7	7	7.00
Effectiveness	4	7	7	7.00
Utility	3	7	3	5.67
Learnability	3	7	7	7.00
Safety	1	7	7	7.00
Memorability	2	7	7	7.00
Aggregate	19			6.79
90% CI Range		7.00	5.63	

Table 7. Autonomous Vehicle Large Battery Receptacle Bracket Overall Usability Results ($n = 2$)

Objective	# of Questions	Evaluator Scores		
		High	Low	Mean
Quality	3	7	5	6.33
Efficiency	3	7	7	7.00
Effectiveness	4	7	7	7.00
Utility	3	7	3	5.67
Learnability	3	7	7	7.00
Safety	1	7	7	7.00
Memorability	2	7	7	7.00
Aggregate	19			6.68
90% CI Range		7.00	5.42	

Table 8. Autonomous Vehicle Small Battery Receptacle Bracket Overall Usability Results ($n = 2$)

Objective	# of Questions	Evaluator Scores		
		High	Low	Mean
Quality	3	7	5	6.33
Efficiency	3	7	7	7.00
Effectiveness	4	7	7	7.00
Utility	3	7	3	5.67
Learnability	3	7	7	7.00
Safety	1	7	7	7.00
Memorability	2	7	7	7.00
Aggregate	19			6.68
90% CI Range		7.00	5.42	

The usability results from the design and printing of each bracket for the autonomous vehicle reflect the researcher's gained experience and knowledge regarding the design software and 3D printing technologies. Each design process was quicker and more fluid than that of the earlier design processes which, in the end, mirrored one aspect of the comparatively better results between the designs for the autonomous vehicle and the designs from earlier in the research.

Six separate usability objectives received a perfect score for every bracket except the battery receptacles. With each bracket, “utility” was the common component not receiving a perfect score. Just as in the previous designs, the brackets for the autonomous vehicle were designed for only one use and the utility component mirrored that finding. That being said, the results from the EOD bracket and the computer engineering jig showed that due to similar questions, if usability were low, then the same should be seen in the results for learnability. Since learnability was a perfect score for all four brackets, the users of the part were questioned regarding this finding. Both users regarded the “discovering different uses for the tool” question as being tied more to the other possible uses for 3D printing, rather than the actual printed tool. This corroborates their answers on the survey, but reaffirms the possible need for additional questions within the survey or at least substantial clarification of certain questions.

For the two printed battery receptacles, each one was marked down in the quality component for not being durable. This finding was expected due to the multiple breaks that occurred during the testing of the part. The final design weighed additional material with additional durability and found that the robot could not hold much more weight; therefore, risk was accepted regarding the durability of the brackets to limit the weight of the part.

While the scores all came out above 4, which is considered usable, the main test for usability is that all four brackets are currently being used on the UGV to study autonomous vehicle utility pipe inspections. This result undeniably proves the overwhelming usability of these printed parts for the need they were intended to fulfill.

Overall Usability Results

The usability survey, given to those members for whom a part was designed and printed, resulted in identifying that each part is undoubtedly usable in the terms specified by the seven components of usability. While each part may be usable for the need for which it was designed, the question of 3D printing's ability to provide a usable product for developing unique solutions for problems within the CE career field still stands. Each bracket's usability components were rolled up to calculate an aggregate usability confidence interval in Table 9, which provides a measure of usability for each bracket.

Table 9. Overall Usability Results (n = 13)

Objective	# of Questions	Evaluator Scores			
		High	Low	Mean	Standard Deviation
Quality	3	7	5	6.56	0.79
Efficiency	3	7	0	6.62	1.39
Effectiveness	4	7	3	6.81	0.69
Utility	3	7	0	5.23	2.18
Learnability	3	7	3	5.83	1.16
Safety	1	7	7	7.00	0.00
Memorability	2	7	5	6.92	0.39
Aggregate	19			6.48	1.33
90% CI Range		7.00	4.78		

The only component to score an overall perfect score was safety, which was not surprising due to the nature of the survey question and the bracket's being designed. Memorability was a close second, with a mean score of 6.92 and a standard deviation of 0.39. Only one member, the EOD technician, believed that the bracket itself required retraining for members who had been away for a certain time period. As discussed in the autonomous vehicle section, the utility and learnability components were the lowest of any of the usability objectives. This was due to the questions regarding additional uses

for the tool. Since each tool was designed for a specific purpose, these objectives had the largest variance in responses. In the end, the mean overall response was 6.48, with a standard deviation of only 1.33. Based on the survey from all 13 users of the designed and printed brackets, the 90% CI suggests that any bracket designed and printed using additive manufacturing technology would most likely fall somewhere between a 4.78 and 7.0 on the usability scale. This score interval, along with the fact that every printed part is currently being used within the intended operation, provides evidence of the usability of additive manufacturing technology as a capable tool for solving problems within CE.

Summary

This chapter presented the results of the identification, design, and printing of potential 3D printing applications, as well as the usability surveys that were conducted for this research. In phase I of the research, specific tools and jigs were identified, designed, and printed using additive manufacturing technology. Following phase I, phase II consisted of conducting usability surveys to determine the overall value and ability of 3D printing for solving unique problems within CE. The conclusions and interpretations taken from the survey were presented to the committee for their final thoughts and opinions. The final results of this research indicate the interpretations and opinions solely of the researcher, with advisory input from the committee members, regarding various topics dealing with additive and traditional manufacturing. In Chapter V of this document, the answers to the investigative questions posed in this thesis will be derived from the results and analysis conducted by the researcher. All discussions, including additional follow-on research, will relate to the overall thesis research objective.

V. Conclusions and Recommendations

The objective of this chapter is to develop conclusions from this research and to propose recommendations for future work exploring AM applications for tools and jigs within USAF CE operations. This chapter will first evaluate the investigative questions that guided the research and ascertain answers to these questions based upon the results presented in Chapter IV. The determining answers to the research questions will then be rolled up to investigate and answer the overall research objective of this thesis. Finally, this chapter will confer recommendations for possible actions in response to the results of this research and discuss future areas of research with regards to the topic of AM within USAF CE operations.

Investigative Questions Answered

To meet the overall objective of this research, four investigative questions were analyzed. The results of the overall design process and of the usability survey were analyzed within the context of these specific questions to reach a final conclusion regarding the overall thesis research objective. Both the research questions and the subsequent analysis are discussed below.

1. What added value does 3D printing bring to USAF civil engineering?

This question was meant to explore the benefits and advantages of 3D printing through a detailed exploration of current applications, within both the civilian and military sector, by members who are utilizing additive manufacturing technology in have operational contexts similar to a USAF Civil Engineering Unit's. Within the detailed literature review, it is apparent that additive manufacturing is a technology with unknown

limitations. Companies are using the equipment in a variety of ways and developing new uses and methods on a daily basis. All of the branches within the DoD are researching applications of 3D printing within their respective operations; however, the Air Force is behind in allowing their technicians to find the best applications for the technology. The Army's Ex-Labs and the Navy's "Print the Fleet" concepts are the epitome of the expression "need drives innovation." Each of these branches realizes that introducing additive manufacturing to their technical experts within an operational environment will cause the most beneficial applications for the technology to emerge. Searching out needs and applications for a technology becomes much more difficult when attempted in the confines of an office or laboratory.

Additive manufacturing is already benefiting certain Army and Navy units through the identification of specific parts by troops in the trenches. The few parts that were designed and printed within this research prove there is a potential need and value within civil engineering for additive manufacturing. As time moves on, an exhaustive database of designs could be the answer to maintaining our outdated infrastructure. The "print to fit," as well as the "just in time" manufacturing could reduce the size of the CE footprint by doing away with inventories and material control buildings. The value added to CE through the use of additive manufacturing has been identified through the design, printing, and implementation of a limited number of parts and tools; however, the real potential value could be identified through the use of strategically placed printers for operational use.

2. *What attributes make a tool or jig a good candidate to be manufactured using additive manufacturing?*

This question looked to explore the characteristics of a tool or jig that was more efficiently manufactured using 3D printing than traditional manufacturing methods. Chapter II pointed out the laborious method that accompanied any product through a traditional manufacturing design process. This process will never go away for those items that allow for high-volume production with minimum customization, because the unit cost is unbeatable. Additive manufacturing is a benefit for those products requiring customization and quick turnaround, and of which a small number is to be produced.

Phase I of the research identified six possible applications where additive manufacturing provided some sort of solution to a recognized problem. Each of the needs could have been solved using traditional manufacturing methods. The requirements would have been identified, the constraints determined, and the design developed; however, this would have taken a greater amount of time and cost a lot more money due to the need for only one part, and the design would not have been refined due to geometric constraints and lack of design iterations. Traditional manufacturing methods would not have provided the best product for the end user.

On the contrary, additive manufacturing provided quick designs and prints. Even if AFIT had no printer for this research, 3D printing companies are emerging more and more to which a person can take a design and have it printed out. The costs were low and the iterative design process allowed for repeated testing of prototypes until the final product was exactly the way the end user desired. The design changes were simple and easy, and most parts were completed in a few weeks or less.

The attributes for benefiting from additive manufacturing extend well beyond the actual product. If the product is already created, then can additive manufacturing improve

the amount of material or design? Is the need for the part dire or can it wait? Speed, customizability, and the number of parts needed are all attributes that drive whether or not additive manufacturing provides the most benefits for the creation of the product.

To civil engineering, deployed environments and outdated equipment are common hurdles dealt with at base level. The ability of a 3D printer to print any design in a matter of hours could bring a new critical tool to the battlefield and make the engineer a more flexible and resilient warfighter.

3. *Can questionnaires about a select few printed tools and jigs be used to illustrate the value of 3D printing over traditional manufacturing?*

This question sought to establish that it is possible to show that a select few tools could be printed and the users surveyed, through the use of a questionnaire, to illustrate the value of additive manufacturing. The usability survey, conducted in phase II of the research, provided consistent results illustrating the benefits of additive manufacturing vice traditional manufacturing. As discussed in the answer to investigative question 2, certain attributes for a product make it more beneficial to be printed using a 3D printer. This point was further strengthened through the use of the usability survey.

4. *How is usability for designing and printing jigs defined and measured?*

By surveying users of the 3D printed parts and tools, this investigative question was intended to explore the benefit of having a 3D printer for the purpose of designing and printing custom jigs within the unit. Defining the term *usability* and determining a method for measuring it offers a validation test for 3D printing within CE units. Within phase II of the research, the concept of usability was integrated into a survey to determine the value of 3D printing for CE operations. Usability is a term commonly used within

software design to determine of the ease with which a user can operate a certain program or if the user can comprehend a certain platform interface. Through six objectives or components, the usability of the product is determined and then either sent back for changes or sent on for testing.

Usability, as defined within this research, is the facility with which the user is able to utilize the designed tool for the original need identified. By rating seven different properties (quality, efficiency, effectiveness, utility, safety, learnability, and memorability), a survey was conducted to determine the benefit brought to specific units for whom this research identified a problem and designed a part to solve it. If the overall consensus is that the 3D printed part provided a useable item for the units, then it will be determined that the questionnaire, coupled with the design, printing, and testing of the part, confirms the value and applicability of additive manufacturing within CE units.

Conclusions of Research

The four investigative questions were intended to provide context and shed light on meeting the overall objective of the research. The overarching objective of the research outlined in Chapter I was to determine whether 3D printing added significant value to the CE career field and if the current technology had reached a point capable of fulfilling the requirements within the career field. Based on the objective and results of the research, the following conclusions were deduced from the printing design process and ensuing usability survey results:

1. Additive manufacturing is a technology that will begin affecting a majority of the processes used on a daily basis. As the technology grows, the capability,

reliability, and technical ability of the printers will provide more efficient options for modernizing the operations within CE.

2. AM technology has reached a point at which the only way to determine and validate specific career applications is to introduce the technology into an operational environment and allow the technicians to identify areas for printing potential. Based on the successes within the Navy and Army with regards to the implementation of AM into operational units, it can be assumed that similar successes will be found over time if the Air Force chooses to strategically integrate AM into their operational portfolio.
3. Successfully introducing AM into an operational CE unit is predicated on teaching all members about the capability of the technology. Additive manufacturing is a new technology that is relatively unknown to many within the engineering career field. To fully identify the possibilities of AM within a unit, the members of the unit must be educated on how the technology works and its potential capability. Additionally, the members must be shown specific examples related to their field of work where AM improved a process, created a unique part, or created a solution based on a past need. No educational tool is more effective than allowing users to see something with which they can relate and visualize. The more members understand the potential of additive manufacturing, the more possible applications will surface.
4. Additive manufacturing offers potentially significant value for the CE career field based on the need for “just in time” manufacturing and rapid prototyping

capabilities. Further studies should explore facility maintenance, contingency basing, and other civil engineer applications.

These statements, deductively constructed from the in depth literature review, specific part design process, and usability survey results, satisfy the research objective of this thesis.

Significance of Research

This research is one of the first studies looking to identify potential applications for additive manufacturing of tools and jigs for civil engineering. As AM is a new technology and its growth seen on an annual basis is significant, this research provides a foundation and baseline for additional follow on research. While being a study for Air Force applications, the resulting conclusions are not specific to Air Force operations and can be used in the decision making of other branches. Similarly, the conclusions of this research can guide leadership and decision makers to understand the need to invest in additive manufacturing and other technologies of the future. It is imperative to continue funding research into possible applications for AM within home station and deployed operations. Only through further exploration and proof will the conclusions provide enough of a basis for a test case for operational civil engineering AM applications.

Within the literature review conducted in Chapter II of this thesis, the current processes of traditional manufacturing were identified and compared to the rapid process of additive manufacturing. An additional in-depth review of current military applications of AM technology illustrates the current state of the technology and its benefits.

Companies and militaries around the world are leveraging the potential benefits of AM as a method for making a leaner, more flexible, and more capable fighting force.

The overall significance of this research proves that “need drives innovation.” There is a need for better-designed parts and improved processes within the operations of CE and the Air Force. Decision makers should understand that the true potential for additive manufacturing will not be determined within a laboratory. The true applications for deployed and home station operations will be identified once the Airman on the ground becomes familiar with the technology and understands the process and benefits it is capable of providing.

Finally, this research is significant in showing leadership that the Air Force is behind the curve because the Army and Navy are already utilizing AM within operational environments. Multiple uses through the Army’s Ex-labs and the Navy’s “Print the Fleet” concept are delivering quantifiable savings of time and money for missions in the theater of operations. This study provides a basic process for the development and design of parts within any environment and is a significant step in determining the potential possibilities for AM within the CE career field.

Limitations of Research

While there is an unequivocal potential need for AM within the CE career field, several limitations caused the research scope to not encompass all types of tools and parts. The printing capabilities at AFIT allowed for minimal material variation within the parts and did not accommodate parts requiring multiple materials. The polymer material used in the printed tools and parts was brittle, requiring sturdy rather than more-efficient

designs. Having access to multiple printing materials would have garnered a wider range of tool applications and optimal designs. Industry employs printers capable of fulfilling these needs; however, they were not researched in depth and were not available for this research.

The other limitation is the governing body regulating the use of parts and equipment within the CE career field. Due to the nature of the work conducted by the technicians within CE, it is recognized that certain parts are considered off limits for design and printing based on regulations and codes set forth for safety concerns. This is not to say that in a deployed environment or emergency situation, AM could not be used to thwart a problem otherwise restricted based on those codes and regulations.

Recommendations for Action

As a part of the conclusions within this research, several actionable items have been identified. Each identified item merits possible future research and validation. Each of the four branches of the DoD is conducting its own research into potential applications for AM; however, very little joint research has been conducted to leverage each branch's knowledge for the betterment of the entire DoD. As a result, the Air Force has to duplicate efforts of the Army and Navy rather than utilizing the strength of their personnel to identify potential applications. Finally, a global network must be created for sharing and distribution of files for 3D printed parts, tools, and brackets. Each of these topics is discussed further in this section.

Duplication of Ex-labs/Print the Fleet

The Army and the Navy are both ahead of the Air Force in integrating AM technology into operational environments. As discussed before, both believed that if they put the technology out for the use of their technical experts, then the applications would identify themselves—and they were correct. Both branches report multiple successes in terms of cost, time, and logistical savings found through the use of printing specific parts. Training on CAD software or the capabilities of the 3D printer was not an up-front requirement—all they technician was asked to do is understand what the technology could provide in a deployed situation and then look for possible applications. If a problem could not be solved by the engineer working with CAD and the 3D printer, then CONUS reachback capability and traditional procurement methods were still available. Still, solutions were derived from 3D printing for problems brought to Ex-lab engineers at their deployed location. Similarly, the Navy is experiencing the same success after making an effort to educate each sailor on 3D printing technology, especially those on a ship carrying the technology. The Air Force does not have to reinvent the wheel when it comes to integrating the printers into an operational unit.

Currently, AM does not have a printer that completely fits all the needs within the Air Force. Each possible application within the Air Force requires the printer to use various materials, as well as specific print tolerances and sizes. Until a printer is able to switch among a large number of materials, the Air Force must realize that researching the technology will require procuring a variety of printers covering the majority of materials and print sizes. Similar to the Army's Ex-lab, the Air Force must make different types of printers available for engineers to use for unique designs and problem solving

application. The pilot study would include thoroughly educating one or two engineers on the CAD and printing equipment, followed by transporting the engineers and the equipment together in a transportable 3D printing package to a large CONUS or deployed environment. At those locations, the engineer's job will be to educate Airmen about the benefits of the 3D printer and help identify and solve problems through the use of AM printing technology. This could start with two packages and then over time expand to the point of having one package covering every region. As time progresses, members will become more knowledgeable about the technology and the number of applications will grow. This is the optimum solution without having to commit a significant upfront investment into the integration of additive manufacturing in operational CE units.

Global 3D Design Sharepoint

To receive the largest benefit from the advantages of AM, its full potential must be realized and acted upon. The difference between traditional manufacturing and additive manufacturing is that additive manufacturing does not need a mold or cast to create the part. A design finished by someone at Wright-Patterson AFB could be e-mailed and printed in Afghanistan within hours. This is why a global 3D design library site could and should be set up for engineers from around the globe to submit their designs for parts, tools, and brackets. A majority of printers accept Google Sketchup® as sufficient design software, so an Air Force-wide license is not required for members to work on individual designs. Each design would be deposited into specific system folders and then identified within the comments as to the make, model, and manufacturer that the part is compatible with. Over time, as the engineers gain experience with the CAD software, the entire CE inventory could be designed and available through this site. Certain Building

Information Modeling (BIM) software could cross reference the available designs and quickly pull them up for building requirements. This would completely negate a majority of transportation costs and risks to sending specific parts to deployed environments.

Possibilities for Future Research

Additive manufacturing is a growing technology that is still finding its place in the world. It is imperative that the Air Force and the DoD maintain their investment in additive manufacturing research to get on the leading edge of the new technology.

Possibilities for future research into additive manufacturing include the following:

- Air Force applications and validity of need for the production of large structures through the use of additive manufacturing.
- Comparison of strength characteristics for traditionally manufactured products versus additively manufactured products.
- Continuing to determine specific applications of additive manufacturing for Air Force civil engineering tools and jigs.
- Development and study of integration protocols for additive manufacturing into Air Force civil engineering operational units.
- A partnership with the Air Force Research Laboratory and America Makes, Inc. to determine methods to increase print speed while maintaining print reliability.
- Specific applicability of metal, composite, and multi-material printers within Air Force civil engineering.

Conclusion

This research has determined that 1) additive manufacturing is a technology capable of affecting future civil engineering daily operations. 2) AM has reached a point that the next step in validating its potential is to integrate the technology into a select few Air Force CE operational units. 3) Successfully integrating the technology into a CE unit is dependent upon the education of its Airman about the benefits and capabilities of the technology. 4) 3D scanning is a technology that could rapidly speed up the creation of accurate designs; however, the technology is approximately 5 years away from being reliable for the use of creating a global CE database of 3D designs. 5) AM leverages CE's need for "just in time" manufacturing and rapid prototyping capabilities within the facility maintenance operations. This approach to determining the value of 3D printing for CE operations is untested for this type of research; however, its use in software development, as well as the committee's overall approval, validates the approach taken to reach the overall research conclusion. With declining budgets and increasing demands on the operations of USAF civil engineers, AM provides a unique tool capable of providing solutions to the maintenance of outdated equipment and customizable products. The need has been identified and validated; therefore, there is no better time than now to invest in and integrate the manufacturing technology of the future into the arsenal of the civil engineering warfighter.

Appendix A – Internal Review Board Survey Exemption Package



DEPARTMENT OF THE AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AIR FORCE BASE OHIO

18 November 2015

MEMORANDUM FOR DR. VHANCE VALENCIA

FROM: Jeffrey A. Ogden, Ph.D.
AFIT IRB Research Reviewer
2950 Hobson Way
Wright-Patterson AFB, OH 45433-7765

SUBJECT: Approval for exemption request from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for An Analysis of the Practicality of Additive Manufacturing within United States Air Force Civil Engineering Squadrons.

1. Your request was based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.
2. Your study qualifies for this exemption because you are not collecting and reporting sensitive data, which could reasonably damage the subjects' financial standing, employability, or reputation. Further, you are not collecting and reporting any demographic data which could realistically be expected to map a given response to a specific subject.
3. This determination pertains only to the Federal, Department of Defense, and Air Force regulations that govern the use of human subjects in research. Further, if a subject's future response reasonably places them at risk of criminal or civil liability or is damaging to their financial standing, employability, or reputation, you are required to file an adverse event report with this office immediately.

11/18/2015

X

Jeffrey A. Ogden

Jeffrey A. Ogden, Ph.D.
IRB Exempt Determination Official
Signed by: OGDEN, JEFFREY, A. 1292682030

Figure A - 1. IRB Exemption Letter (Dated: Nov 18th, 2015)



**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY (AETC)**

5 November 15

MEMORANDUM FOR AFIT EXEMPT DETERMINATION OFFICIAL

FROM: AFIT/ENV
2950 Hobson Way
Wright Patterson AFB OH 45433-7765

SUBJECT: Request for exemption from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for An Analysis of the Practicality of Additive Manufacturing within United States Air Force Civil Engineering Squadrons.

1. The purpose of this study is to determine the potential value of having additive manufacturing, or 3D printing, capability within an Air Force Civil Engineering squadron. The objective of the research is to identify potential applications for solutions to 5 separate problems using a method of design, printing, and implementation of a 3D printed device. The results will offer validity to including more 3D printing capability on installations for Airman to use for problem solving and Civil Engineering operations.

2. This request is based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

3. The following information is provided to show cause for such an exemption:

- a) Equipment and facilities: Survey will be conducted following the design, printing, and testing of an additively manufactured tool. It will be administered in person following the final test of the tool. The survey will be in paper form to be printed with AFIT supplied paper and ink.
- b) Subjects:
 - *Source of subjects:* Subjects will be military personnel within a Civil Engineer squadron between the grades of E-3 to E-7 and O-1 to O-4.
 - *Total number of subjects:* No more than 12 subjects will be given the survey

Figure A - 2. IRB Memorandum for Exemption

- *Inclusion/exclusion criteria:* 2-3 military members per printed tool who work with and understand the operation and use of the tool.
 - *Age range:* Subjects will be 18 years and older
 - c) *Timeframe:* The survey will be administered during the month of November and December 2015. The printing and testing of the tools is already underway and will be completed prior to the survey being administered.
 - d) *Data collected:* The survey will be anonymous and will not collect and Personally Identifiable Information (PII). Demographics information collected will be limited to total number of years of service and job title. Survey format and questions can be seen in attachment 1. The principal investigator will securely store paper copies and digital analysis files of completed surveys.
 - e) *Risks to Subjects:* Risks to subjects that participate in this survey are minimal. Responses to survey questions will not be associated with individuals and will be kept confidential. Only the principal investigator and student researcher will have access to complete surveys.
 - f) *Informed consent:* All subjects are self-selected to volunteer to participate in the survey. No adverse action is taken against those who choose not to participate. Subjects are made aware of the nature and purpose of the research, sponsors of the research, and disposition of the survey results. See attachment 1 for exact statements provided to subjects. Signed informed consent documents will not be collected. Subjects will be given the opportunity to ask questions prior to participating in the survey.
4. If you have any questions about this request, please contact Major Vhance V. Valencia (primary investigator) – DSN 785-3636, ext. 4826; E-mail – vhance.valencia@afit.edu

Vhance V. Valencia, PhD, PE, Maj, USAF
Principal Investigator

Attachments:

1. Shields_Survey Format
2. Shields_IRB CITI Course Completion Certificate
3. Valencia_IRB CITI Course Completion Certificate
4. Shields_Verbal Statement for Participants
5. Valencia_CV
6. Shields_Official Resume

Figure A - 3. IRB Memorandum for Exemption (Cont.)

Verbal Statement for Participants

Hello, I am Capt Brad Shields. I am a Masters Student at the Air Force Institute of Technology. I am conducting research in collaboration with my advisor, Maj Vhance Valencia that is being sponsored by the Air Force Civil Engineer Center (AFCEC). You are being asked to participate in a short survey on the applicability of 3D printing technology within an operational squadron. Participation in the survey is voluntary, anonymous, and there is no penalty for non-participation. If you choose to participate in the survey, no PII will be collected. I will hand out the survey forms and you can choose to participate after looking over the survey content. There are several assumptions that need to be mentioned prior to starting the survey. This survey is focused on validating the potential use of 3D printing technology to solve current operational problems within a squadron. Those participating in the survey need to have a working understanding of the original problem, as well as the problem solution using the 3D printed part. Please indicate whether the printed part actually solved the problem or made it more difficult to accomplish the mission. Please let me know if you have any questions at this time. Thank you for your time.

Figure A - 4. IRB Verbal Statement for Participants

INFORMED CONSENT

Researcher: Captain Bradford L. Shields
 Research Advisor: Major Vhance V. Valencia
 Research Sponsor: Air Force Civil Engineer Center

You are being asked to participate in a short survey. This survey is part of research examining the applicability of 3D printing technology within an Air Force Civil Engineering squadron. Please answer the questions on page 2 according to your personal experiences and body of knowledge based on the 3D printed part and the problem it was designed to solve. This should take approximately 5-10 minutes of your time.

This survey is the final phase of a plan to identify, design, print, and validate the need for a 3D printer. Your participation in this survey is voluntary. You may leave any question blank that you do not feel comfortable answering. There is no penalty for non-participation and no anticipated risks are associated with participation.

No personally identifiable information (PII) will be collected. The only demographic information that is being requested, should you choose to participate, is number of years of service and your AFSC.

Printed Part Name/Description _____

AFSC: _____

of years of service: _____

SURVEY QUESTIONS:

- 1) Your overall view of the 3D Printed part: (Quality)
 - a. Useless 0 1 2 3 4 5 6 7 Useful
 - b. Difficult 0 1 2 3 4 5 6 7 Easy
 - c. Fragile 0 1 2 3 4 5 6 7 Durable
- 2) Compared to original process, the new tool makes the process: (Efficiency)
 - a. Less efficient 0 1 2 3 4 5 6 7 More efficient
- 3) For its desired purpose, the size of the printed part is: (Effectiveness)
 - a. A Hindrance 0 1 2 3 4 5 6 7 Optimal
- 4) The installation of the part is: (Effectiveness)
 - a. Easy 0 1 2 3 4 5 6 7 Difficult
- 5) Due to the part being printed, _____ specialized tools are needed for installation: (Efficiency)
 - a. Several 0 1 2 3 4 5 6 7 None
- 6) Overall safety of product: (Safety)
 - a. Dangerous 0 1 2 3 4 5 6 7 Safe to Use
- 7) The printed part could be used in _____ (Effectiveness)
 - a. Training Only 0 1 2 3 4 5 6 7 Fully Operational uses
- 8) Aside from the primary purpose, there are _____ other possible uses for tool (utility)
 - a. No 0 1 2 3 4 5 6 7 Multiple
- 9) Learning to use the tool was: (learnability)
 - a. Difficult 1 2 3 4 5 6 7 Easy
- 10) The tool Exploring additional uses: (learnability)
 - a. Difficult 1 2 3 4 5 6 7 Easy
- 11) Tasks when using the tool can be performed in a straight-forward manner: (efficiency)
 - a. Never 1 2 3 4 5 6 7 Always
- 12) A _____ amount of Supplemental Reading/Training Required prior to using the tool (learnability)
 - a. Time Intensive 0 1 2 3 4 5 6 7 minimal
- 13) Retraining needs to be done _____ to stay proficient on the tool (memorability)
 - a. Often 0 1 2 3 4 5 6 7 Never
- 14) Advanced technical skills required to use the tool (memorability)
 - a. Expert 0 1 2 3 4 5 6 7 Basic
- 15) At home station, _____ other uses within your flight exist for 3D printed solutions to improve operations: (utility)
 - a. None 0 1 2 3 4 5 6 7 Multiple uses exist
- 16) In deployed environment, _____ other uses within your flight exist for 3D printed solutions to improve operations: (utility)
 - a. None 0 1 2 3 4 5 6 7 Multiple uses exist
- 17) Iterative testing process _____ additional unforeseen problems (effectiveness)
 - a. Created 0 1 2 3 4 5 6 7 Solved

Figure A - 5. Additive Manufacturing Survey

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Vita

Captain Bradford Shields, an officer in the United States Air Force, completed his Bachelor of Science degree in Civil Engineering at North Carolina State University in 2011. He received his United States Air Force commission in May 2011, after completing Air Force Reserve Officer Training at North Carolina State. Captain Shields' first Air Force assignment was at Luke AFB, AZ, where he worked as a Project Programmer, an Executive Officer, and as the Operations Engineering Chief. In 2014, he entered the Graduate School of Engineering and Management at AFIT, where he is currently earning a Master's degree in Engineering Management. While attending AFIT, he also completed his Master's in Business Administration from American Military University with a perfect 4.0 GPA. His follow-on assignment is to the Kunsan Air Base, Republic of Korea. Captain Bradford Shields can be contacted at: bradford.shields.1@us.af.mil.

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14. ABSTRACT Additive manufacturing is a technology taking the manufacturing revolutionizing the manufacturing industry. By creating three dimensional objects from the ground up, the technology does away with the traditional manufacturing methods used to design and create all products. This research examines the application of additive manufacturing (AM) with regards to tools and jigs in United States Air Force civil engineering (CE) operations. After testing the parts, a usability survey was conducted to determine the value of AM. The results of the overall research indicated that AM will definitely impact the daily operations of a CE unit and a clear need exists for the use of AM. Further, the research determined that AM has reached a point where the integration of AM into strategically coordinated units, along with proper education and training, can be beneficial for the CE career field. Finally, the results indicate that 3D scanning technology will reach a point within the next 5 years where it can help foster the rapid build-up of 3D CE asset designs for printing applications. The overall results push forward the Air Force's 3D printing knowledge while providing critical information for decision makers on this up and coming technology.					
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