MENTOR2 Final Report

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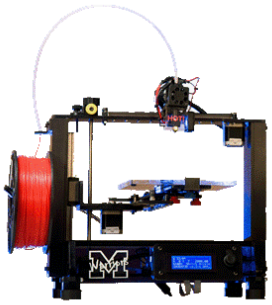
Executive Summary

MENTOR2 Program's overall objectives are to develop and deploy tools and curricula for collaborative design and digital manufacturing, and to instill innovative problem-solving skills through effective design and manufacturing. The program builds upon progress achieved during MENTOR1 and other programs during 2011 to '13; AST2 developed Virtual Collaborative Learning Environment (VCLE) during MENTOR1, and subsequently developed a number of education and training programs and a rapid prototyping laboratory. Through these, we are reaching thousands of users, primarily in high schools, and created an innovative learning curriculum. Under MENTOR2, we leveraged these efforts and developed hardware, software and training programs, and utilized them to train civilians and military personnel to address problems methodically and to develop solutions through effective design and manufacturing. Marines and sailors have shown exceptional enthusiasm and ability to leverage these tools and training, both under normal and combat situations, and solved numerous problems that improved both operational readiness and efficiency while simultaneously achieving cost savings. We have successfully transitioned products from MENTOR2 to US Marine Corps (USMC) and US Navy (USN), Veterans Administration (VA), academic institutions, and are laying the foundation to create a nationally accredited training and certification program in additive manufacturing (AM).

Digital manufacturing is revolutionizing both manufacturing and sustainment. Virtually all manufacturing processes are now (or can be) digitally controlled. Developments over the past two decades created bench-scale digital manufacturing tools; a noteworthy example is AM, also known as 3D printing. As recognized during MENTOR1, AM has the potential to change the way designers and engineers produce systems and reduce development/ production cycles and costs, particularly in the defense industry. It allows production of small batches (even a single item) without the expense of tooling. We made AM the focal element of our effort under MENTOR2 due to these advantages while simultaneously integrating other digital manufacturing technologies to provide a full suite of digital manufacturing technologies.

Even though AM is known for over 20 years, it is still a mystery for most. This was a problem we had to overcome to enable students, veterans and military personnel develop comfort and utilize AM to create and produce solutions. Additionally, most small 3D printers were not reliable and manufacturers offered little or no maintenance support (recent commercial developments have addressed this to a significant extent). These was addressed, during MENTOR2, by developing a kit, known as INVENT3D printer kit, that can be assembled by users. Assembling and troubleshooting a printer created a high level of comfort, and facilitated users to utilize the technology and training to produce products within a few hours.

1.1 Hardware Development



A small bench-top 3D printer for fused deposition molding (FDM) using polymer materials was developed under MENTOR2. It is designed as a kit that can be assembled (and disassembled and reassembled as needed) and made operational in about 8 hours. All components are designed for easy maintenance and most components can be replaced in less than 30 min. Over 100 printer kits were produced by AST2, and deployed for education, training and sustainment operations in both civilian and defense sector.

1.2 Software and Other Products Developed

Major products developed under MENTOR2 are summarized below; it must be noted that some of the products were codeveloped utilizing a number of parallel programs, in collaboration with and funding from other organizations, including Northrup Grumman (printer kit), AmericaMakes (Boot Camps), University of Texas El Paso (UTEP, curriculum), NAVAIR (digital manufacturing), and the VA (vocational therapy and projects).

STORM: The virtual collaboration learning environment (VCLE) too, developed during MENTOR1, has been significantly augmented during MENTOR2 to allow two-way audio and video communication, and to enable virtual use of digital manufacturing equipment.

Printer Curriculum: A detailed instruction manual was developed describing how 3D printers work, the role of each component, how to maintain and operate 3D printers, and the process of converting design files (STL format) into a three-dimensional arrays for printing (called slicing).

Design Thinking for Additive Manufacturing (DTAM): A workshop format course was developed that instills design thinking for the creation of practical solutions using AM, what items can be produced (and what cannot be) with AM, basics of designing and slicing for AM, and the leaning through hands-on projects, in small teams.

Design Basis Analysis Tool (DBAT): In collaboration with NAVSEA and NAVAIR representatives, the formal engineering processes employed by large corporations were simplified and codified to help DoD personnel develop sound basis for design solutions. The tool also produces a document that includes the analyses for peer review and approval.

Reverse Engineering: Working with marines and sailors, we recognized that sustainment operations may require reverse engineering of components when engineering designs are not available. Hence, we developed a module that aids in reverse engineering, and provides guidance on utilizingg 3D scanners or similar equipment to assist in reverse engineering. The module can be used in combination with DTAM and/or DBAT.

Hands-on Projects: Hands-on projects, exemplifying the development of solutions, were found to be a valuable tool to enthuse enlisted personnel in the learning process. Utilizing the feedback that we received during our collaborative effort with sailors and marines, we developed a series of hands-on projects, ranging in complexity and required diversity of digital manufacturing equipment.

STEM Workshops: Developed stimulating 3- to 4-day STEM workshops for delivery to high school students or junior defense personnel. The courses cover topics ranging from energy, biology and physics, and involve group project design and production using AM.

1.3 Transitioning Activities

Primary focus of our transitioning effort has been aimed at military personnel; however, we have transitioned the products for civilian use and veterans as well. A summary of these activities is provided below.

Printer Kit/DTAM: We conducted a number of training sessions with groups ranging from 10 to 30, and in formats ranging from week-long boot camps, visits to military installations and virtual training. Important transitioning activities include:

> "The Marines built the printer? Press on!!!!!" General Neller, Commandant, USMC, March 31, 2016

- Visited military installations including MARMC (Navy's Mid Atlantic Regional Maintenance Center), Camp Pendleton and Camp Lejeune (USMC). Groups of about 10 enlisted and civilian personnel were trained at each location over 2- to 5-day sessions. The scope was adjusted to accommodate time allowed, and faculty from Old Dominion University (Dr. Jennifer Michaeli) and Francis Marion University (Dr. Justin Yates) supported in the delivery of the courses.
- Boot camps were conducted, in collaboration with a number of organizations including AmericaMakes, Youngstown State University (YSU) and UTEP in Youngstown (OH) and El Paso (TX). The Youngstown training was attended by several members of USMC and USN.
- Professional development courses were conducted in Youngstown in class rooms as well as virtually to 'train the trainers.' Continuing education units (CEUs) were provided when appropriate.

Digital Manufacturing: The printer curriculum and training program was extended to cover a wide variety of digital manufacturing technologies (the effort expanded using funding from NAVAIR and USMC). Week-long training sessions were conducted at 3 NAVAIR locations; Patuxent River, Oceana and New Orleans. Approximately 40 civilians and sailors were trained

in design and production using hands-on projects. One training session was also conducted at Camp Pendleton covering a smaller set of digital fabrication equipment.

Printer Kit/DTAM for Vocational Therapy: Under a SEED grant from the VA, we explored the use of printer assembly and DTAM to provide vocational therapy and job skills to veterans. The first session at White River Junction, VT, engaged VA staff and veterans from the drug rehab program. The effort was quite successful with the veterans utilizing printers regularly and training other veterans. A second session is planned at Chillicothe, OH.

Printer Kit/Fleet Maker: We are supporting ODU under a program funded by the Office of Naval Research (ONR) to train expeditionary forces in the use of AM. To date five 2-day (Friday and Saturday) workshops were conducted at ODU; each workshop typically trained two teams of 10 sailors each from 2 separate ships or Naval organizations. A EMNTOR-developed 3D printer is provided to each team for use during subsequent deployments.

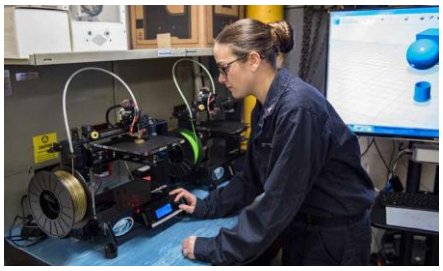
STEM Workshops/Printer Kit/DTAM for JROTC: Conducted a 3-day workshop at Camp Lejeune High School for children of marine families enrolled in Junior ROTC program. The workshop focused on biomimicry; students designed relevant projects and produced them using assembled printers.

1.4 Deployment

We also worked in collaboration with other agencies to deploy systems and programs, developed under MENTOR2, including under combat situations. Highlights of our deployment efforts are summarized below.

> "We have a part called the TruClip. It was designed by three sailors on Truman, half a world away on deployment" VADM Phil Cullom, Deputy CNO, 6/22/2016

- Developed mini Fab Labs involving an INVENT3D printer, a small CNC (computer numerically controlled) mill and a design station. Sailors on USS Truman produced a number of mission critical components, improved operational readiness, reduced work stoppages, and lowered costs.
- MENTOR 3D printer and DTAM were the first activities during the development of EXMAN (expeditionary manufacturing unit), in collaboration with SPAWAR. First Maintenance Battalion at Camp Pendleton produced a number of components and spare parts using EXMAN.



- 3D printers deployed on Naval vessels including USS Wasp and USS Truman were used to produce numerous items required on the ships, while at sea. Sailors from USS Kearsarge reported that the printer was used daily during a 6-month deployment.
- A 3D printer kit was deployed to USMC in Kuwait to support operations; marines assembled the printer and are using it since January 2017.
- Fully integrated Fab Labs have been designed and deployed to four NAVAIR operations; all integrated several MENTOR products such as the 3D printer, virtual use through STORM, and training products.

1.5 Special Comments

Deployment of products developed under MENTOR2 to both sailors and marines demonstrated their ability to learn and utilize the knowledge, almost instantaneously, to produce solutions. Our experience, in collaboration with other organizations, in working with over 100 defense personnel and many civilians is summarized below.

- Even a few days of stimulating training will instill problem solving skills among military personnel
- Training is much more effective when combined with team work and hands-on projects that address real life challenges that members of military are likely to encounter
- Digital manufacturing, additive manufacturing in particular, offers a unique way to develop manufacturing solutions
- In virtually every case, defense personnel were enthused to learn problem solving skills; sought next levels of training and deeper knowledge
- Enlisted personnel created innovative and economic solutions with available tools and equipment
- Even small and simple equipment can be used to stimulate design thinking and to produce solutions

1.6 Implications for Further Research

Products developed under MENTOR2 have been successfully transitioned to both military and civilian sectors. This successful adaptation shows a promising area where even small investments can produce critical thinking and problem-solving skills, and lasting impacts on operational readiness of deployed forces. Additional efforts in developing and deploying tools that result in utilization of basic STEM (science, technology, engineering and mathematics) knowledge will significantly enhance problem solving skills of deployed forces and produce significant benefits.

2. Test Objectives

MENTOR2 Program's overall objectives are to develop and deploy tools and curricula for collaborative design and digital manufacturing, and to instill innovative problem-solving skills through effective design and manufacturing. Specifically, the program had the following objectives.

1. Develop a Design Basis Analysis Tool for use by DoD personnel/students that will inculcate the process of developing and understanding the "why" of the system/component design into problem solving approach. The tool will be incorporated into the project challenges that provide an opportunity for applying and reinforcing this skill.
2. Develop the next generation of STORM that can be embedded in a variety of computer/tablet platforms without the need for a STORM:BOX (hardware). This will significantly enhance deployment, especially in austere environments.
3. Create interactive MENTOR2 learning modules, full curriculum, and project challenges for military and civilian use including for education in high schools.
4. Develop project kits to assist education and training with 3D printing and its utilization with other tools to solve practical problems.

AST2 has successfully accomplished the above objectives as described in the report. Additionally, during the project activities, we have learned that transitioning the MENTOR2 developed tools to the military personnel required hands-on equipment training as well as workshop-format training to develop required critical thinking and problem-solving skills. Hence, a significant portion of the project efforts were dedicated towards this goal; additional efforts were funded by other agencies to continue transition of the technologies which furthered Program's overall objectives.

3. Problems Encountered

We have encountered some broad technical challenges and other problems during the program; however, we were able to successfully address them through program efforts. The problems and our approach to addressing the problems is discussed below.

1. **Unreliable and inexpensive 3D printers**: At the beginning of the program, many of the 3D printers within the price range that can be afforded by K to 12 schools were not reliable and susceptible to frequent malfunctioning, and technical support from manufacturers was often expensive or unavailable. It must be noted that this problem has been satisfactorily addressed by the commercial sector in the past 2 years and many reliable printers are currently available at a cost in the range of $1,000 to 2,000. AST2 addressed the challenge in an innovative way to turn the problem into a learning opportunity. We developed a printer kit, supplied to users in a reusable container, that is assembled by the users using directions and support from AST2 (face to face, via video conferencing, STORM meetings and other techniques). Assembling the printer provided benefits beyond maintainability. Working with enlisted personnel and high school students, we learned that putting the printer together removed the mystery surrounding 3D printing, developed ownership and resulted in members trying to start designing and printing immediately following printer assembly. We have used the printer kits for training at multiple locations with over 100 civilians and military personnel.
2. **Hot End Challenges and Printer Temperature Overshoot:** Hot Ends in 3D printers are one of the most critical items and are notorious for maintenance problems and temperature overshoots. The small mass of hot end coupled with significant heat input for heating the filament has caused a number of reported temperature excursions and fire accidents. We explored and experimented with a number of hot ends during this program. One of the hot ends we used, an integrated unit with a built-in fan, performed well and was used in a number of printers. A thermistor in the hot end from a printer supplied to Youngstown State University (YSU) dislocated, out of position, resulting in continuous heat input, temperature overshoot and a fire accident. The thermistor was a separate component inserted into the hot end. How it became displaced at YSU is not known. This required us to perform a significant root cause analysis. We replaced all the hot ends, at our own cost. Additionally, we updated the firmware to provide an extra layer of protection. We worked with stakeholders to ensure that appropriate fixes were applied. We have not had any reported problems since the fixes were implemented in January, 2017.
3. **Design Software and Internet Connectivity:** Our initial default software for design training was Autodesk 123D. The software was discontinued during early part of 2017. Simultaneously, over the course of the program, most of the cost-effective design software programs have been transitioning to the 'Software As A Service' (SAAS) model requiring internet connectivity, at least on a periodic basis. This was a challenge at most

of the DoD locations during our training sessions; internet service was either not available or was restricted. We overcame this problem by using Creo, a high-end software for NAVAIR. We also identified an open source software, On Shape, that is simple to use and versatile for use with both PC and MAC versions, as well as with mobile computing.

4. **Lack of Standards for Training:** Training and certifications standards do not currently exist for additive manufacturing (AM) or other rapid prototyping technologies. ASTM International, AmericaMakes and other community members are working on this effort. A number of performers on the MENTOR2 program have developed a significant amount of training material that can potentially be turned into standardized training. AST2 has initiated such efforts in collaboration with other organizations, and to explore credentialing AM training through an apprenticeship program approved by the US Department of Labor (DOL).

4. Technical Results

Technical work performed under MENTOR2 program is broadly grouped into four items; hardware, software, training and curriculum, and transitioning of products to civilian and military users. Highlights of the activities under each of the four groups are presented below, followed by a description of technical results in subsequent subsections. Additional details of technical data are referenced in individual subsections, and provided in respective appendices.

AST2 has successfully transitioned the hardware and deployed a number of the training programs, described below, through different formats, and has trained a number of military personnel, educators and others; examples of transitioning these programs are provided in Sections 4.4 and 5. We are also working with USMC to build on the efforts and develop additional content and make it accessible to all members via self-learnt, web-based modules. AST2 also secured a contract under General Service Administration (GSA)'s multiple-award schedules to provide continued access to the products following the conclusion of the MENTOR2 program.

Hardware: Development of a rugged 3D printer for education and training was a key activity and result of the program. The printer development, started under earlier finding from Northrop Grumman, advanced significantly under MENTOR2, and AST2 started deploying the printers during late 2015. The printer was subsequently modified as a kit, under the program, for training users on its assembly, troubleshooting, operation, and maintenance. Over 100 printers and kits were deployed to both civilian and military users during 2015 and '16, and used for training by AST2 and others.

In collaboration with the Navy, we have also developed, first a Mini-Fab Lab, and subsequently a full-scope, transportable digital Fabrication Laboratory (TDFL). Both have been successfully deployed by the Navy.

Software: Software development during MENTOR2 focused on prior work, conducted under MENTOR1, for creating a virtual collaboration learning environment (VCLE). The developed software, known as STORM, was modified to work with newer versions of the code and to add multiple features to improve stability and usefulness. It is currently used by a number of academic institutions and has also been installed into TDFL. It is noted that utilization of STORM by the military will require resolution of internet connectivity.

Training and Curriculum: In collaboration with a number of separately funded programs and organizations, we have developed curricula and deployed a number of training programs to both the military and civilian members. They range from in basics of 3D printing to advanced design/engineering software. To date, the training programs have been utilized to train over 150 marines and sailors.

Transitioning of Products to Civilian and Military Users: The second half of the program focused on transitioning the products, including hardware, software and training, to both civilians and military personnel. The transitioning efforts continued through the whole program duration, and we anticipate that these will be sustained over the following years under separately funded contracts. Transitioning has been very effective, and successfully met the program goal for teaching practical problem-solving skills through innovative design and manufacturing to both students and military personnel.

4.1 Hardware

We developed three separate hardware packages during the program period. These are summarized below, and are further discussed in Section 5.

3D Printer and Kit: AST2 expended significant effort towards the development of a 3D printer, rugged and maintainable, for use by member with a competence equivalent to high school students. The printer was subsequently modified into a kit form; 3D printers can be assembled and disassembled, from the kits, repetitively for training, use and transportation. The printer kit proved to be a useful tool during training.

Mini Fab Labs: We developed mini Fab Labs, in collaboration with and funding from MARMC, and fielded two such units on USS Truman and USS Kearsarge. The fab labs consisted of a 3D printer, a CNC mill (Othermill) and a design station on a transportable cart. The deployed labs were extensively used, and sailors on USS Truman have demonstrated ability to produce operationally critical components under combat conditions, improved operational readiness, reduced work stoppages, and achieved cost savings.

Transportable Digital Fabrication Laboratory (TDFL): In collaboration with and under a separate contract with NAVAIR, we integrated MENTOR efforts to produce conceptual designs and to fabricate TDFLs. Each TDFL contained a full suite of digital manufacturing technologies, virtual use via STORM, and was designed for use both as a training trailer as well as to support sustainment and maintenance activities. Four such units were developed, and delivered to Navy; each is currently in use.

4.2 STORM

The STORM:Tool software (also known as STORM) was initially developed during the MENTOR1 contract to assist with virtual collaboration in designing materials and for use of advanced pieces of equipment remotely (especially when such equipment is rare, expensive, or otherwise unavailable). This tool was the basis for virtual collaborative learning environment

(VCLE) that AST2 deployed to numerous schools and other users. During MENTOR2, the software was updated to improve its performance on current operating systems. Additional feature improvements were introduced to utilize STORM for troubleshooting, instruction, and virtual presence (as is provided by multiple webcam views of equipment). Development effort and current state of the software are discussed in this section along with its transitioning activities for both military and civilian use.

4.2.1 Software Development

STORM:Tool is a Java based software program based on Jitsi, an open source software (located at https://desktop.jitsi.org/) similar to Skype which includes the ability to remotely view and control a computer.

STORM, prior to the MENTOR2 contact, was developed to allow scheduled use of a remote computer for a set duration, start date and time, and entry passcode. During a session, a user acquired the following controls:

- View and control of a computer allowing for remote operation of equipment (attached to that computer)
- Ability to view all aspects of that machine (with multiple webcams)
- Ability to gesture to the operator (via drawing on the screen) instructing that operator to manipulate physical controls on the machine.

Before and during the MENTOR2 contract, this software was and is being used by a number of high schools (hundreds) to assist them in contacting AST2 staff for curriculum assistance and equipment access. Additionally, the software was and is currently being used to assist in support related calls for the 3D printer.

STORM's modification of the Jitsi code required that Jitsi be extensively modified. Jitsi modifications, to allow for its operation with modern PCs and to eliminate notable bugs, introduced a development hurdle for STORM. Additionally, STORM required significant rewrites to allow for its integration with Jitsi's newer code. As that development proceeded, additional features were added to STORM; we also undertook additional testing and troubleshooting to identify and eliminate bugs. The added features are described in section 4.2.2, below.

Current version of STORM is written with Jitsi version 2.8 as its base code. We are monitoring current/planned updates to Jitsi with consideration for migration of STORM code to the latest Jitsi version, when Jitsi adds significant new features or when notable bugs are addressed with successive revisions.

4.2.2 STORM Feature Improvements

A summary including a point by point analysis of notable additional features or software changes implemented during the MENTOR2 contract, is provided below.

STORM Desktop (as referenced below) is the virtual presence aspect of STORM. This allows for webcams to be seen and accessed by remote users.

- Base code updated to Jitsi v2.8 fixing bugs which improved stability.
- User interface updates
  - Changes made to main window
    - Storm now provided as a unified program, eliminating the need for a separate "Learn Tool" and "Teach Tool" program. Computers needing both tools (to allow for both outgoing and incoming sessions) now require half the installation space and now only run one program.
    - Functionality of Learn Tool and Teach Tool from STORM:Tool 2 has been replaced with a 'toggle checkbox' on the main interface called Learn Mode. When toggle checkbox is checked, STORM:Tool 2 will behave like the old Learn Tool, and when unchecked, it will behave like the old Teach Tool. This checkbox is checked, by default, and locked during calls or if the user does not have call hosting privileges as a resource.
    - Added a new button for the host called 'Reload Storm Desktop' under the tools dropdown. This button reloads STORM Desktop as if the application has been restarted. It will apply any changes made to the StormSessionDesktop.properties file to be seen. This saves time when configuring cameras for STORM Desktop or if something happens to STORM Desktop causing it to malfunction, it can be easily restored by using this option. This option is disabled during a call.
  - Changes made to caller interface
    - Button to view yourself, only works in VideoBack mode to view yourself in a small corner window in order to center your camera or show what is being sent to the host.
    - Technical Call Information button, symbolized with an "I" for information was added. This button shows call information and statistics useful in debugging call issues.
    - File Transfer button was added. This button prompts the user to choose a file to be transferred to the host. The host then chooses to accept or deny it. This method for in call file transfer is slow, but useful for text documents or other small files under 2MB.
  - Changes made to call host interface
    - Buttons added to Storm Desktop

- VideoBack button added. During a call, clicking this button will switch off all desktop sharing and remote control, and then change the session into webcam style two-way chat. When this mode becomes active, the desktop sharing button will unlock and the clicked button will lock, telling the user that it they can switch to the other state if they wish.
- Desktop sharing button added. During a call, this button will switch off all video viewing and rebuild the call, for stability reasons, and the host will share desktop with the caller with remote control off, by default. When this mode becomes active, the video button will unlock and the button clicked will lock, telling the user that they can switch to the other state if they wish.
- Remote View button added. During desktop sharing the host may click this button and toggle on and off the caller's webcam, allowing the host to see the caller on his own window if the host desires.
- Remote Control button added. During desktop sharing, clicking this button will toggle remote control (the ability for a calling person to manipulate the remote computer) on and off. Button's color changes from green to red, and back again, to indicate to the user visually that the remote control is on by seeing the button as green or off when it is red

▪ Add Session Window Changes
- VideoBack checkbox added. Checking this box will cause the session to start in a two-way webcam style call instead of STORM:Tool's default host side desktop sharing.
- STORM Relay checkbox added. This box is checked on, by default, to use Storm's relay for handling video and audio packets. Unchecking this box will enable Jitsi's relay, which handles packets differently from STORM:Tool's, and in some cases, will work when STORM:Tool's's relay will not work.

4.2.3 Transitioning and Implementation

STORM software continues to be used for assisting the curriculum and equipment access with high schools. Efforts to use this software at military installations were unsuccessful since authorization could not be granted (this failed effort lead to the on-site instructions during our training programs at USN and USMC locations, in particular at Camp Lejeune High School during the delivery of the Biomimicry module). The software continues to be used for troubleshooting of the 3D printers and others.

4.2.4 Appendices

4.2.B STORM Software Download
4.2.A StormTool-33.exe
4.2.C StormTool Source.zip

4.3 Training and Curriculum

4.3.1 Printer Curriculum

Even though 3D printing has been known for over 20 years, its operation and maintenance are still a mystery to many users. 3D printers have a number of moving components, controlled by motors and belts, and require maintenance. Upkeeping of 3D printers is a significant challenge due to inadequate support from companies that sell inexpensive ($2,000 or lower cost range) printers and/or high cost of maintenance support. We noticed that a number of 3D printers, particularly those purchased by high schools, are often not maintained and are thus inoperative. Hence, one of the early efforts of the program, in combination with the printer development discussed in Section 4.1, was to develop a training program that focuses on basics of 3D printers, its components and their functionality, theory behind 3D printing, operation, trouble shooting, and maintenance of 3D printers.

The program entitled, "Your 3D Printer is Not Rocket Science," has been used to train a number of civilians and military personnel through boot camps (held in Youngstown, OH and El Paso, TX), professional development programs for high school teachers, and via STORM. Most of the sessions were aimed at 'training the trainers' so that the trained participants can teach 3D printing to others. When appropriate, we were also able to award continuing education units (CEU).

Appedix 4.3.1.A provides full curriculum in Microsoft Word. Even though many of the graphics, included to explain printer operations, are from the MENTOR-developed printer, the content is applicable to all printers. In particular, the curriculum is aimed at fused deposition molding (FDM) printers.

4.3.1.1 Appendix

4.3.1.A Printer Curriculum

4.3.2 Design Thinking for Additive Manufacturing (DTAM)

The Design Thinking for Additive Manufacturing (DTAM) curriculum was developed to meet one of the primary objectives of the program; develop innovative tools to assist military personnel in developing problem-solving skills. DTAM provides a generalized introduction to additive manufacturing paired with advanced methods in design thinking. The curriculum is meant to facilitate the training of individuals or groups and consists of instruction materials and

additive manufacturing projects. Moreover, it is meant to build application skills in the training of practitioners. DTAM training materials may be used as a single-document (i.e., textbook), in whole or as modified by the instructor, or in a modular manner (i.e., on-line course).

DTAM has been used by AST2 for training both sailors and marines; we have also worked with other educators from ODU and other organizations to adapt DTAM and to deliver the program to military personnel. Our experience, coupled with survey results, show DTAM to be a stimulating workshop that facilitates participants to apply design and manufacturing techniques to solve practical problems (see Section 4.4.3 as an example).

4.3.2.1 DTAM Content

The DTAM workshop teaches how to create practical solutions using AM, what items can be produced (and what cannot be) with AM, and emphasizes good design practices. The course was developed in three versions:

1) a text base course with included activities, reading assignments and exercises. This course was designed for an instructor led class room setting.;

2) A modular, workshop format course consisting of a slide-deck for each topic, led by an instructor. This course can be tailored by the instructor depending upon the teaching goals of the workshop; and

3) A self-paced, web-based course.

The curriculum in DTAM does not require or presuppose any prior experience in additive manufacturing or design. Participants in the workshop are expected to have a high-school education (GED or diploma) or higher and should have access to a computer capable of running a CAD program (the curriculum is not built to any specific CAD program. Many free, open-source versions exist in addition to commercially available CAD software). Similarly, the curriculum does not require purchase of any specific 3D printer brand, but does assume that students will have access to a FDM printer for completion of the assigned projects (3D printers are not required to proceed through the course content).

4.3.2.2 Development History

Curriculum development began in the second half of 2015, beginning with development of the single-document text curriculum. Transition to the modular course was started in January 2016 and completed in March 2016. This transition included a more formal definition of hands-on projects and added project rubrics to assist trainers in evaluating participant performance. Adaptation of the modular workshop to a web-based course began in July 2017 with the creation of 'instructor scripts' based on the self-paced modular curriculum. The final web-based DTAM course will consist of a series of videos with voiceover recorded to the module slide decks.

As discussed, DTAM was originally developed as a classroom training material; classroom training is perhaps the preferred mode to learn DTAM. We recognize that it may not be practical in all cases; hence, we developed the slide decks with quizzes, etc. Our experience with sailors from over 10 ships, as part of the ODU program, has shown great benefit from such training. Under the MENTOR program, we have developed a wide range of training modules with the intent that the instructor would pick and choose content, based on participants, and customize the training program. Similarly, we have also identified and catalogued a number of training aids in the form of videos and self-study materiel. We are providing a number of such files, as part of appendices, that could be used by instructors. The content can be easily downloaded and utilized by any instructor. We recognize that providing some 100 files under DTAM can be overwhelming; we organized the content in a logical manner, in respective appendices, to make their utilization and learning as easy and convenient as possible.

4.3.2.3 Transition Status and Use

Marines and Navy personnel have been trained for using DTAM curriculum in multiple events, including multi-day training efforts at Camp Lejeune and at MARMC, Norfolk, VA. Feedback from events is collected formally (survey's, report-out from the sponsor, etc.) and informally (conversations, observations, etc.) to enable improvements and revisions to the curriculum, as appropriate.

Training sessions conducted with military personnel to date involved following activities:

a. Introduction to 3D printing
b. Assembling MENTOR-developed 3-D printers
c. Introduction to CAD (when required)
d. Teams of participants picking projects that are relevant to their roles in the military, and developing the project design
e. Brain storming their ideas followed by presentations to the entire group
f. Production of the projects using assembled printers

Two to 3 days (two-day training was assessed to not provide enough time by several marines, and thus a three-day program is probably the preferred duration) was adequate for participants to develop the thinking skills to create solutions to practical problems utilizing design and 3D printing. When additional time was available (example MARMC), participants had opportunity to practice and perform problem solving, design and production, and gain further experience. Since 3D printers were available to the participants following the training, they often continued to create solutions as exemplified by marines from the First Maintenance Battalion, Camp Pendleton. Marines from the 2nd Maintenance Battalion also reported additional use of the printers during field exercises.

4.3.2.4 Appendices – Self Learning Modules

4.3.2.A Module 0 DTAM Course Objectives Slide Deck

4.3.2.AA Instructor Led DTAM Modular Curriculum files

1a_WhatisAM

1a_WhatisAM

1b_HistoryOfAM

1b_HistoryOfAM

1c_AMToday

1c_AMToday

1d_AdvantagesOfAM

1d_AdvantagesOfAM

1e_DisadvantagesOfAM

1e_DisadvantagesOfAM

1f_ChallengesOfAM

1f_ChallengesOfAM

2a_HowTo3DPrint

2a_HowTo3DPrint

2b_OverviewOf3DPrintingSoftware

2b_OverviewOf3DPrintingSoftware

2c_TolerancesAndThresholds

2c_TolerancesAndThresholds

2d1_AdvancedDesignTechniques

2d1_AdvancedDesignTechniques

2d_SupportStructures

2d_SupportStructures

2e_TriangleOfChoices

2e_TriangleOfChoices

2f_ExamplesOf3DDesigns

2f_ExamplesOf3DDesigns

2g_Scanning3DDesigns

2g_Scanning3DDesigns

3a_IterativeDesign

3a_IterativeDesign

3b_DesignIn10Steps

3b_DesignIn10Steps

3c_DesignRequirements

3c_DesignRequirements

3d_DevelopingAProblemStatement
3d_DevelopingAProblemStatement
3e_CreativeProblemSolving
3e_CreativeProblemSolving
3f_SystematicDesign
3f_SystematicDesign
3g_KSAA
3g_KSAA
4a_ApplicationsInAerospace
4a_ApplicationsInAerospace
4b_ApplicationsInHealthcare
4b_ApplicationsInHealthcare
4c_ApplicationsInManufacturing
4c_ApplicationsInManufacturing
4d_ApplicationsInMilitary
4d_ApplicationsInMilitary
4e_ApplicationsInFood
4e_ApplicationsInFood
4f_ApplicationsORNLandLocalMotors
4f_ApplicationsORNLandLocalMotors
4g_MakerMovement
4g_MakerMovement
NASA AAQ References
4.3.2.BB Instructor Led DTAM Modular Projects Rubrics and Resource Guides
Project1Memo
Project1ResourceGuide
Project1Rubric
Project2Memo
Project2ResourceGuide
Project2Rubric
Project3Memo
Project3Rubric
Project4Memo
Project4Rubric
4.3.2.B Module 1a What is AM Slide Deck
4.3.2.C Module 1b History of AM Slide Deck
4.3.2.CC Instructor Led DTAM Modular Sample Syllabus

4.3.2.D Instructor Led DTAM Modular Sample Schedules
4.3.2.D Module 1c AM Today Slide Deck
4.3.2.DD DTAM Course Full Curriculum
4.3.2.E Module 1d Advantages of AM Slide Deck
4.3.2.EE DTAM Course Appendix- CAD and SLIC3R Training
4.3.2.F Module 1e Challenges of AM Slide Deck
4.3.2.FF Instructor Led DTAM Modular Sample Schedules
4.3.2.G Module 2_HowTo3DPrint_Ver A Rev 2
4.3.2.G Module 4_Applications of 3D printing Ver A Rev 0
4.3.2.G_Module_0a_Course Objectives GCS Rev
4.3.2.G_Module 1a_WhatisAM 2
4.3.2.G_Module 1b_HistoryOfAM2
4.3.2.G_Module 1c_AMToday2
4.3.2.G_Module 1d_AdvantagesOfAM2
4.3.2.G_Module 1e_Limitation Barriers Challenges Of AM2
4.3.2.G_Module 3_Design2 Ver B Rev 0
4.3.2.H Module 3 The Design Process Slide Deck
4.3.2.H Quizzes for Slide Deck Module 3
4.3.2.I Module 4 Applications of 3D Printing Slide Deck
4.3.2.J Quizzes for Slide Decks Modules 1 and 2

4.3.3 Design Basis Analysis Tool (DBAT)

The Design Basis Analysis Tool (DBAT) was developed to improve the ability of users to produce sound engineering and design solutions. The tool follows a systematic approach to design thinking that encourages critical analysis of the problem(s) faced and facilitates the comparative analysis of proposed design solutions. It codifies processes commonly used by large engineering corporations to develop a 'design solution' for a project requirement – a process that normally involves pulling together a team of multi-disciplinary engineers to arrive at design solutions, evaluations of the developed solutions and consensus on the recommended solution, and review and approval of the recommended solution by peers and supervisors. Such an established process has been simplified and codified as DBAT; the process can be completed with relative ease, by a small team, within a few hours to develop a solution for a simple, noncritical component. Additionally, DBAT automatically creates the documentation required for peer review and approval for production/use.

DBAT uses a combination of quantitative methods to support the decision-making process, and allows for the generation of project reports, helping to standardize documentation and improve the transfer of knowledge both horizontal and vertically within decision groups. The ultimate

goal of DBAT is to improve design solutions by inculcating a thought process of strategic, systematic design in trainees. DBAT is currently implemented as a system-independent executable software program capable of running on most (PC-compatible) desktop/laptops.

Design solutions developed through DBAT (or similar processes) by the military may be catalogued and stored at a secure website; such a repository of frequently required replacement parts' designs can be downloaded, as and when required, produced using in-house prototyping equipment or a local fabrication facility, and used as a replacement. This will save significant time and cost associated with procuring items that are not stored in local inventory, and reduce logistics burden.

4.3.3.1 DBAT Content

DBAT analysis begins with the definition of a series of Design Requirements surrounding six major categories: Functionality, Health & Safety, Security, Serviceability, Operational Environment and Interfacing Systems. Users determine significance/importance of the design to each of these six categories by assigning two ratings: criticality score and detection score. Once the Design Requirements are input, the user begins creating their Potential Design Solutions. DBAT provides users with the ability to upload design files directly into the program to aid with transparency during the evaluation process. Each Potential Design Solution is again evaluated by the designer through the assignment of a compliance score, a score for Knowledge, Skills, Abilities and Attitudes (KSAA), a score for planning and a score for implementation. In all cases of designer scoring, detailed justifications and supportive explanation must be provided by the designer.

The output of DBAT is a report that collects and presents the designers justifications and ultimate decision in a systematic, single-file PDF report. Additionally, six metrics are used to quantitatively represent the perceived design problem and potential solutions. These metrics are discussed in detail in the appendices and are presented graphically in the generated PDF report.

4.3.3.2 Development History

The bulk of DBAT development took place in Mar – October 2015 and included a series of participants, internal and external to AST2. A number of representatives from NAVSEA (MARMC and DC-area) and NAVAIR participated extensively both in its development and in ensuring that the tool is useful for military use, and incorporates Navy's common practices; AST2 is grateful for their participation and support.

DBAT began as a conceptual framework for design thinking collected in a series of slide decks. These slide decks were unified after a series of group discussions/meetings to gain consensus on the systematic approach of DBAT. The unified slide deck served as reference for the development of an Excel-based DBAT prototype that included a basic graphic user interface and excluded the auto-generated PDF report-out functionality. Further iterations were made on DBAT and the finalized Excel-based version was transitioned to a stand-alone executable file written in Python Kivy. The Kivy tool was further modified to improve the user interface and eliminate bugs. The current DBAT tool is capable of being run on most laptops/desktops, features a uniform user interface, and includes automatic report generation functionality.

4.3.3.3 Transition Status and Use

Navy personnel, in collaboration with AST2, used a development version of DBAT to test it for the design of an improved Motor Mount that was known to fail during ship usage. Navy personnel formed three separate groups and undertook a design modification through the use of DBAT; all three teams completed their designs, produced consensus designs using DARPA-developed 3D printers. We incorporated lessons learned from this exercise in further development of DBAT. Even though the Motor Mount was relatively simple, it was a good test case in the development process.

The DBAT tool is ready for beta testing; further verification, prior to its use, will require one or two such exercises with a team of USN/USMC personnel and incorporation of lessons learned. A tool, such as DBAT, would develop standardized processes. Additionally, such tools can support the development of design repositories.

4.3.3.4 Appendices

4.3.3.A DBAT Spreadsheet-based Tool
4.3.3.B DBAT Executable.exe
4.3.3.C DBAT Tutorial with Questions and Case Studies
4.3.3.D DBAT Explanation of Metrics and Calculations
4.3.3.E DBAT Source.zip

4.3.4 Reverse Engineering Curriculum

The Reverse Engineering curriculum is meant to act as a sub-module capable of integrating with DTAM or the Printer Curriculum to provide additional skills and methods training. The curriculum is meant to facilitate the training of individuals or groups and consists of one instructor presentation and one collection of instructor notes. The curriculum is structured as a two-day lesson which includes group projects to reinforce and apply the skills and methods learned. Content areas in this training include an introduction to reverse engineering, ethics and legality, approaches and best practices and review of the DBAT (an integrated product created

under this DARPA MENTOR2 program).

4.3.4.1 Curriculum Content

The curriculum in the Reverse Engineering module assumes introductory knowledge in additive manufacturing (3D printing) techniques. Participants or trainees are expected to have a high-school education (GED or diploma) or higher and should have access to a computer capable of running a CAD program (the module is not built to any specific CAD program. Many free, open-source versions exist in addition to commercially available CAD software). Similarly, the curriculum does not require purchase of any specific 3D printer brand, but does make the assumption that participants will have access to a FDM printer for completion of the assigned projects (if 3D printers are not available, projects may be shortened and completed through the design phase). The module also benefits from use of the DBAT, a software program meant to assist in the inculcation of formal design thinking and to aid in decision-making and reporting.

4.3.4.2 Development History

Curriculum development began in March 2017 and was completed in August 2017. Content for the course was pulled from published resources (cited as indicated) and from the requisite knowledge and expertise of the project lead.

4.3.4.3 Transition Status and Use

The curriculum has not been transitioned to either civilian or military customers. AST2 has included this in its GSA Schedule to provide access to Government agencies.

4.3.4.4 Appendices

- 4.3.4.A Reverse Engineering Slide Deck
- 4.3.4.B Reverse Engineering Instructor Notes
- 4.3.4.C Reverse Engineering Small Group Project
- 4.3.4.D Reverse Engineering Team Design
- 4.3.4.D Reverse Engineering Team Design
- 4.3.4.E Reverse Engineering Sample Training Schedule

4.3.5 STEM Short Courses

Science, technology, engineering and mathematics (STEM) are generally seen as difficult subjects in school, and the traditional teaching methods do not always relate the subjects and the usefulness of the information to day-to-day activities. AST2 has spent considerable effort, under DARPA and other programs, addressed this challenge and developed project oriented, cross-cutting curricula that is exciting and stimulating to immerse students in a learning environment. The curricula were offered as semester-long courses in a number of high schools, primarily in OH. In order to broaden the application of such curricula to other schools, particularly those attended by children of military families (such as high schools managed by DOD Educational

Authority or DODEA), we developed content for short courses that can be offered as STEM camps. We developed 5 such topics for STEM camps, each integrating problem-solving approach through STEM; they are summarized below and details are provided in appendices. First camp, based on biomimicry, was offered at Camp Lejeune High School to Junior ROTC students, and received excellent response. AST2 will seek other opportunities to deliver the STEM camps at other schools.

1. Biomimicry: This course looks at innovations that are inspired by nature. Lessons focus on how nature has provided us with new ways of looking at problems and solutions. Biomimicry is "an approach to innovation that seeks *sustainable solutions* to human challenges by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies that are well-adapted to life on earth over the long haul." Biomimicry is based on the belief that nature has already solved many of the problems with which we humans are grappling today. Well known examples include Velcro and shark-skin like swim suits.
2. Asteroid Threat: This course looks at the real-life threats and opportunities asteroids bring. Based on National Air and Space Administration (NASA)'s plans to capture an asteroid, lessons focus on asteroids, and how they both threaten life on Earth and provide us with a variety of opportunities. Like the asteroid that struck Earth 65 million years ago, asteroids threaten life on Earth; however, they also provide us with opportunities to both learn about our solar system and profit from the minerals we suspect exist there.
3. Repairing the Human Body: This course looks at the role of existing and ever-changing technologies in human health. Specifically, lessons focus on using technology to diagnose and treat ailments and injuries, to design and build 21st Century prosthetics, and to 3D print human organs. In addition, the course also looks as some of the ethical and moral issues raised by employing these technologies and abilities.
4. World's Energy: As the earth's population continues to increase, humanity faces crises from water to food to energy and everything between. How we create and use the planet's energy resources will greatly affect the future of the human race. This course studies energy resources, renewable and non-renewable, and traditional and alternative. Students will also investigate the role humans play in climate change/global warming and how we can decrease any effects humans have on the earth's climate.
5. Robotics: A four-phase module that progressively teaches about robots, and how to make and program the robots. Industrial applications of robots, current state of technology, Hollywood demonstrations and a host of other topics are covered with the aid of publicly available videos.

The above STEM camps can be delivered over a 3- to 5-day duration, with course content that can be adjusted based on camp duration. Each course includes class room coaching followed by team projects to develop solutions to a problem. Students also learn to design the solution using simple CAD tools and print the solution. The projects enhance students' learning to work together as teams, develop creative solutions, and in cultivating problem solving skills utilizing STEM knowledge.

4.3.5.1 Appendices

4.3.5.A Biomicry
4.3.5.A.A Biomimicry and 3D Printing
4.3.5.A.B Biomimicry Discovery
4.3.5.A.C Awesome Inventions
4.3.5.A.D Biomimicry Support
4.3.5.A.E Lesson Schedule
4.3.5.B.A The Asteroid Threat Student Edition
4.3.5.B.B The Asteroid Threat Teacher Edition
4.3.5.B.C Asteroid Capture Resource Sheet
4.3.5.C.A Repairing the Human Body Student Edition
4.3.5.C.B Repairing the Human Body Teacher Edition
4.3.5.C.C Supplemental Ideas for Repairing the Body
4.3.5.C.D Repairing the Human Body Resource Sheet
4.3.5.D.A The World's Energy Camp Module Student Edition
4.3.5.D.A The World_s Energy Camp Module Student Edition
4.3.5.D.B The World's Energy Camp Module Teacher Edition
4.3.5.D.B The World_s Energy Camp Module Teacher Edition
4.3.5.D.C Supplemental Ideas and Resources
4.3.5.E Robotics Module

4.3.6 Job Worker Card (JWC)

Wide industrial adaptation of AM requires the establishment of standards and credentialization of users; as a manufacturing method, 3D printing operators may obtain skills and credentials similar to other machinists. In parallel to efforts by organizations such as the ASTM International (ASTM) that are focusing on developing technical standards for production and quality control (ASTM Committee F-42) of components made using AM, worker training, certification and credentialing are important.

AST2 initiated an effort to develop a standard for the JWC during August, 2017. We recognize that developing the standard for JWC and getting its approval through Department of Labor (DOL)'s apprenticeship program, and the development of related technical instructions as well as creating on-the-job training (OJT) programs in coordination with employers is a long process and will not be completed prior to completion of MENTOR2 program. However, beginning of this effort is included in this report as the JWC will integrate a significant portion of 3D printer

training programs developed under MENTOR2 program.

4.3.7 Integrated Projects

During the transitioning efforts conducted by AST2 and others, we learned that hands-on projects are integral to creating the innovative problem-solving skills as well as to practice the curriculum using digital manufacturing equipment. Even though participants should be encouraged to develop projects utilizing their creative skills, providing some challenges that can be improvised is helpful. Based on the efforts of MENTOR2 program and training, we developed a few integrated hands-on projects; they are summarized below with detailed information provided in appendices. Problem statement, and aids in developing solutions are provided as separate appendices. The projects leverage some or all of curriculum developed under MENTOR including DTAM, DBAT and Reverse Engineering.

The hands-on projects are also structured to involve only 3D printing for simplicity; however, other technologies can be easily incorporated by participants. They are also of increasing complexity. Each project presents a scenario a deployed person may experience, how they can conceive an innovative, temporary solution, and regain use of the equipment to complete their mission. The process integrates several of the training programs discussed in this report; thus, they stimulate problem-solving skills utilizing innovative design and digital manufacturing concepts.

4.3.7.1 3D Printer Bracket Replacement

This project is a hands-on project to design and produce a 3D printer component, a bracket. The project walks users through the problem, reasons for components' failing, improvements to design to rectify identified flaws, and to create solution and produce components. Use of modules from both DTAM and DBAT are integrated to assist in the process.

4.3.7.2 Creation of a Sling Psychrometer

Military personnel are often faced with a missing piece and are required to improvise with what is available under combat conditions. This hands-on project discusses a scenario of a missing sling psychrometer, and how its function can be recreated using conventional analog thermometers and psychrometric charts.

4.3.7.3 Replacing a Rudder Control Valve

The project presents a scenario of a coast guard vessel losing rudder control far from the coast. The project discusses downloading designs from the manufacturer (may also be done by reverse engineering in similar scenarios), designing and producing a replacement to gain rudder control.

4.3.7.4 UAV Challenge

The project presents a requirement to improvise available inexpensive quadcopters to perform a task they were not designed for. The project also covers identifying an appropriate sensor, potential improvements to the quadcopter utilizing available material, and testing.

4.3.7.5 Mission Modeling

The project represents the planning activities of a mission, that are usually done on a piece or paper with a map to draw out and visualize scenarios, utilizing 3D printers to create 3-D renderings to help in planning. Project can integrate various configurations and movements for deployment to test against a series of anticipated enemy counter-offenses. Participants can integrate extreme terrain in the region and any other challenges.

4.3.7.6 Appendices

4.3.7.A 3D Printer Part
4.3.7.B 3D Printer Part - Solution Sketch
4.3.7.C Humid Climate
4.3.7.D Humid Climate - Solution Sketch
4.3.7.E Rudder Control Lever
4.3.7.F Rudder Control Lever - Solution Sketch
4.3.7.G UAV Challenge
4.3.7.H UAV Challenge - Solution Sketch
4.3.7.I Mission Modeling
4.3.7.J Mission Modeling - Solution Sketch

4.4 Transitioning Products to Civilian and Military Users

Transitioning of products developed under MENTOR2 program was a significant program focus, particularly during the second and third years. In collaboration with DARPA program management staff and other DOD collaborators, primarily from USMC and USN, we were successful in transitioning the products to the military. Examples of transitioning are summarized in this subsection.

4.4.1 3D Printer and DTAM Programs with Camp Pendleton

First Maintenance Battalion of USMC, located at Camp Pendleton, was in the process of initiating a program, during early 2016, to create a capability to augment sustainment efforts via rapid prototyping. The program, entitled EXMAN or expeditionary manufacturing unit, was focused on solving significant maintenance and sustainment issues associated with hard-to-procure or non-procurable components that were impacting operational readiness and efficiency. AST2, in collaboration with USN's Space and Air Warfare Center (SPAWAR), had the opportunity to utilize a number of MENTOR2-developed products to support this effort. Within the first six months of our support,

the First Maintenance Battalion successfully adapted 3D printing and other rapid prototyping technologies, developed EXMAN, developed solutions to a number of maintenance and sustainment issues, and demonstrated that these technologies can indeed enhance both operational efficiency and readiness. They have also won SPAWAR's highest award, Lightning Bolt Award, for their exceptional efforts.

4.4.4.1 Training, Support and Printer Use

Working with the First Maintenance Battalion was our first attempt for transitioning the 3D printer kits and printer curriculum; both items were still in the development stage at that time and hands-on working with the marines was quite helpful in the development efforts.

Marines that participated in the training program included experienced machinists and maintenance members with significant expertise. The team was also provided a weeklong Solidworks CAD training course by SPAWAR in preparation for the EXMAN program. Their experience and CAD training helped our efforts significantly, and the training program achieved success beyond our expectations.

We assembled 4 printer kits, a large set of spare parts, filament and other supplies for the training program. About 12 marines participated. Even though the marine team was experienced in machining and maintenance, they were not exposed to 3D printing prior to this training. Every member participated with great enthusiasm and contributed.

The first day of training involved the construction of 4 kit printers following the assembly instruction developed under MENTOR2. Since most of the participants were experienced, they were able to complete printer assembly, trouble shooting and leveling in about 6 hours; we had estimated 8 to 10 hours for the task. That allowed additional time for operation and maintenance training.

The second day of training was focused entirely on computer aided manufacturing (CAM), maintenance, and troubleshooting of the 3D printers. The maintenance and troubleshooting guides were developed integral to the printer kit curriculum, as separate appendices, and were utilized for this instruction. Some elements of DTAM were discussed in parallel as the discussions quickly elevated to the design process.

Camp Pendleton training did not include group projects, normally included in such programs, due to the accelerated timeframe. Marines were encouraged to bring in their own designs to print which inevitably reinforces the troubleshooting process. All of them came back the next morning with projects they completed overnight. All the marines downloaded AutoCad 123 overnight (if they did not already have it) at their residences, worked on designs and brought them the next morning. This was a clear testament to their enthusiasm to learn from the program and excitement about using the 3D printers. We were able to print the projects using assembled printers.

We left behind printers for their use and provided telephone support. During a subsequent visit the following week (to support visit by MG Berger), we were surprised to witness the number of components they had designed and produced to support maintenance activities.

4.4.1.2 Production Using Printers and transition to EXMAN

> **"It is more than just parts, it's about changing the way we think."**
> *Major General Coglianese*

MENTOR printers were used by the First Maintenance Battalion for a few months, and were useful in creating a number of solutions and improving performance. Marines moved to production scale printers in the EXMAN after using the MENTOR printers for about 5 months; EXMAN was subsequently equipped with a Fortus 250 printer and other digital manufacturing equipment. Table 1 provides a few highlights of replacement components that were designed and produced using both MENTOR printers and subsequently using EXMAN's full-scale equipment. Many of them have already approved for use by the Marine Corps and are in use. A detailed presentation, prepared by SPAWAR is attached as an appendix.

Table 1. Examples of Components Produced at Camp Pendleton

Maintenance and Sustainment Challenge	Solution and Benefits
Over 2% of RT 1916 components broken in AN/VRC-100 Vehicular Amplifier Units	• Design completed in 45 min • Each part production time 1 hr 45 min • Cost of material $2.00 vs. $1599 for replacing the broken component
Over 75% of the Harris 1694 and 1796 have broken COSMIC port parts that retain cryptographic fill	• Design completed in 30 min • Each part production time 45 min • Cost of material $1.00 vs. $1599 for replacing the broken component
Over 25% plastic cable shield broken in AN/VRC-110	• Design completed in 90 min • Each part production time 5 hr 30 min • Cost of material $2.00 vs. $8 for replacing the broken component
Hard to procure Amphibious Assault Vehicle (AAV)'s broken power take off Yoke Shifter	• Designed replacement part in 1 hour • Print time 2 hr 30 min • Improved operational readiness by 199 days

A significant observation to be made from information presented in Table 1 is the improvement in operational readiness; it is challenging to replace small components through normal logistics processes and units are often saddled with reduced performance. Digital manufacturing offers an excellent solution, as demonstrated by the First Maintenance Battalion.

4.4.1.3 Lessons Learned

Every transitioning effort we undertook was an opportunity to improve the products from lessons learned. Since Camp Pendleton effort was our first with the Printer Kit and DTAM, we learned a lot. Important items are summarized below.

- Lack of internet access, and even cell phone coverage, was a significant challenge. We had difficulty in transferring the files developed by marines at their homes to printers. We utilized a two-step process to overcome this. First, marines accessed the files via internet and stored them on their smart phones. We were able to transfer the files through the SD cards. This was not an easy task; using SD cards as the main printing driver was problematic. The lack of SD card readers and ports on military personnel computers was just further evidence that a work around was necessary for sustained use.
- The second lesson was around the capabilities of standard polylactic acid (PLA) filament used in 3D printers. The kit printer kits, at that time, did not have the capability to equip them with a heated bed, the materials that can be adhered to the printer surface are limited. This was something that the marines voiced as a concern very early. AST2 addressed this and incorporated a heated bed into the printer design and to print using alternate materials such as ABS.

4.4.1.4 Appendix

4.4.1.A AM Way Ahead, Dr. Kristin Holzworth, SPAWAR, October 3, 2016

4.4.2 Training at MARMC

AST2 organized a training session for sailors at the Mid-Atlantic Regional Maintenance Center (MARMC) during early March 2016, immediately following the training program at Camp Pendleton. This session was week-long and included sailors that had some familiarity with design and AM. Hence, we focused more on discussing design thinking. Additionally, in order to get an independent evaluation of the training program and to evaluate if others can deliver the program, AST2 subcontracted Old Dominion University (ODU) for the training at MARMC.

A summary of the report prepared by ODU is presented in this section.

A week-long seminar on additive manufacturing, or 3D printing, took place at the Mid-Atlantic Regional Maintenance Center (MARMC) from March 7-11, 2016. The purpose behind the instruction was to get students familiar with general principles behind additive manufacturing so they may pass on the instruction to future students and students.

4.4.2.1 Review of the course outline

A summary of the DTAM's relevant sections, utilized at MARMC, is provided below along with observations made by ODU.

Section 1 is an introduction to AM. The introduction was received well. During the discussion with sailors, including those who had some prior experience with 3D printing, many were still

amazed to learn some of the things they didn't know (i.e.: history behind 3D printing, advantages vs. disadvantages, material properties of plastic grades, etc). AST2 noticed this during other training sessions as wee; even though participants use 3D printers, general and relevant information on 3D printing is still lacking.

Section 2 discusses 3D Modeling and CAD software. Several sailors that participated in the session were familiar with CAD models. Hence, this was not covered in detail at MARMC.

Design process discussion begins in Section 4 and continues into Section 6. Emphasizing the process of design through this step-by-step process (i.e.: brainstorming, iterations, etc.) is helpful for the sailors to gain familiarity with the process as well as practice these steps to improve design skills.

As covered in Sections 9 and 11, learning about the different types of additive manufacturing techniques is important. The discussion on widespread applicability of 3D printing from biomedical to aerospace applications enhanced sailors' curiosity. Additionally, the discussion on the steps to prepare a part for 3D printing, as well its advantages/disadvantages and the different types of additive manufacturing techniques that exist, inspired creativity and innovation to use resources beyond what may be currently available.

4.4.4.2 Projects

The training program started with the sailors building printers from the kits, and was followed by hands-on projects. Assembling and troubleshooting printers from kits started on the first day and continued into the second day. Following a CAD training session, sailors began drawing items of their choice and developing designs. Additional instructions were provided on converting a pdf image into a CAD file (an exercise that can be useful during reverse engineering if only paper drawings are available). One sailor designed a Spongebob Squarepants figurine as well as a car, and was able to get the car printed on one of the newly constructed printers. A number of such projects were successfully performed during the training program.

4.4.2.3 Course Assessment

Students were asked to complete a post-assessment survey. Feedback on the short course was overwhelmingly positive, and are summarized in Table 2**.**

Table2: Student Assessment for MARMC Training

	Factor	Highly Disagree	Disagree	Neither Agree nor Disagree	Agree	Highly Agree
1	The course was well organized.	0	25%	0	75%	0
2	The course gave a good introductory overview of additive manufacturing.	0	0	25%	50%	25%
3	The topics covered in this course are relevant to my job.	0	0	0	75%	25%
4	The course objectives met my training needs.	0	0	0	100%	0
5	The activities used in the course were appropriate and helped me to learn.	0	0	25%	75%	0
6	The instructor was knowledgeable on the subject.	0	0	0	100%	0
7	The instructor presented the material clearly.	0	0	25%	75%	0
8	The course materials were presented on an appropriate level for the introductory course.	0	0	50%	25%	25%
9	Overall the course was valuable to me.	0	0	0	100%	0
10	I would recommend this course to my colleagues.	0	0	0	100%	0

4.4.2.4 Appendix

4.4.2.A ODU Summary Report. Technical Workshop on Naval Applications for Additive Manufacturing, Dr. J Michaeli and M. Polanco, June 22, 2016

4.4.3 Printer Assembly and DTAM Training at Camp Lejeune

After successful training of the First Maintenance Battalion, we organized an additional training session with the Second Maintenance Battalion at Camp Lejeune. The group of marines were selected to have a wide diversity of job functions at the Camp even though the Maintenance Battalion hosted the session. The diversity was planned to seek feedback from a broader group of marines, beyond those involved in maintenance functions. The group indeed represented a wide diversity from supply chain staff to electronics technicians, and even included two medics from the Navy stationed at the Camp. This proved to be extremely valuable, and provided feedback on how marines and Navy medics, of diverse duties and experience, could utilize the training material and develop critical problem-solving skills and practical solutions.

Training of Marines was conducted on 1 and 2 June 2016. Content was selected from the DTAM curriculum (Section 4.3.2). Marines had limited to no prior experience in 3D printing or CAD. Over the course of this two-day training, Marines assembled a 3D printer from a kit, calibrated and tested the 3D printer, were introduced to Additive Manufacturing concepts, learned introductory skills in CAD and pursued team projects.

4.4.3.1 Training Summary

Maine Corps assembled a team of 10 marines and 2 sailors with a wide range of backgrounds. They were actually a great test group for the training, based on the following observations:

- None of them had any exposure to additive manufacturing
- Only 5 had machining experience (few had familiarity with design) and one is a welder.
- Job duties within USMC/USN included supply administration, medic, driver, armament.
- All had only high school education
- All male
- Average age was probably 20 (only one marine and a Navy medic had more than a few years experience)

The group at Camp Lejeune was a better 'test sample' than the group at Camp Pendleton; a number of the marines we trained at Camp Pendleton had years of experience and were of higher rank. It was easier for Pendleton marines to pick up information. Camp Lejeune marines, on the other hand, were closer to young recruits with little experience (3 of them had less than 6 months in the Marine Corps). Including the team from outside the 2nd Maintenance Battalion was a great benefit; they not only provided diversity of backgrounds, but provided insights into what marines can do, a broader input than what only machinists could have provided. In fact, the Medic wanted to start using the printers to produce parts they need right away. Marine from the supply chain was talking about how it could make supply chain easier to maintain. The interaction between the maintenance Marines and others was also a great benefit as they were learning about how they could help each other.

Most of the Day 1 morning was spent going over additive manufacturing, what can be done using the technology, what its limitations are, some examples of items that have been produced using AM, etc. Modules selected for use from the DTAM curriculum were:

1a. What is AM	2b. Overview of Software	3a. Iterative Design
1b. History of AM	2c. Tolerances	3b. Design in 10 Steps
1c. AM Today	2d. Support Structures	3c. Design Requirements
1d. Advantages of AM	2e. Triangle of Choices	3d. Problem Statements
1e. Disadvantages of AM		3e. Creative Problem Solving

Day 2 emphasized 3D design with students using a free, open-sourced CAD program (123D) to create their 3D designs. The second half of Day 2 was spent pursuing a project in small groups of 2 – 3 marines. Each team identified a theme and created an object centered around that theme (i.e., one team used a medical theme to design a holder for various small tools that otherwise lay separate from one another). Iterative design and the use of 3D printing to enable/enhance rapid prototyping was a major point of emphasis during the team project.

Marines absorbed the material, and did not immediately jump into design (being Type A) utilizing the training they received during the previous day. Most of the teams spent about an

hour or more talking to each other before deciding how to proceed. It also gave us an opportunity to download 123D and install it on each of the computers. Marines learned CAD software usage readily, and started designs.

One team picked medical supplies as a theme. They designed a plastic holder that can be used with multiple types of scalpels. Produced two with varying thicknesses (the first one was too thin and weak). We discussed methods to make the scalpel holder stronger (higher density or thicker); the team improvised and produced a good holder. We learned that there are a lot of small plastic parts that are not readily available, particularly for practicing skin related surgeries. We also had discussions on what materials might be suitable for sterilization in an autoclave or the possibility of chemical sterilization.

The second team picked light weight drones as a theme. They were excited about how they could utilize 3D printing to produce lower density components and attendant benefits in flying such drones. They designed propellers and other items and started to produce them.

The third team picked a complex item – a Vernier caliper; they included marking units and had a sliding caliper. The design was completed in about 2 hours. Printing was deferred to the following day.

4.4.3.2 Feedback and Evaluations

We used pre- and post-course evaluation forms. We were able to collect all the pre- forms, and most of the post-evaluation forms back; some of the team members had to leave for other assignments and could not fill them.

Overall the training received positive reactions from the participants. Except for one marine, the participants saw the training having an impact on their jobs. They were universal in saying that we rushed through (a valid criticism) and did not provide adequate time on most topics.

4.4.3.3 Lessons Learned

Lessons learned at Camp Lejeune were similar to those from Camp Pendleton, and are summarized below.

- General consensus from the Marines was that the time spent training was too short. They would have preferred a full week in order to more completely master the concepts and gain exposure/experience with the printers.
- Loading 123D on USMC laptops proved more challenging than expected. Required software should be installed on all computers to be used during training prior to the start of Day 1.

4.4.4 JROTC Training at Camp Lejeune DODEA High School

AST2 has been successful in transitioning MENTOR1- and MENTOR2-efforts to educational institutions, particularly high schools in OH and PA. We wanted to transition the efforts to high

schools administered by the Department of Defense Educational Authority (DODEA) as well so that the children of military families, attending these schools, also benefit from the program efforts. We coordinated meetings with DODEA HQ in collaboration with DARPA and one of its high schools at Camp Lejeune in collaboration with USMC. We learned that implementing a semester-long or other activity as part of the regular curriculum requires an extensive planning and approval process. However, the local high school management and others at Camp Lejeune were excited about the idea and suggested working with JROTC to explore potential for incorporating program efforts and its benefits. We devised a 3-day program and delivered for JROTC students with exceptional feedback; demonstrated the value of MENTOR2 efforts in improving STEM experience at DODEA high schools.

4.4.4.1 Biomimicry Curriculum

The 3-day program, consisting of biomimicry curriculum content, integrated with elements from our 3D printing boot camps, was offered to 27 students at Camp Lejeune High School in October 2016. It consisted of approximately 19 hours of classroom time. The curriculum used video presentations, document presentations, and curriculum presentations along with a decent amount of lecture material which took up approximately half of the course (10 hours).

A detailed content is provided in an appendix (Biomicry), and a summary is provided below.

- Day 1: 3D Printing and Printer Assembly: Students learn basics of 3D printing via lecture and reading of published articles, assemble 3D printers from kits. We used 3 kits and formed 3 student teams to work with each kit.
- Day 2: Biomimicry and CAD Training: Students learn about biomimicry in nature, how humans have utilized it in design for enhanced efficiency using a number of examples, and proceed to learn about CAD.
- Day 3: Projects: Students form teams with defined roles for individual team members, follow a methodical process to develop project designs, review published articles for suggestions, and present projects.

The module emphasized group work by utilizing three projects during the class. Students successfully completed their tasks which included construction of printers (one printer per team with three teams) from printer kits, basic instruction in a CAD software (123D Design), and presentation of three team projects. Each team 3D printed an object to represent their team using the printer they have assembled. Camp Lejeune high school also acquired one of the printer kits for continued education and classroom use.

Surveys were held before and after the course. Due to changing student population (some students did not attend all days of course), there were only 18 students that could be analyzed for improvements in their education level.

4.4.4.2 Learning Printer Assembly and Design

Students constructed the 3D printers from kits. The kits were fully disassembled units requiring full assembly, testing and calibration before use. Student teams were able to successfully construct their printers (including testing and calibration) in roughly 4 hours (with 2 teams being successful in construction by 4 hours and 1 team needing an additional hour). The printers were further utilized to print one project file (roughly 1.5 hours printing time). During the assembly time, students were rotated away from printer assembly to complete a self-paced CAD instruction module based around the Autodesk 123D Design CAD software. This module takes around 30 minutes to complete. Students had to design a CAD model for printing (an object to represent their team) as well as an object for visual presentation for their team project final deliverable. Each team was able to competently design both objects.

4.4.4.3 Biomimicry and Group Projects

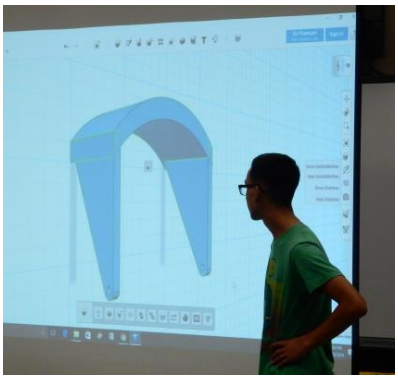
The module instructed students on developments and inventions based on analyzing nature's advantages at handling certain problems. Student population at this camp consisted of JROTC students who are experienced in group work. The students were presented with a variety of group work elements in a larger team context.

Student groups consisted of approximately 6-10 students (number varies due to varying student population on each day of the course). The group work consisted of one main project (covering all 3 days) and one smaller project (covering the last 2 days). The main project had students creating a useful element for business, commercial, or military use. Students were required to present their work via a CAD model (visual presentation only), a PowerPoint presentation, and a verbal presentation/defense of their project.

The smaller project (2 day) was to design an object to represent their team. This object was then printed after being designed and had to successfully print. The team then presented their experiences with the 123D Design CAD software as well as presenting their designed part. One team printed a kangaroo and two printed medallion disks that featured their team names.

The main project was to think of an object that would be developed after viewing a specific element from nature. A video of an element from nature (a hovering leaf in the wind) was shown to the class before their course work. Groups then presenting what they believed would

be invented from that element. This presentation only involved a verbal presentation/defense due to the shorted duration. The teams presented armadillo like defensive armor pieces, a tail like balancing apparatus, and armadillo like flexible armor.



All projects were presented successfully on the third day of the camp.

4.4.4.4 Assessment and Lessons Learned

The module was well received by both students and teachers; and we received a letter of appreciation from LTC Valore.

Assessments were issued both before and after the course. There were 18 students that were present both at the beginning and end of the course. General analysis shows only 2 students did not have a positive reaction to the. Sixteen of the 18 students provided positive feedback encouraging us to proceed forward. The questionnaire used was an abbreviated version of the survey developed by Carnegie Mellon for evaluation of INVENTORcloud program's effectiveness under the Gates Foundation grant.

Quantitatively, average score of the students in being able to and willing to self-learn, perform design and conduct innovative programs increased from 3.8 prior to the workshop to 4.2 after the workshop. Qualitatively, the most frequent comment we received as a result of workshop was – "**yes, I can**." Students gained self-confidence and developed curiosity.

The mixed team approach (with one large team being broken into 3 sub-teams with each sub-team having specific goals) was successful and the overall project approach (where teams were making projects to compete with the other teams) assisted in keeping students interested in the program.

4.3.5 Training of Naval Expeditionary Forces

ODU has adapted some of the training curriculum and 3D printer developed under MENTOR2 program to train expeditionary forces under a ONR Grant (No. N00014-16-1-2819), 'Creating the Fleet Maker.' The main purpose of this program is to advance STEM education and outreach to active duty military personnel, improving the Navy 's STEM workforce. Key project components are:

1. Engagement of active duty personnel in a Maker environment
2. Informal STEM learning through collaborative workshops
3. Workforce development for both active duty STEM and non-STEM professionals interested in technologies such as 3D printing, 3D scanning and meshing, computer aided design, geometric modeling and computer integrated systems.

AST2 is a member of the ODU team, and MENTOR-developed 3D printer and some of the curricula have been incorporated into the program. The program has trained about 100 sailors to date, and is an additional successful transition of MENTOR efforts.

4.4.5.1 Workshops

ODU has completed 5 workshops through the first year (ending in June 2017), and plans to conduct 10 additional workshops. A total of 300 to 400 sailors would be trained through these programs. Constitution of participants for the first 5 workshops are presented in Table 3. Five additional workshops have also been scheduled for the 2nd year. Each workshop aims participation of about 10 sailors from two separate ships or organizations, and is conducted over Friday and Saturday.

Table 3: Fleet Maker Training Participants

Workshop	Schedule	Participants
Workshop # 1	January 27 – 28, 2017	USS San Jacinto (CG 56) USS Kearsarge (LHD 3)
Workshop # 2	March 17 – 18, 2017	USS Mason (DDG-87) USS Normandy (CG-60)
Workshop # 3	April 14 – 15, 2017	Naval Station Norfolk USS Whidbey Island (LSD-41)
Workshop # 4	May 12 – 13, 2017	USS WASP (LHD 1) U.S. Navy Sealift Command
Workshop # 5	June 2 – 3, 2017	USS Monterrey

4.4.5.2 AST2 Participation in Workshop # 4

AST2 supported all workshops, and was able to participate in Workshop # 4. Participants were two teams of sailors (5 female and 15 male) from USS Wasp and Navy Sealift Command (NSC), each with 10 participants. Participants represented significant diversity ranging from ordnance inspection to IT specialists. Both crews were somewhat unique and provided valuable insight in terms of going forward. The Wasp team were mostly young sailors and included one senior member, a maintenance chief, who had a good perspective as the Wasp team was lent one of the MENTOR-developed 3D printers from MARMC during a six-month deployment in 2016. As a result, he was aware of its use on the ship during the deployment. The Wasp sailors were glad that they could keep the printer now. The NSC team included both junior and senior sailors including a CDR, a senior supply chain officer at NSC. Having been both an enlisted member and an officer, the CDR had good insight into how rapid prototyping could help in supply chain management.

During the 2-day training program; every sailor was totally engaged and enthused. Just as we noticed earlier with marines from Camp Pendleton and Camp Lejeune, sailors absorbed the information like sponge and developed skills very quickly.

4.4.5.3 Observations and Lessons Learned

The most important observation and lesson learned was the limitation on what sailors could do on the ship with the printer without a design station. Even though there are computers on the ships, sailors are unlikely to be able to download design software or even be allowed to use the ship computers. Future plans should include a dedicated laptop with a CAD software with the printer (as it was during 2015 deployments on USS Truman and USS Kearsarge).

Even though the training was with the MENTOR-developed 3D printer, it is just as relevant to any simple 3D printer. Few sailors needed help with leveling, but most learned to use them in less than 30 min.

Virtually all expressed that they would benefit from additional training on other types of digital manufacturing equipment. A number of applications for use of 3D printers and other equipment, while ships are sailing, were identified.

4.4.6 Vocational Therapy for Veterans

Physical therapy during rehab is often monotonous. AST2 wanted to explore potential of 3D printer programs to enhance therapy. Assembling the printer kits would engage mind as well as body, and subsequent use of the printers could provide skills for entrepreneurship or employment. We explored the potential of this concept with the Veterans Administration (VA), and obtained a SEED grant to evaluate at two different VA Medical Centers; White River Junction (WRJ), VT and Chillicothe, OH. We completed the training program at WRJ, and are scheduled to conduct training at Chillicothe starting in October, 2017.

The first training session at WRJ was extremely rewarding, and VA has expressed interest in implementing the program broadly across the Nation.

4.4.6.1 WRJ Training

The week-long training held at the WRJ was attended by a number of veterans engaged in a drug rehab programs and staff from the medical center. It was based around the concept of teaching art therapy using 3D printing. We utilized MENTOR-developed printer kits, printer curriculum and DTAM.

Training program started with small teams of veterans assembling three printers from kits. Once assembled, general operation, maintenance, and troubleshooting were discussed. Veterans were also introduced to the slicing software for computer aided manufacturing (CAM).

The veterans were also taught parametric modeling (CAD) using Onshape. The CAD classes utilized generic premade curriculum, but adjusted to accommodate participants' ability to absorb the material. This allowed the trainers to gauge the skill level and modify the approach

whenever necessary. The scope and duration of the training program did not allow for deep learning of the software, but provided adequate time for veterans to gain knowledge and learn the basics and to access additional resources when one runs into a challenge.

Veterans practiced some basic designs during the CAD instruction; however, the main focus was creating a project that they would find useful or one would benefit the VA in some way. Maintaining the projects as open as possible empowered all of the veterans to be creative without restrictions. Once their concepts were put together, AST2 staff supported their efforts to learn what was achievable via 3D printing and what would need post processing (hardware, painting, etc.).

Creating the project was the best avenue for veterans' teams to implement what they learned during the training programs, including about 3D printing process and the design process. We integrated best practices from DTAM, and encouraged veterans to first draw their design on paper before starting to design on the computer. This simple step accelerated the design thinking process and allowed them to see what they were doing from a wider perspective. Veterans also had to be creative to achieve some of their goals as the limitations of 3D printing became more apparent. Some examples of completed projects are: painted duck (displayed at WRJVT), fidget spinner, hand-bike (1/10 scale), and an empty magazine flag insert.

4.4.6.2 Observations and Lessons Learned

The main lesson learned involved hardware restrictions from the VA and the limitations of Onshape, CAD software used during training. The initial goal was to use iPad mini's for the CAD modeling tasks. This proved to be extremely difficult due to the mobility and control limitations of some of the veterans. Using laptop computers was a far more manageable method for the design work.

Internet usage wasn't consistent at the medical center. The computers were regularly removed from the network for random intervals of time. Since Onshape is web-based, this presented significant challenges.

Participating veterans found the program to be very useful, and started teaching other veterans within 2 weeks after the training program. In addition to the main purpose of vocational therapy, several members immediately realized that the program could help in creating products for sale or gain employment. A video prepared by the VA is included in an appendix.

> **"This will make people useful and give them a sense of accomplishment,"**
> *Mitzi Frazzetta, Veteran*

4.4.6.3 Appendix

4.4.A WRJ Training Video

4.4.7 AM Boot Camps

In collaboration with and funding from AmericaMakes and University of Texas at El Paso (UTEP), AST2 conducted two separate week-long boot camps where participants learned about 3D printing. MENTOR-developed printer kits and curriculum were integrated into the Boot Camps.

The first boot camp, held in Youngstown, had the following main objectives:

- Train members on AM processes
- Printer operation and maintenance training involving the assembly and operation of the printer kit
- Train the trainers to transfer the training to others in schools or military

An additional objective of the boot camp was to evaluate how easy the printer kit was to assemble and use by members with wide technical backgrounds. Observations by AST2 staff and feedback received from the attendees was quite helpful in revising the printer design, assembly/disassembly manual, and organization of the kit. The finalized printer kit benefited from the feedback we received during the boot camp.

All attendees were given a tour of the rapid prototyping laboratory (developed subsequent to MENTOR1 program), and introduced to the entire range of bench-top prototyping equipment.

The boot camp was interspersed with lectures from notable experts in AM including several faculty from YSU and UTEP. The attendees were a mix of school teachers (of all grade levels) and DoD personnel (both active duty and civilians) from USN and USMC. The concept for the military personnel is same as for the one for teachers; they would become trainers that would instruct colleagues the basics of AM, design and production.

AST2, in collaboration with UTEP and AmericaMakes, conducted a second boot camp in El Paso, TX during October 2016. The El Paso camp targeted school teachers with primary focus towards training teachers to incorporate AM education into regular curriculum. AST2 continues to instruct in the use of AM and occasionally uses printer kits to assist in these endeavors.

4.4.7.1 3D printer assembly/disassembly

All attendees participated in the assembly of a printer from the kit, its use and final disassembly. We shipped the printer kits to all the attendees for their subsequent use and training purposes.

Assembly of the printer required that the attendees to render the printer operational for use during other segments of the camp, this required the attendees to troubleshoot the printer if they assembled the printer incorrectly. An assembly manual was provided, and experienced personnel were available to assist in the activity.

At the end of the camp, the printers were disassembled back into kit form, using disassembly portion of the manual, ready for future trainings and ease of transport. Disassembly of the printers emphasized the correct reconstruction of the kit container allowing for future successful constructions.

AST2 staff observed the assembly and disassembly procedures and denoted when instructions were unclear or led to undesirable actions taken by the attendees. When staff observed issues, they stepped in to provide individual instruction and assistance. Modifications were made to the supporting documentation to assist with continued development and redesign of the printer kit.

A video documenting the Youngstown Bootcamp is provided in the appendix.

4.4.7.2 Project Designs

All attendees were instructed on free CAD software appropriate for beginning users. The software used at that time was Autodesk 123D (discontinued as of the writing of this document) and BlocksCAD. CAD instruction was necessary so that teams could develop and print projects by the end of the camp.

Attendees used the assembled printers to print projects. Each group was challenged to make an interesting project, which was used as a stimulating tool, in daily discussions about their progress towards designing the project in CAD as well as their final result on the last day of the camp. Attendees subsequently used the printers to produce their designs. AST2 personnel assisted where needed. All participants successfully completed their projects and presented them on the final day.

4.4.7.3 Feedback and Lessons Learned

In addition to the informal feedback during the boot camp, we used surveys to capture more quantitative data. It is noted that only some of the attendees answered the survey. We received positive feedback (summarized below), and comments on the needed improvements to both printer design and assembly/disassembly instructions. All required improvements in the printer kit design and documentation were implemented prior to the second boot camp at El Paso, TX.

Most members expressed that the boot camp enabled them and provided confidence in their ability to build and operate 3D printers. Except for one, all responders expressed confidence in building 3D printers from kits. All responders expressed confidence in operating 3D printers.

Assembly documentation was found to be generally satisfactory; disassembly documentation was found to be inadequate with suggestions for improvement

All members felt they learned to use CAD to design for AM. Some felt that an additional day of CAD and another project would have been helpful.

Hands-on projects were favored over class room lectures (a recurring theme from most sessions); we utilized this feedback to focus on learning through projects for Navy and Marine Corps training.

4.4.7.4 Appendix

4.4.7.A Summary video of the Youngstown Boot Camp

5. Significant Hardware Development

5.1 Mini Fab Labs

Working with MARMC, we created simple fab labs to determine how simple rapid prototyping laboratories, mini Fab Labs, would find an application on naval vessels and to evaluate their functioning during voyage on open seas. A simple design comprising a MENTOR-developed 3D printer, a small CNC mill, Othermill, and a design station consisting of a lap top computer with 123D CAD software and a large screen monitor, all installed on a mobile cart for easy transportation on ships was selected. We fabricated 2 such mini Fab Labs and they were provided to USS Truman and USS Kearsarge for use and evaluations.

Sailors from both ships reported extensive use of the mini Fab Lab. Equipment performed well during voyage. Sailors from USS Truman have reported extensive use, and reverse engineering and production of a number of components that were used on USS Truman, and subsequently by other Navy organizations. Notable examples include:

- The development of a clip, TruClip, that is used by sailors on ships to carry radios: The part gets usually broken, and the whole unit requires replacement. Truman sailors designed and produced the clips saving over $14,000 in replacement costs over 2 months. USS Truman spent $146,000 over a two-year period to replace the radios due to the broken part, each replacement clip can be printed at a cost of 6 cents per clip (as opposed to $615 to replace the radio). The design was also selected as the top winner in Navy's Apollo Project challenge, and its design was transmitted to the International Space Station for printing under zero gravity conditions.

- Enabled surgeries: Designed and produced broken waste gas coupling critical for anesthesiologists to perform life-saving surgery.
- Reduced work stoppages: Prevented 7- to 10-day work stoppage by designing/fabricating a fitting for the nitrogen purge kit so the corroded wrap around panel brackets on F/A-18 aircraft could be replaced.

A number of other items, including non-procurable items such as a clamp for the Air Plenum Fixture for the Radar Test Bench Set were designed and produced on Truman.

The 3D printer has been subsequently deployed for extended periods on several ships (as discussed in Section 4.4.5) though MARMC and ODU.

5.2 3D Printer and Printer Kit

AST2 began development of a rugged 3D printer, particularly for use in high schools to aid in education, during 2014. Initial printer development was funded by Northrop Grumman Corporation, and the effort provided the foundation for the development of first a printer and subsequently a kit under MENTOR2 program. The need for the printer was identified when we noticed that most of the schools were not able to maintain the printers purchased commercially, and thus has nonworking 3D printers. The quality of inexpensive 3D printers, used by high schools, was poor and maintenance was difficult. Hence, we began the development and production of printers as a part of after school program for high school kids; the goal was to make printers that high school students can operate and maintain.

The 3D printer was originally designed and produced as an assembled unit. This allowed for complete testing and troubleshooting, and eased the support burden. Assembling the printer also allowed for proper alignment of the hot end and filament drive. The initial design however was intended to be a repeatable assembly process, and this quickly evolved into the development of a kit that can be assembled and disassembled, repetitively, for training, operation and transportation.

5.2.1 Printer Design

The structural frame braces were made of square solid and the support channels were made from structural aluminum. All the frame components were made of quarter inch aluminum and the linear rails are made of hardened steel. This robust design proved to be a solid foundation to adapt the 3D printer into an unassembled kit.

Before significant time was invested into the kit making process, the printer, its components and process needed to be evaluated at every level to eliminate any deficiencies in the process that could create confusion or problems during printer assembly or use. To properly evaluate what could be assembled with a high reliability of performance, we held test builds during certain sections of the assembly process to evaluate their repeatability versus complexity. We held these efforts with various age groups and competency levels.

The data collected from these efforts indicated a need for reduced use of hand tools. Initially, some of the younger groups were unfamiliar with the tools necessary to complete the assembly, and this required the development of a section in the instructions explaining how to properly use hand tools. To eliminate that recurring problem and to speed up the assembly, thumb screws were developed using existing hardware. These thumb screws encased the bolts with a 3D printed head that allowed for hand tightening as opposed to requiring the use of a hand tool. The concept was not successful as structural thumb screws still needed the use of a hand tool to ensure proper tightness.

Thumb screws were assimilated into the head design as well. The 3D printer development involved a significant amount of effort towards making the hot end and print head easily accessible, as they are known to require maintenance during normal operations. This approach was necessary for troubleshooting and alignment. Two thumb screws were implemented into the head mounting bracket to allow easy removal of the driving motor. This method proved to be fairly reliable although the thumb screws needed to be tightened with a hand tool for final tightening.

The frame remained secured by non-thumb screw type hardware. The internal mounting blocks were pre-assembled. This was done to maintain repeatability in the building process because flat head hardware is likely to strip.

Printer designs and the kit assembly/disassembly instructions are provided in appendices. Printer designs are provided as STL files; they can be downloaded and used for production of printer or any component.

5.2.2 Printer Production and Deployment

We produced over 100 printers and kits; approximately half of them were supplied to educational institutions and the remaining were used in Boot Camps or supplied to military organizations. We also used printer kits for training over 100 civilian and military members. Using the kit as a training tool was found to be extremely useful, particularly when working with members that had no prior knowledge of 3D printing. Assembling printers removed the mystery surrounding 3D printing, and made members comfortable in designing and producing items with 3D printers.

5.2.3 Printer Fire

The original hot end manufacturer for the Invent3D discontinued making the V3B hot end. We explored alternate hot end suppliers, and tested several models including the Pico Hybrid from B3 Innovations and the E3D V6 All-Metal. Failures seemed extremely common amongst both but more so for the Pico Hybrid. That failure was magnified by a complete printer malfunction resulting in printer fire with a printer deployed at YSU.

AST2 spent considerable effort to investigate the cause for fire; it is believed that the thermistor that is inserted into the hot end was displaced. As a result, heating continued and the hot end temperature increased eventually causing fire due to the plastic filament and parts in the printer. AST2 performed a root cause investigation, and developed a two-level redundant process to eliminate temperature runaway. First, we replaced all the hot ends with a different unit that includes a built-in thermistor. Additionally, we modified the firmware to avoid continuous power input. Printers seem to be functioning well, and we have not received any reports of such incidents since January 2017.

5.2.4 Current Status

After producing and deploying over 100 printers and kits, AST2 stopped production of printers. As the technology has already been demonstrated, printer production became a commercial venture and does not align with AST2 interests in providing services, particularly associated with digital manufacturing and workforce training. Additionally, a number of rugged commercial printers have come into market during 2016 thereby providing a multitude of options to acquire rugged, inexpensive printers.

5.2.5 Appendices

5.2.A Printed Part Design files

- *belt clamp x-axis.stl*
- *belt clamp y-axis.stl*
- *belt stop.stl*
- *end stop.stl*
- *extruder bottom E3D.stl*
- *extruder top.stl*
- *feet.stl*
- *filament drive.stl*
- *filament guide.stl*
- *HB clamp front.STL*
- *HB clamp rear L.STL*
- *HB clamp rear R.STL*
- *INVENT3D Printer Kit Parts List Alphabetically V7b.docx*
- *LCD cover.stl*
- *LCD knob.stl*
- *power plug adapter.STL*
- *print board spacer.STL*
- *side clamps.stl*
- *spoolholder.stl*
- *t-scr blu_bla_o_y.stl*
- *t-scr gr_s.stl*
- *t-scr M3 black.stl*
- *t-scr M3 gold.stl*
- *t-scr M4 white.stl*
- *t-scr M5 red flat.stl*
- *t-scr M5 red.stl*
- *z motor bottom.stl*
- *z trigger.stl*
- *z-axis knob.stl*
- *z-lock plate.STL*

6.2.B Invent3D Printer Assembly Instructions V.7

6.2.C Printer Disassembly Instructions V.7

6.2.D Printer Parts List and Kit Organization

6.2.E Printer Operating Instructions _ Trouble Shooting Guide

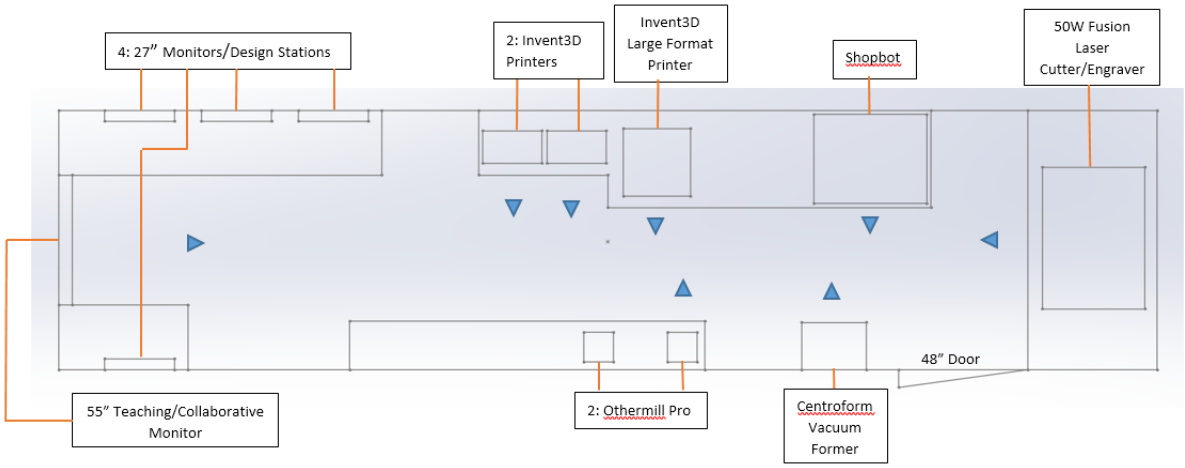
5.3 Fab Labs for Navy and Marine Corps

Demonstrated success in adapting MENTOR's and other training programs, and demonstration by both sailors and marines (Truman, MARMC, Camp Pendleton, for example) to leverage the training to create innovative solutions for sustainment and maintenance enhancements have led the Navy and the Marine Corps to further the deployment of such equipment. Several MENTOR2 performers including AST2, Fab Foundation (Massachusetts Institute of Technology) and TIES (Teaching Institute for Excellence in STEM) developed and delivered the training programs.

AST2 received a contract to create, fabricate and deploy broader digital fabrication equipment and training. For USMC, the program included providing equipment to three locations; 29 Palms, Camp Pendleton and Quantico. The Fab Lab at 29 Palms was modeled after Fab Foundation's laboratory design, similar to the one established at MARMC under MENTOR2. We worked with the Fab Foundation and TIES to establish the laboratory. For the Navy, the program included four transportable digital fab labs (TDFLs) with one of them being a modification of the Fab Foundation specifications. TDFLs were deployed to NAVAIR facilities at Patuxent River, Oceana and New Orleans.

5.3.1 Transportable Digital Fabrication Laboratory

The TDFL was configured with several goals in mind. Its main goal was to streamline as many processes as possible with the given set of equipment and to optimize the limited space available. Additionally, transportability via a large pick-up truck (as opposed to a tractor) was considered important to allow for easy transportation of the laboratory over short distances. Hence, we selected a standard 34-ft trailer as the base configuration, and modified it extensively for its intended use with climate control, power distribution, work and storage areas, etc. The trailer has two zones, design/teaching and prototyping/manufacturing. These zones were necessary to ensure the protection of computers and other sensitive equipment. The layout of the trailer allowed for optimized use of STORM virtualization technology. It also allows for multi-functional use as one group can be training while another can be working. The design layout of the trailer can be seen in the figure below.



Fabrication equipment for the TDFL was selected to allow working with the most feasible materials in an enclosed trailer. TDFL was thus designed to allow digital manufacturing utilizing electronics, polymers and wood as the "base materials". Equipment list was subsequently developed, in collaboration with the Navy, to provide as much high-end equipment as possible while still ensuring the equipment's safety during transport and use.

Ability to digitally integrate and remotely operate (such as via STORM virtualization) was also a factor in selecting the equipment. Virtual access to the equipment, at a minimum, for remote monitoring using overhead cameras was necessary for training. The space available inside the trailer for training is limited; hence, the remote monitoring is an advantage to hold training sessions outside the trailer. Networking also played a role in design as each piece of equipment and design station must be able to connect to the network. The network storage needed to be positioned at a locale where the network points converge but also have access to the power cable ports in case the client wants to bring hardline internet into the trailer.

5.3.2 Training

The training provided to each TDFL was based around four days of curriculum. The goal of the training was to ensure proper use of the trailer and its systems but also the equipment inside. The TDFL overall has a set up and tear down protocol for transport so that instruction carried the most value. Secondary instruction was focused on learning all the details of operation and maintenance for the equipment inside. This covered how to set up the equipment for travel and staged protocol to reinforce its importance.

Software instruction was another significant area of focus. With the limited amount of time, computer aided design (CAD) training was restricted to quick walk-throughs. Proprietary software, like V-Carve Pro, was focused heavily to ensure computer aided manufacturing (CAM) processes were being set up correctly. This ensured that the equipment would be operated in a safe manner. We also provided CAD training using Creo in some locations.

5.3.3 Projects

A significant amount of training time was utilized to learning via performing projects. Even though we prepared training programs around equipment, project-based training was more appealing to Navy participants. There were two forms of projects used, prescribed projects and self-guided projects. Prescribed projects were used as a vehicle to illustrate the software, machine set up, and maintenance. Self-guided projects, on the other hand, were devised to teach creative problem solving. When participants bring a project idea in to TDFL during training, we found that only a portion of that project can be accomplished inside the TDFL. The instructors would then work with participants do develop a creative solution to achieve their goal through a varied approach, different equipment, post processing, etc. Such collaborative, hands-on working incubated the collaborative and innovative problem-solving skills.

5.3.4 Lessons learned

- Software proved to be quite the bottleneck as many software companies moving toward annual renewal instead of purchased stand-alone copies (as mentioned earlier with other training programs in Section 4). In a place where internet isn't always available, this proved to be a significant challenge. Licensing aside, software selection was also an issue. There is no standard CAD software among the different military groups so deciding on a software to serve the largest mass was difficult. Future deployments of Fab Labs shall include a variety of software tools that are commonly utilized by the service agency and those that can operate without continuous internet connectivity should be integrated into the laboratories.
- Internet in the trailer was an issue that came up fairly early in the design discussions (another recurring theme). The limited internet availability on base combined with security risks of bringing in our own internet was a concern. The decision was made to make the trailer as network friendly as possible to an outside internet source. This allowed for the liability to be on the customer in terms of any security issues or base concerns. A solution implemented at 29 Palms could be a potential approach. An independent, commercial internet service was added in the Fab Lab with a local router; this created an isolated local area network for the computers and equipment that are integral to the Fab Lab.
- Availability of power was the last major lesson learned. Relying on the bases to set up site power was complicated and a fairly long process. None of the bases had power set up by the time training was organized (even several months after TDFL delivery). A built-in generator would have overcome this problem even though it has its own logistic challenges (noise, pollution, diesel supply, etc.). The generator would also make it easier to transport and set-up at another location.

6. Special Comments

MENTOR2 program produced a number of products including hardware, software and training, all focused on stimulating innovation and problem-solving skills. The products assist users in analyzing a problem and creating an innovative solution through design and engineering. This was demonstrated through our working with users of diverse backgrounds ranging from high school students at Camp Lejeune High School to skilled machinists from the First Maintenance Battalion at Camp Pendleton or high school educators during Boot Camps to experienced military engineers or training at NAVAIR.

Most of the products (hardware, software and training) developed are based on or leverage 3D printing. 3D printers offer an easy and quick method to transform ones' imagination to a physical form, necessary to visualize, share and utilize. We utilized 3D printers (or other digital equipment) as a tool to stimulate such innovation and problem-solving skills. The process utilized is the creative component and is important with the projects as learning tools; the process can then be utilized to address many problems they may encounter.

Few observations to be noted from our work with military personnel include:

- Even a few days of stimulating discussions will instill problem solving skills among military personnel
- Training is much more effective when combined with team work and hands-on projects that address (and simulate) problems members of military are likely to encounter
- Digital manufacturing, additive manufacturing in particular, offers a unique way to develop manufacturing solutions
- In virtually every case, defense personnel were enthused to learn problem solving skills; sought next levels of training and deeper knowledge
- Enlisted personnel created innovative and economic solutions with available tools and equipment
- Even small and simple equipment can be used to stimulate thinking and to produce solutions

MENTOR2 has been a great team effort that integrated our customer, DARPA, participating members from USN and USMC, other performers and numerous collaborators. A few team members deserve special mentioning; their active participation was a key factor in making the program successful. AST2 thanks Mr. Tim Bailey, DARPA contractor and project manager, LT Todd Coursey of USN, LTC Howie Marotto, LTC Greg Pace and CAPT Chris Wood of USMC, and Dan Green of SPAWAR.

ASTM project team included Messrs. Jack Scott, Nick Mazurek, Craig Richards, Joe Moran, Julie Smith, Bill Scott, Rob Bagzis, Justin Yates, Harsh Dev and Al Unione. Their diligent efforts are acknowledged.

7. Implications for Further Research

Collaborative working with service organizations, particularly nearly 100 enlisted personnel, showed that the military and the Nation have a significant untapped resource – creative minds that can be tapped to create innovative solutions. It does not take a lot to stimulate them. Cultivating this opportunity should be a significant focus for future efforts; research should integrate service organizations and deployment to ensure that research does not remain as a research report. This will integrate a 'Silicon Valley innovation' into our military personnel, and enhance preparedness and operating efficiency.

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14. ABSTRACT

MENTOR2 Program's overall objectives are to develop and deploy tools and curricula for collaborative design and digital manufacturing, and to instill innovative problem-solving skills through effective design and manufacturing. AST2 developed digital manufacturing hardware including 3D printers, software and training programs, and utilized them to train civilians and military personnel to address problems methodically and develop solutions through effective design and manufacturing. Marines and sailors have shown exceptional enthusiasm and ability to leverage these tools and training, both under normal and combat situations, cultivated innovative problem-solving skills, and solved numerous problems that improved both operational readiness and efficiency while simultaneously achieving cost savings. AST2 successfully transitioned products from MENTOR2 to US Marine Corps (USMC) and US Navy (USN), Veterans Administration (VA), academic institutions, and are laying the foundation to create a nationally accredited training and certification program in additive manufacturing (AM).

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