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Creating the Fleet Maker: a 3D Printing-centered STEM Learning Environment for the Stimulation of Innovative Thinking and Empowerment of Sailors

Abstract

This paper describes an ONR-funded project, "Creating the Fleet Maker" dedicated to the skill development and STEM education of active-duty Navy personnel. This effort will provide a workforce development platform for training of sailors to be capable of reverse-engineering and 3D-printing components while onboard of ship.

While far away from any supply chain point, an insufficiency of components needed for maintenance and successful mission continuation can threaten the essential function and successful operation of ship systems. The wait for parts might be much longer than it would be if the similar situation were to happen in any civilian engineering system. Hence, the project team is interested in using the Maker approach for workforce development of active-duty military personnel.

Fifteen Fleet Maker Workshops will be developed, executed, and assessed at the Old Dominion University Monarch Maker Laboratory. These workshops will serve Navy servicemen to 1) increase their skills related to the concepts of making such as computer-aided design, reverse engineering, additive manufacturing, product lifecycle management and part retrieval, 2) foster STEM knowledge and professional development, 3) introduce skills needed for opportunities in advanced manufacturing, and 4) empower them to solve problems through a creative design approach. Ultimately, active duty personnel will acquire the skills needed for successful on-board maintenance of naval vessels and other problem-solving scenarios.

This project is aligned with a nationwide initiative, led by the President, focused on professional development of American workforce that thrives through technological developments especially in additive manufacturing. Rapid prototyping, or 3D printing, started in 1980's and recently gained attention for Navy fabrication shops supported by sailors that solve logistic problems on the fly. As rapid prototyping costs continue to decrease, these technologies become more accessible for educators. Also, this project also emphasizes reverse engineering techniques based on affordable, portable range-sensing and computer-assisted design.

1. Introduction

1.1 Naval Relevance

The *Print the Fleet* Navy initiative started as the result of Chief of Naval Operations' Rapid Innovation Cell (CRIC), led by a group of junior officers [1]. This resulted in a more coordinated effort for applications of additive manufacturing for naval purposes. *Print the Fleet* has so far created about 20 items, including oil reservoir caps, medical equipment spare parts and board game-like pieces for tracking flight operations onboard a ship and it has 60 currently active additive manufacturing projects in the Navy, as shown in Figure 1 [1]. One example of such parts is a Ouija-type board which is basically an aircraft carrier and amphibious assault vessel modes which are usually bought in a set ranging from $8,000 to $10,000 whereas printed version costs $300-$400 [1]. Navy scientists and engineers are working on the application of cutting-edge 3D printing technologies to spare parts produced same-day and on-the-fly, in Dam Neck Annex in Virginia Beach, which is at close proximity to ODU [1]. Efforts related to printing of oil caps and medical equipment spare parts and others, with polymer-based substances such as thermoplastics, are enabling a higher level of fleet readiness and logistics. Moreover, metallic parts can be printed on other military commands in Norfolk and Virginia Beach which have metal 3D printers. Sailors will basically either create a new computer-aided design (CAD) part or download the existing CAD file in format for 3D printing (.stl file). It is anticipated that by enabling sailors to resolve maintenance problems, by either designing or reverse-

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Figure 1: 3D printed maintenance spare parts - wrenches at Print the Fleet workshop at the Navy [1]

engineering a part by themselves, they will cultivate a sense of ownership and improve their overall job productivity and satisfaction [1].

1.2 Purpose of Project

Although 3D printing equipment are becoming readily available, their use is still in its infancy. Therefore, this project intends to educate military personnel on how to generate solid geometries of desired parts in a common CAD system, and fabricate those parts using 3D printing equipment. This project will feature instruction to military personnel on how to use reverse-engineering tools and integrate them into the recreation of needed components and the development of new components. It will also include a section related to product data management and part retrieval, to enable sailors to find required replacement part geometry information in a product lifecycle management platform when available, thereby saving time and money. The project will also address issues related to survivability of 3D printed parts under realistic conditions. The project will also include a section on part optimization. As the parts can be easily manufactured in the field, one can manufacture a variety of disposable parts to reduce the overall load on the supply chain. This will allow sailors to start thinking outside of the box and be creative in developing new solutions. The sailors will, at some point, leave the service and join the civilian life, and the skills that they will acquire in this program will open the doors for them to either become entrepreneurs or become valuable members of research and development teams in companies.

The proposed research is a fundamental first step in understanding the use of the *Maker* approach to shorten the time needed for spare parts for active military personnel on board naval vessels.

1.2 Summary of Objectives

The following objectives are emphasized in the project.

- *Engage active duty military personnel* in a *Maker* environment and provide them necessary tools to enhance their skills needed for application of additive manufacturing for in-situ ship maintenance.
- *Reduce the downtime in naval subsystems*, which is related to waiting for the necessary part to arrive for repair, by providing the Navy with a significant number of naval personnel trained in 3D printing.
- *Provide an educational workforce development program* for active duty sailors in additive manufacturing to support the Navy's *Print the Fleet* initiative that can be later replicated at other places.

1.3 Summary of Proposed Methods

The research team will focus on workforce development founded by the application of *Maker* approach by developing, executing, and assessing a series of *Fleet Maker Workshops* held at the *Monarch Maker Laboratory*. Case study parts from the USS Harry S. Truman (CVN 75) 3D Fabrication Lab will be structurally redesigned, rebuilt, and tested under supervision by the research team. The impact of the DIY approach on learning for the active duty military population will be assessed. The research team will investigate and test the effectiveness of the program through the use of skills assessment related to the areas covered in the workshop.

1.4 Summary of Expected Outcomes

The successful fabrication of case study parts requires knowledge of computer-aided design, product lifecycle management, reverse engineering, and 3D printing. In the proposed workshops, an introduction of these topics will be presented in an informal and accessible manner with the purpose of advancing engineering skillset of the participants.

The assessment activities will measure the impact of the *Maker-based* approach on participant skillset related to fabrication of spare parts for naval ships. As the workshops are executed and assessed, the lessons learned will be applied to other upcoming workshops. The proposed activities will: 1) Increase the number of trained sailors in use of 3D printing equipment; 2) Shorten the time needed for necessary parts for on board in-situ maintenance; and 3) Reduce the overall cost related to the supply chain of spare parts in naval applications.

2. Methodology

A total of 15 workshops will offer an overview of the design-*Making* process, starting with a brief introduction to the design and fabrication of case study parts, including reverse engineering, 3D modeling, and 3D printing of parts, then concluding with the experimental prototype. The workshops will be developed based on curriculum already created through the DARPA MENTOR2 program [10], by manufacturers of 3D printing technology [11], and by the investigators [12]. The workshops will focus on the connection between computer-aided design and 3D printing through case study parts provided as examples. The workshops will be held in the designated ODU-MML *Maker* space, and will take place throughout the year. Upon completion of the workshops, participants will receive a Certificate of Completion, which will give them access to the 3D printers and other technologies available at the Fab Lab in the Mid-Atlantic Regional Maintenance Center (MARMC). The Certificate of Completion will serve as recognition at MARMC's *Fab Lab* and OPNAV41/CNO's *Print the Fleet* project that the individual has completed training in the use of 3D printers, computer aided design, and reverse engineering.

2.1 Fleet Maker Workshop Contents

A total of 15 workshops will be developed, executed, and assessed. Each workshop will accommodate 20 to 30 individuals, and it is anticipated that at least 300 individuals will be directly impacted through participation in the developed workshops, who will acquire new knowledge and skills in all major areas of *Making*. Participants will be exposed to reverse engineering, computer-aided design, product lifecycle management and part retrieval, 3D scanning and meshing, and 3D printing. The workshops will be executed in the form of a two-day program divided into several modules.

2.1.1 Module 1: Dive into Printing – Applications of 3D Printing in Ship Maintenance & Introduction to 3D Printing

The module will start by presenting several case studies of printed parts from the USS Harry S. Truman (CVN 75) 3D Fabrication Lab, and sending example parts of these studies for printing while others topics are covered. Examples of parts include designs created for Ship Maintenance and problem solving such as a hose adapter for anesthesiologist's waste gas equipment, a replacement fixture clamp for the Radar Test Bench Set, a spanner tool replica, a custom oil funnel, custom switch guards, clips, and caps shown in Figure 2. The parts will be sent for printing to see how a 3D printer works. An overview of 3D printing will be presented, including a historical review and the technological shifts that made 3D printing a reality, the advantage of 3D printing over other

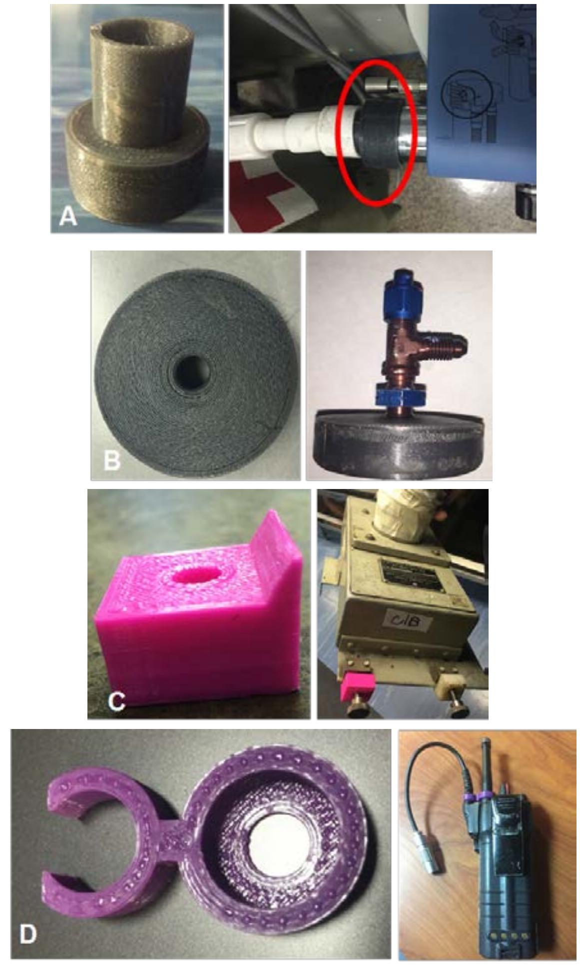


Figure 2: 3D printed maintenance spare parts from the USS Harry S. Truman (CVN 75) 3D Fabrication Lab case studies. A: Hose adapter for anesthesiologist's waste gas equipment. B: Custom fitting for Nitrogen Purge kit. C: Replacement fixture clamp for the Radar Test Bench Set. D: Custom clip to hold adapter.

technologies, comparison of various 3D printing technologies (applications, advantages, accuracy, materials), introduction to the STL files, layer slicing, and build parameters to consider. Another activity in this module will consist of an exercise where the participant will receive parts created using different 3D printing technologies and are asked to determine which technology was used to create each part.

2.1.2 Module 2: CAD and Reverse Engineering Introduction

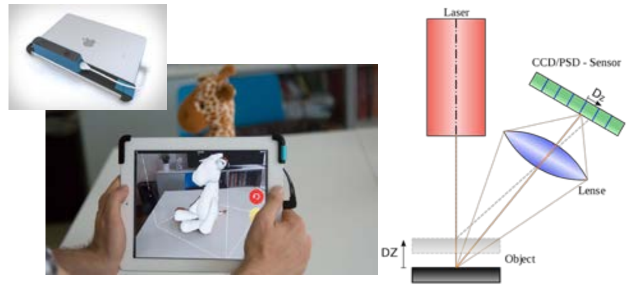
This part of the workshop will focus on introducing participants to computer-aided design: creating a sketch; feature-based modelling (extrusion); exporting a part as an STL file which is commonly used in 3D printing applications. The module will include a hands-on activity of reverse engineering of case study parts using a manual caliper. Students will draft 2D drawings of the case study parts, create a 3D model in CAD software, extrude the shape, and save the part in STL format ready for 3D printing.

Feature-Based Modelling- Participants will be introduced to the concept of 3D feature-based modelling. There are two basic CAD paradigms that are used for solid modelling: boundary representation (B-rep) and parametric feature representation [13]. Engineering CAD systems widely used in industry for product design are mostly based on the parametric feature-based modelling approach. In this approach, the final 3D part is a sequence of features such as prisms, holes, chamfers, fillets, slots, etc. Features in the final model have mutual relationships that are called: “the parent”, a feature that has some other features developed after it and that holds the reference geometry for some other features, as well as the “child”, a feature that cannot exist without some other “parent” feature and that has references attached to some other feature. In this exercise, participants will go through a feature-based modelling activity that will include extruding a base geometry such as a circle or a rectangle.

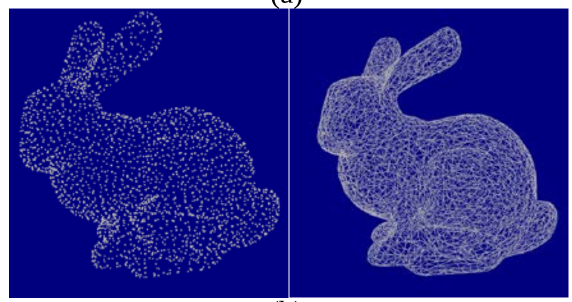
Introduction to Reverse Engineering - Reverse engineering (RE) is the procedure of discovering the technological principles of devices, objects or systems through analysis of its structure, function, and operation. It often involves taking something apart and analyzing its parts in detail to try to make a new device or program that does the same function without using or plainly duplicating it. A variety of objects or devices can be reverse-engineered; it is not always necessary to understand everything about the original. Originally, this technological process has been developed primarily for commercial or military purposes. Its main goal was to build the product in a shorter time without initial design phases. RE is often done because the documentation of a particular device has been lost (or was never written), and the original builder is no longer available [14]. Although RE is not a new engineering method, it has gained attention with recent developments in CAD and its supporting technologies. Development of robust computers and high processing power had enabled use of devices such as 3D scanners and coordinate measurement machines that enable engineers to achieve a faster embodiment of their ideas or to analyze and develop products that are improved versions of existing designs [14].

2.1.3 Module 3: Making – 3D Printing

Using the 3D design and STL file created in the previous module, participants will send a part for printing. The parameters that can be controlled and that affect the printing process and the created part will be discussed. These parameters include the print toolpaths (e.g. infill, number of shells) and the printer settings (e.g. extruding



(a)



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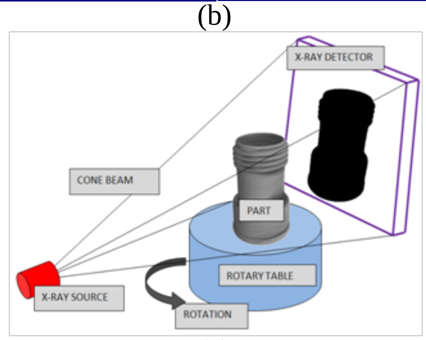

(c)

Figure 3: Basic concepts in reverse engineering of 3D objects. (a)(b) Range-sensing: (a) Ipad-mounted, $400 Structure sensor (courtesy of Occipital); triangulation geometry of range-sensor (Wikipedia). (c) Point cloud to triangulated surface conversion in range-based method (Stanford bunny). (d) CT-based industrial scanning (Wikipedia).

temperature and speed, movement speed.) Participants will use the printer software to handle the STL file to be sliced into layers, and choose parameters for printing.

2.1.4 Module 4: Scanning and Meshing - Advanced Reverse Engineering

This portion of the workshop will provide instruction to students on two main kinds of scanning technologies in use for producing 3D models suitable for 3D printing: laser-based range imaging and computed tomography (CT), with an emphasis in the class of range imaging applications. The second phase of the scanning-meshing process, also to be covered, is the conversion from dense 3D point data or tomographic volumes respectively to a closed surface mesh composed of triangles, which in turn are typically saved in a format suitable for 3D printing. In addition, the conversion from range imaging or CT data to surface meshes often results in surfaces with artifacts present, such as holes, self-intersections, and inconsistent surface normals; these artifacts have to be eliminated in order to produce a "watertight" surface that will enable trouble-free 3D printing. The intent of this module is not to train proficiency in this area, but rather to promote awareness of the various issues involving scanning and meshing.

Range-based imaging - The basic principle of a laser range-sensor is the projection of small laser ray from the sensor to the scene, which is reflected from the scene back to a charge-coupled device (CCD), which in turn produces a digital image of the illuminated 3D point. The geometry of the incident and reflected laser rays forms a triangle (Fig. 3a,b), and this triangulation determines the geometric relationship between the distance of the illuminated point in the scene to the sensor: the further an object point is from the sensor, the more acute the triangle. The precise nature of the triangulation, i.e. the relationship between the object point P(x,y,z), and the CCD pixel (i,j), is determined by a calibration process at the sensor factory. Subsequent to this multi-surface acquisition, these surfaces are fused together through a registration process, resulting in a fully covered surface of 3D points.

Meshing & Mesh Repair- At this stage, these surfaces are still relatively sparse, like the left duck on Figure 3c, as far as the 3D printer is concerned. What is needed is a collection of triangles that cover the whole closed surface: a closed watertight surface mesh, saved in an appropriate digital format such as .stl or .obj. The latter stage is termed point cloud to surface reconstruction, and while these techniques are typically covered in a senior or graduate medical image analysis class, the basic principles will be presented in a pictorial approach to the instruction, in a manner intuitively understood by Navy personnel. The instruction will cover the complete process: range-sensing, fusion of multiple 3D surfaces, meshing, and fixing mesh artefacts. Practical mesh repair will also be emphasized in this module, namely: getting rid of "non-manifold" edges and faces that protrude from the surface, plugging the large hole that typically coincides with the bottom of the object typically scanned from the top, and plugging smaller holes.

CT scanning - In addition to the discussion on range-based reverse engineering, the module will also feature brief instruction on CT-based scanning (Fig. 3d), so that Navy personnel will also be introduced to reverse-engineer parts using tomographic scanning. The CT approach is advantageous in producing surface meshes with fewer ambiguities than laser range-sensing, which would otherwise require manual correction, given that the complete volume of the part is identified, as CT is not vulnerable to laser reflectivity artefacts. In contrast, a laser range-sensor is significantly cheaper; the Structure sensor of Fig. 3a sells for $400 (including software) and mounts on an iPad.

2.1.5 Module 5: Part Data Management Module

An application of product lifecycle management software and digital manufacturing concept is enabling transfer of accurate, updated data. This technology enables reduced development and manufacturing costs [16]. The use of different CAD software programs in industry results in the use of neutral exchange formats, such as IGES, STEP and STL. These neutral formats are also used for advanced manufacturing processes, such as those supported by numerical control including advanced machining, rapid prototyping and rapid manufacturing [17]. Different exchange CAD formats do not necessarily have the same results in a CAD transfer process. The problems in geometry are not always visible in the native CAD file [18]. PLM software platforms can have integrated visualization, software plug-ins allowing for the conversion of proprietary CAD files into neutral files that can be viewed even without the CAD software that created the native file. For this purpose, neutral exchange formats are beneficial. They serve as a carrier of transferable data, such as future manufacturing files, and information can be reviewed with the support of open source translators, which some CAD companies are providing [18].

2.1.6 Module 6: Final Part Printing and Testing

This portion of the workshop is divided into three parts. The first part will complete the basics of 3D printing. Each group of participants will print their design with different assigned printing parameters. The influence of printing parameters on the quality of printed parts will be qualitatively examined.

The second part of this module will provide instruction to participants on how to do basic mechanical testing and structural examination. The purpose of the testing is to evaluate: (1) basic functionality of the 3D printed case study part, (2) stiffness analysis of the structure, (3) strength analysis of the structures. To test basic functionality, the participants will use (operate) the case study part on a simulated bench stand. To test stiffness, the case study part will be subjected to a 3-point load test. To test strength, the case study part will be subjected to a 3-point bend load with increasing amplitude until fracture/failure is observed. The tests for the 3D printed fuel cap will also be conducted on a standard fuel cap. As a part of the testing, qualitative metrics such as functionality, perceived appearance and quality, and quantitative metrics such as stiffness and strength will be measured, recorded and compared. During these experiments, the participants will take notes, generate and fill out Excel sheets for data and metadata, as well as record experiments by capturing photos and videos.

The third part of this module deals with the analysis, compilation, discussion and the presentation of the design, building and testing processes. The participants will be first presented with an example presentation which effectively communicates the entire process for a different structure. The participants will use this example to develop a PowerPoint presentation. After each presentation, a review panel will comment on the strengths and weaknesses of the presentation.

2.2. Metrics and Evaluation

At the beginning of each workshop, participants will respond to a pre-workshop assessment survey to understand their technical background, as well as knowledge and disposition to CAD and 3D printing. The project will be subjected to a formative assessment exercise conducted at the middle of each workshop where both implementation and progress will be evaluated, leading to corrective steps to be implemented at the workshop. A summative assessment will occur at the end of each workshop. The assessment will evaluate the project goals, objectives, and activities. It will take into account methodology, resources, procedures, and techniques used to complete planned deliverables, as well as goals and outcomes of the project and to assess their impact of the participants.

The assessment will center on three main components: accountability, effectiveness, and impact. *Accountability* will focus on assessing the project activities to determine if they are performed on time and under the given constraints and resources. *Effectiveness* will examine the project from the perspective of the participants and project team staff. *Impact* will focus on data retrieved from participants related to the measurement of their attitudes, behaviors, and skills. These will be assessed on the project level; the team will also assess dissemination to the broader engineering education community. At the participant level, summative assessment will evaluate content knowledge of reverse engineering, computer-aided design, product lifecycle management and part retrieval, 3D scanning and meshing, as well as 3D printing. Evaluation will include formative design with summative report deliverables. It will evaluate students' responses to the informal learning environment intervention from the workshops.

2.2.1 Data and Measures

Feedback about the workshop and its effectiveness will be measured by four instruments: Anonymous responses to both surveys will be recorded using an online survey tool.

1. A formative, qualitative survey conducted at the end of Day # 1.
2. A summative, quantitative survey conducted at the end of Day # 2.
3. An end-of-workshop group debriefing (at the end of Day # 2).
4. A reflection from each participant – online via Google Form (at the end of Day # 2).
5. Evidence from the workshop project (at the end of Day # 2).
6. A 6-month follow up survey post-workshop.

Examples of Mid-point survey questions are as follows [19]: Is the use of face-to-face time in this workshop effective? What about this workshop is working for you? What about this workshop is not working for you? Does the pacing of this workshop enhance your learning experience? Do you have enough work time? Have any new concerns surfaced during the workshop? If yes, what?

Final workshop evaluation questions will be organized into seven sections [19]: overall satisfaction; workshop as a whole; the instructors; workshop support staff; workshop materials; hands-on exercises; feedback. The 6-month follow-up survey post-workshop will assess if participants have applied the making concepts (either on board during deployment or in other settings), if they have exposed others to making, and if they have made use of the Fab Lab at MARMAC post workshop, to understand the broader impact of the workshop on the fleet personnel. For these assessment and evaluation activities, the program will use the current approved IRB MENTOR2 project as a model to obtain the necessary approvals.

2.3 Management Approach

The multidisciplinary nature of *Making* is reflected in the project team. In particular, the team is composed of experts from the complementary fields: modeling and simulation, mechanical engineering technology, engineering management and systems engineering, mechanical and aerospace engineering, engineering technology, material science, chemical engineering, and engineering education.

3. Conclusion

This paper presents a nascent project on STEM education of Navy shipmen, newly funded by the Office of Naval Research, which will emphasize a series of workshops on 3D printing as well as on reverse engineering techniques, which are needed to produce 3D models. The emphasis of these workshops will be to develop hands-on ability of participants to reverse engineer and print parts needed by the Navy that would otherwise require significant time and resources to replace and would otherwise entail significant downtime of affected systems.

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Dr. Anthony W. Dean Ph.D. has been both a NASA (2004) and ONR Faculty Fellow (2007, 2014, 2015) and has most recently been involved with the NSWC-DD's support of the Navy's OPNAV41/CNO's "Print the Fleet" initiative. He has also been involved in the creation of programs specific to the Hampton Roads workforce, creating initiatives in marine engineering for women, underrepresented minorities, and veterans (NSF S-STEM Grant 0728610), and with veterans (ONR Grant 11899718).

Dr. Vukica Jovanovic Ph.D. is ODU PI on ONR Grant 141512422 which is focusing on marine mechatronics pathways. She has worked on multiple workforce development projects related to digital manufacturing (funded by DOL) where she developed 69 modules including topics of rapid prototyping, reverse engineering, and PLM; and developed a PLM Certificate program – Digital Manufacturing while at Purdue

University [12]. She is trained in surface modelling (CATIA Generative Surface Design & Pro/Engineer Advanced Surface Design), reverse engineering (Z Scan and ProForm) and 3D printing (Object Eden 500V, Z-Corp, Pro-Metal and Optomec Lens).

Dr. Onur Bilgen Ph.D. is an Assistant Professor in Mechanical and Aerospace Engineering. He brings his expertise in solid mechanics, composites, and modeling, simulation and experimental validation of aerospace structures and electromechanical systems. He is the director of the Smart Systems Laboratory, which holds an eight-week Smart-Systems Summer Camp every year in cooperation with the Virginia Beach and Chesapeake high schools.

Dr. Karina Arcaute Ph.D. brings her expertise in materials and 3D printing, and her experience in chemical engineering, material science and mechanical engineering. She has 10 years of experience as a user and tester of different additive manufacturing technologies and materials. She has experience working with various rapid prototyping systems, including fused deposition modeling (FDM), stereo lithography (SL), and electron beam melting (EBM).