Collaboration on Engineering Technology Capstone Projects with the UNH University Instrumentation Center

T. Sean Tavares, Shawn C. Banker, Christopher D. LeBlanc,
Jonathan Ferguson, University of New Hampshire

Abstract

Collaboration with partners located in industry and at research centers has been the source of many high quality Engineering Technology senior capstone projects. A recent capstone project hosted by the University of New Hampshire (UNH) University Instrumentation Center (UIC) was focused on improving the efficiency of the process involved in producing large scale 3D printed models from images obtained with a scanning electron microscope (SEM). The project was motivated by a desire to showcase new technical capabilities of the UIC, for both commercial and K-12 educational outreach purposes. The students focused primarily on automating to the extent possible the challenging tasks of converting a series of (SEM) images taken of complex specimens found in nature to a 3D CAD description suitable for generating instructions for a 3D printer via photogrammetry software. The methodologies and tools incorporated by the students is described and examples are shown of successful modeling efforts. The challenges remaining and opportunities to improve the technical process are discussed. The project is reflected upon in terms of its educational and professional development value for the students, the benefits to the sponsors and academic program, and lessons learned regarding collaboration on capstone projects and possible improvements that can be applied to this and other partnerships.

Introduction

Collaboration with the University Instrumentation Center (UIC) at the University of New Hampshire (UNH) has turned out to be a source of high-quality capstone projects for students in the Engineering Technology (ET) Program. While the center is part of the University, it performs a significant amount of work for external industrial customers. There are three core areas at the UIC, including the Imaging Core (electron microscopy and related technologies), the Spectroscopy Core, and the Engineering Services Core. The need to deliver technological services within the constraints of schedule and budget means that students working with the UIC experience many business-related aspects that are present when working with an external industrial partner. At the same time, being part of the University, the personnel at the UIC have a particularly good understanding of ET capstone projects. In particular, they are able to provide an appropriate scope of work, understand the level of guidance needed at key points in the project, and are sensitive to the constraints of the academic calendar. The paper focuses on a capstone project that involves processing images of samples obtained with the UIC's scanning electron microscope (SEM) into CAD representations suitable for 3D printing macroscopic scale models of the samples. The capstone project involved developing a systematic and reliable method for producing CAD models from SEM images. This included automating some of the most tedious steps in the process to the extent possible. In the course of the project, the students also had the unique experience of being trained in the use of the SEM and other sophisticated laboratory equipment.

In the sections that follow, the authors first describe the UNH Capstone Experience as realized within the ET program, the capabilities of the sponsoring Center, and the mutual interests that foster collaboration. Next, the specific capstone project is described in terms of the goals, work performed by the students, results obtained, and potential to extend the work in the future. This is followed with combined reflections from the sponsor and faculty on the learning and skill development outcomes for the students, and some ways in which the collaboration can be strengthened for the benefit of the students, the sponsor, and the ET academic program. Finally, some summary conclusions are given along with a description of the collaborative work that is being continued in this project area.

Background: The Capstone Experience and the Project Sponsor

The UNH Engineering Technology Capstone Experience

The Senior Capstone Project is an important part of the both Engineering Technology (ET) program and for the other Bachelor's Degree programs at the University of New Hampshire. The Capstone experience is intended to synthesize knowledge and skills and to provide opportunity for reflection on the undergraduate experience (UNH Discovery Program web page, 2018). The Capstone experience is especially valued at the University's Manchester Campus. The college located at Manchester is an urban campus serving primarily commuter students, and there is strong focus on experiential learning. The college mission is focused as much on giving the students real-world experience as on providing them with the traditional UNH liberal arts education.

The UNH ET Program has been accredited by the Accreditation Board for Engineering and Technology (ABET) since 1980, and the Senior Capstone Experience is aligned with the relevant ABET Outcomes (ABET, 2017). The UNH program is somewhat unique in that it provides the Bachelor's component of a 2+2 program. Bachelor's Degrees are offered in both Electrical Engineering Technology (EET) and Mechanical Engineering Technology (MET). Students entering the program are required to have completed an Associate's Degree in a field that gives adequate preparation to allow success. Typically, the Associate's is earned at a community college in New Hampshire, but this is not a requirement. There is a mix of full-time and part-time students, most of whom are holding jobs while they are in school. There is a wide range of ages, and levels of professional experience. It is not untypical for some time to have passed between completing an Associate's Degree and starting the Bachelor's program. Some students have considerable experience working in a technical environment, but often as hourly rather than salaried employees. Often they have worked as technicians, drafters, or designers.

In a recent paper (Jin et al, 2018), faculty in both the UNH Engineering Technology and Computing Technology Programs discusses lessons learned from Capstone Projects over the last 25 years. The authors describe the advantages and challenges associated with projects carried out internal to the college, and with those carried out with external partners. External partners could be companies or laboratories and centers within the University outside of those directly responsible for the undergraduate programs. Both approaches can be successful, and the paper discusses attributes that are beneficial to each type of project.

Project Sponsor: The University Instrumentation Center

The University Instrumentation Center (UIC) at the University of New Hampshire was established in 1973 as a centralized research facility within the Office of the Senior Vice-Provost for Research. The UIC, located at the main campus of the University in Durham, New Hampshire, houses much of the shared, high end scientific, analytical instrumentation for the university. The main campus is approximately 1 hour from the Manchester campus where the ET Program resides.

The mission of the University Instrumentation Center (UIC) is to support the research, teaching, and engagement missions of UNH by providing access to the best analytical instruments, scientists, and engineers. In support of the university's engagement mission and as a broader impact requirement for many federal grant programs, the UIC partners with UNH faculty and staff to provide K-12 outreach programs and demonstrations and also engages in its own independent outreach activities to encourage and raise the interest in STEM related fields. The UIC typically engages with K-12 students and teachers through onsite tours and demonstrations, remote demonstrations to offsite classrooms, and through high school internships. In the academic year 2017, the UIC connected with over 500 K-12 students and educators through these activities.

The acquisition of a new Tescan Lyra scanning electron microscope (SEM) obtained through a National Science Foundation Major Research Instrumentation grant in 2014 provided the UIC with a level of capability that surpassed previous microscopy techniques. The UIC actively searches for new and exciting uses for this popular instrument. The ability to obtain very high resolution images up to 1,000,000X and the 3D capabilities was an exciting area to explore. During a UIC sponsored workshop specifically focused on 3D SEM capabilities, the idea of printing 3D scaled objects was explored and although the process was cumbersome, it looked like a great opportunity for the UIC to gain another tool to support research, teaching, and our outreach goals.

Through discussions with K-12 educators and other faculty, it became clear that the UIC could increase this participation by developing tools to expand its offering in this area as well as support ongoing university teaching and research. Being able to hold a larger, to scale object of something you can only see microscopically was of high interest to educators we spoke with. In addition, being able to create a 3D model from a set of scanning electron microscope images would allow information like volume measurements to be accurately obtained. Other microscopy techniques, for example Laser Scanning Confocal microscopy, could be explored as alternatives.

The UIC is also a source for analytical testing and research support for many local companies and routinely engages to support a variety of business sectors. Mr. Shawn Banker joined the UIC as the director and had previously spent the majority of his career in manufacturing engineering and has made it a priority for the UIC to increase its engagement with local industry. Mr. Banker, also a graduate of UNH's Mechanical Engineering Technology Program, serves on the ET Industrial Advisory Board and previously sponsored many ET senior capstone projects prior to joining UNH. In his role as director of the UIC, he was eager to sponsor another ET senior capstone project.

Description of the Capstone Project

The goal of the project was to develop an optimized process to create accurate, scaled 3D printed replications of small objects using electron microscopy based photogrammetry. Project deliverables included a proven automated process for obtaining images, creating a 3D CAD surface description, and printing of a physical model of the sample at a greatly enlarged scale. In this section, the processes involved in each step of capturing quality SEM images and processing them into a 3D printed model are first described briefly. Next, the areas where the capstone students worked to create or improve steps in the process are discussed. This is followed by showing and discussing some sample results that show the results obtained.

Steps in the Process

The process of capturing SEM images, processing them into a 3D CAD model, and producing a 3D printed model is illustrated in Figure 1. The process can be visualized as consisting of four major steps.

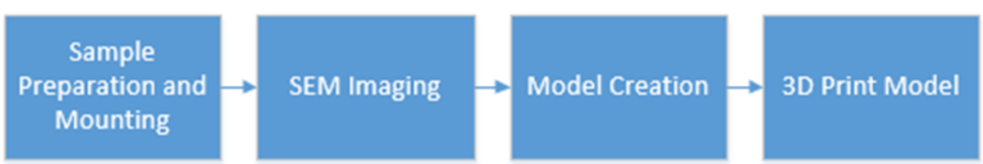

Figure 1. Steps involved in producing a 3D-printed model of an object from Scanning Electron Microscope images.

The first step in the process is *Sample Preparation and Mounting*. In this step the sample is mounted to either a pin or a stub and coated in a thin film of conductive metal before being placed in SEM. The conductive coating allows the SEM to capture a high-resolution image.

Figure **2** shows examples of samples mounted on a pin.

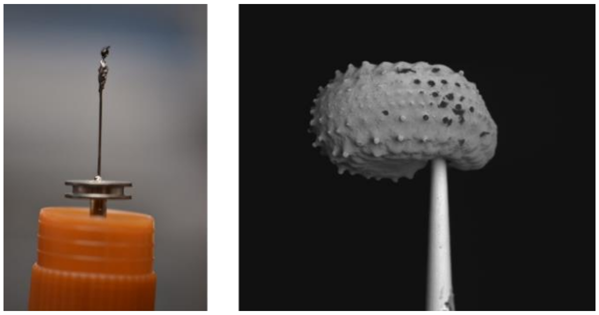

Figure 2. Mounting of a sample on a pin for imaging with the electron microscope. Left: Sample on pin prepared for SEM. Right: SEM image of a seed showing a portion of the mounting pin.

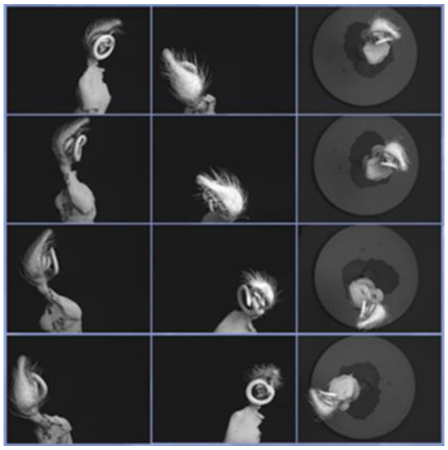

Figure 3. Multiple SEM images taken at a variety of orientations to the sample. Photogrammetry techniques are used to create a CAD model of the object. Example shown is a pedipalp appendage from a funnel spider.

The next step in the process is *SEM Imaging*. This consists of using the SEM to take a series of high-definition 2D images from multiple angles in order to resolve as much surface topography as possible. Figure 3 shows a selection of typical images obtained on a sample at various orientations in the SEM.

In the *Model Creation* step the set of SEM images are loaded into photogrammetry software. The photogrammetry software uses the information in the images to compose a 3D CAD solid model. The 3D model is exported in the Standard Tessellation Language (STL) which is commonly used in 3D printing. The Autodesk ReCap program (Autodesk 2018) was used for model creation in this project.

Figure **4** shows a portion of a solid model produced from photogrammetry using ReCap. The image shows the tessellation of the surface and how the density of the mesh is increased in areas where the shape of the object is changing more rapidly. The example shown is a small appendage on an insect, and shows the detail which can successfully be represented.

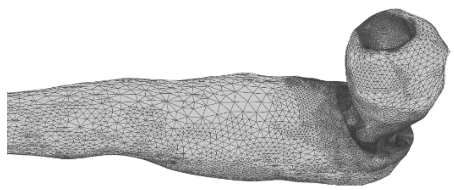

Figure 4. Detail of the tessellation used in a 3D solid model of a portion of an insect appendage.

The *3D Print Model* step is the final part of the process. The STL file obtained with the 3D CAD model is exported to Computer Aided Manufacturing (CAM) software. The CAM program generates the support structures that are necessary to steady parts of the model that would otherwise be prone to deforming during the 3D printing process. An image showing an object to be printed after the addition of support structures is shown in Figure 5. Finally, the CAM instructions are sent to a compatible 3D printer to produce the physical model with the desired size and material composition.

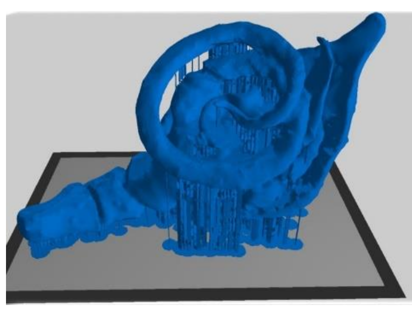

Figure 5. CAM model with support structures in preparation for 3D printing.

Areas of Concentration in the Capstone Project

This capstone project was a first attempt at the UIC to investigate coming up with a systematic process for making 3D printed models from SEM images, and for making the process efficient through automation and other innovative means. As a result the degree of difficulty that would be encountered in any given step was something of an open question. For this reason, the students were encouraged to take an exploratory approach with the understanding that the project would be fairly open ended in regard to the specific deliverables. As the project evolved it was found that the steps in the process requiring the most technical effort would be *SEM Imaging* and *Model Creation.* The other two tasks in the process were found to be fairly straightforward. An initial part of the investigation was to perform a literature search in order to identify previous work that might provide useful guidance for the project.

Some of the most difficult challenges were encountered in the *SEM Imaging* step. This step involves using a central pin-mounted specimen and obtaining a series of SEM images indexed rotationally in a way that could adequately resolve sufficient details of the object. Challenges to be overcome included the utilization and modification of a pre-created script provided by the SEM manufacturer, and positioning each specimen to obtain complete and accurate resolution of all external features. One task that was attempted, but not successfully completed was development of a compucentric script (TESCAN, 2018) which would automatically refocus the SEM each time an image is taken. This task will be revisited in a future project since being able to automate most or all of this step would substantially increase the efficiency of the process.

The *Model Creation* step involves converting a series of SEM images into a 3D mesh model. This task requires the use of photogrammetry software. After some investigation, the students chose the Autodesk ReCap software (Autodesk, 2018). The most challenging part of creation of the model was minimizing the amount of manual manipulation required to compensate for missing or conflicting information contained in the SEM images. These inconsistencies needed to be reconciled before the model could be finalized and exported as an STL file to be used by the 3D printer.

The *Sample Preparation and Mounting* step was fairly straightforward, mostly requiring that the students learn and apply established practices for Scanning Electron Microscopy. Likewise the actual *3D Print Model* step was also straightforward, amounting mostly to selecting the right printer for the job. There were a number of 3D printers available from University and private sources. The students mainly needed to select a printer that could produce a model of the size and material desired without excessive cost.

Sample Results

Three examples of 3D printed models successfully produced from SEM images by the project are shown and discussed. The examples are shown in order of increasing geometric complexity, and decreasing physical size. Increasing complexity, and decreasing size both add to the challenge of capturing high-quality images and translating them into 3D printed models.

The first example is a common black peppercorn. Measuring approximately 5mm the geometry is roughly spheroidal and characterized by a well-defined pattern of ridges on the surface. This sample met the requirements of being relatively easy to mount on account of its size, and is readily relatable to K-12 students. Figure 6 is a series of 3 images related to the peppercorn, showing one of the SEM images, the 3D CAD model, and a photograph of the 3D printed model. The printed model has a diamter of 152.5 mm, thereby representing a scale factor of 30.5. The images all show approximately the same portion of the peppercorn. Examination of the images shows that the ridges and other surface features were reproduced with good fidelity in the 3D model. It is also seen that the printing process did a good job of reproducing the features seen in both the solid model and the SEM image. This was considered a success, and a good initial test of the process and tools. However, imaging an object of this relatively large size did not necessarily challenge either the imaging or magnification capability of the SEM. Also being a relatively simple geometric topology, it did not provide a severe test of the ability to handle complex geometries.

Figure 6 SEM image, 3D CAD representation, and scaled 3D printed model of a black peppercorn.

The second example shown is a case that provided a significantly more challenging test of the process. Measuring 1.7 mm in length and having extended features, this sample was more in line with the types of geometries that it was desired to model and print. This sample is the head and antennae of a small arachnid known as a pseudoscorpion. This object proved more challenging to prepare and mount for imaging. Figure 7 shows representative images from the SEM and the solid model, and also a photograph of the final printed model which has length of approximately 199 mm. The SEM image shows the presence of small hair like features. Attempts to make a 3D model that included these numerous small features proved to be unsuccessful, and they had to be manually deleted before a successful 3D model could be obtained. The cleaned up geometry proved to be straightforward to represent as a solid model, and subsequently to print.

The third example that received major focus during the capstone project was the imaging and modeling of a portion of a pedipalp from a male Funnel Web Spider (*agelenopsis potteri*). Spiders have two pedipalps attached to the head which look somewhat like legs or claws and serve a variety of purposes. This spider is small, having a body length of about 4-5 mm, and the portion of the pedipalp that was imaged measures about 700 microns. Figure 8 and Figure 9 show the pedipalp from two orientations.

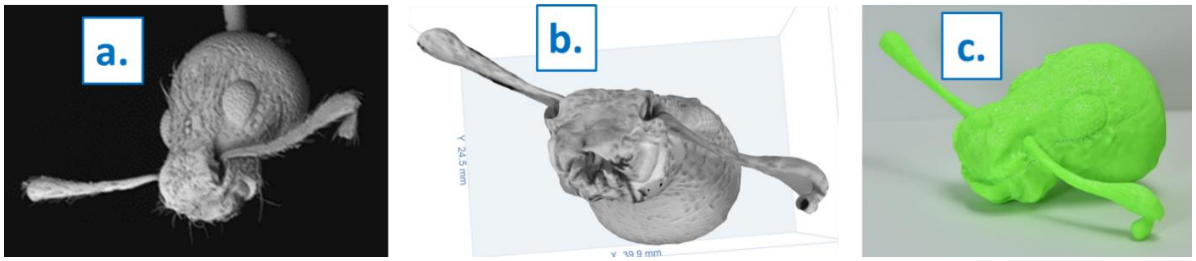

Figure 7 SEM image, 3D CAD representation, and enlarged 3D printed model of a pseudoscorpion.

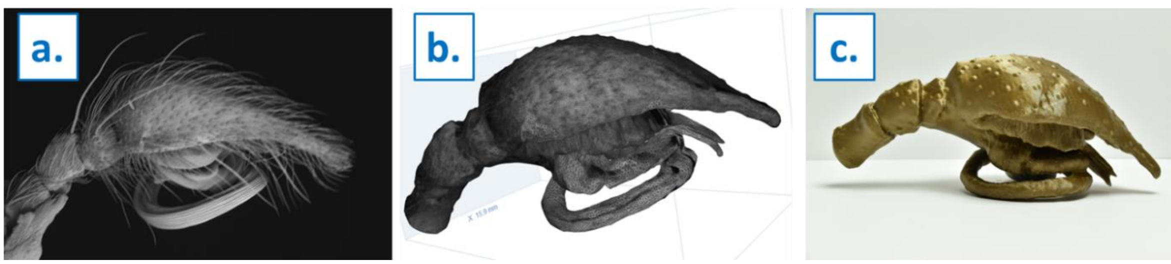

Figure 8. Side view of a spider pedipalp showing SEM image, 3D CAD representation, and enlarged 3D printed model.

Figure 9. Inner surface view of a spider pedipalp showing SEM image, 3D CAD representation, and enlarged 3D printed model.

The images in each Figure follows the convention used for the previous objects, with the SEM image at the left, followed by the tessellated CAD model, and the 3D printed object at the right. In this case the 3D printed object was rendered in gold colored plastic. The Figures show a considerable increase in complexity over that of the pseudoscorpion. This increased complexity substantially increased challenges in the imaging and modeling the object. In particular the SEM images show the presence of a large number of prominent spines along with one surface with a coil-like feature and other rather complex protuberances. As with the pseudoscorpion, the hair-like features needed to be deleted. However, the students were successful in modeling the rest of the object, including the relatively complex coiled feature and other protuberances.

Post Capstone Project Extensions

Following completion of the formal capstone project, one of the students, co-author Jonathan Ferguson, continued working on the process as an independent summer project. During this time, a researcher at the University saw the results that had been achieved during the capstone, and inquired about the possibility of creating a scaled model of a 500 micron long Rumen Protozoan that she could use for demonstration purposes in classes of young children. In order to meet the educational aims, the researcher required with which she could demonstrate both the internal and external features of the organism. In order to resolve the internal features, an alternative imaging technique would be required. A laser-scanning confocal microscope was able to provide the images required for this purpose. Incorporating the new imaging technique into the process gave rise to a new set of challenges. However, using experience gained with the processing of SEM images, it was possible to come up with manual procedures that allowed these more complex images to be processed into workable CAD models for each of the components of the protozoan. It was then straightforward to use these CAD descriptions to generate the 3D printed plastic models of each component.

The 158 mm long physical protozoan demonstration model was composed of a number of individually printed pieces as shown in Figure 10. The two largest pieces of the model were printed in a transparent plastic as they enclose a number of the internal parts of the organism. The disassembled view shows that the internal parts were printed in various colors. Small external pieces are shown printed in grey, and are evident in the photo showing the assembled protozoan model.

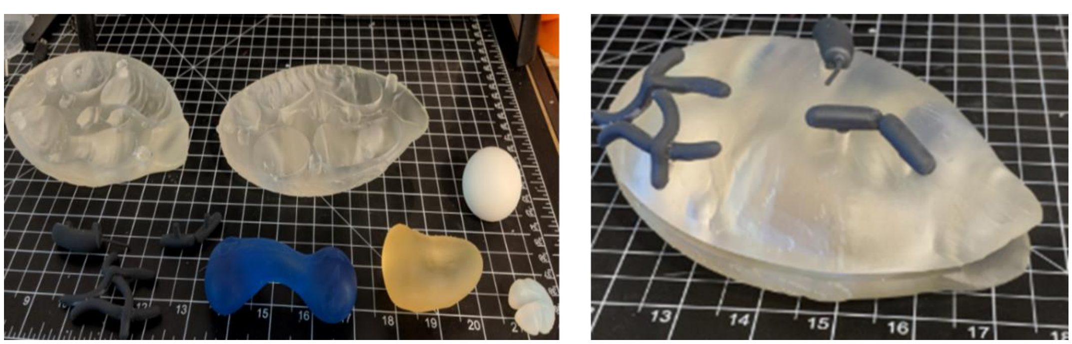

Figure 10. Extension of techniques developed during capstone project to a protozoan model reproducing both external and internal features.

Outcomes: Benefits and Learning Opportunities

The collaboration with the UIC on a capstone project has been deemed a success not only on account of the technical results described above, but also for the wide range of learning opportunities provided to ET students. The students found the project interesting, felt they made a contribution by making substantial progress on the project objectives, and appreciated the opportunities to work in a professional research environment. They also gained an appreciation for synthesizing the various research components toward meeting the overall project goals. In addition, the collaboration has provided the ET faculty and the UIC personnel insights about how to structure collaborative projects to provide high quality experiential learning opportunities to the students, and also derive benefit for the sponsors.

Benefits to Students

Reflection on the outcomes of the project revealed that the capstone experience had provided the students with a number of valuable experiences. These experiences were related to both the technical work associated with the project, and also to development of professional skills that would be useful in the workforce in general. Some important benefits to the students gained during various components of the project are as follows:

1. Exposure to new Instrumentation and analytical techniques – The capstone project provided opportunities for the students gain skills on utilizing equipment and instrumentation that they would not normally get exposure to during their undergraduate ET education. Skills such as those gained in proficient use of a Scanning Electron Microscope can be a major asset that can be drawn upon in their professional careers.

2. Formal Training in Laboratory Practices and Procedures – Formal training was provided to the students on the operation of the Scanning Electron Microscope, and in the operation of associated equipment like critical point drying equipment, and in the coating and preparation of samples to obtain high quality images. They also received essential training on laboratory practices and procedures including X-Ray safety, safe use of chemicals and cryogenic liquids, and in exercising safety in the general laboratory environment.

3. Constraint Management – The project provided an opportunity for the students to experiment with a variety of specimens. This helped them to gain a better understanding of the constraints of the systems and processes of Scanning Electron Microscopy and photogrammetry.

4. Programming and Automation – One of the important goals of the project was to reduce the amount of time and manual effort involved in the production of a 3D printed model from electron microscope images. This required evaluation of the practicality of opportunities to automate the process and implementing automation where feasible. Within the capstone project, this involved learning and implementing Python scripting to increase the level of automation of the acquisition of SEM images.

5. Photogrammetry Software Selection – At the outset of the project, the need was recognized for better photogrammetry software for the production of quality 3D models from scanned images. The students performed evaluation of the capabilities of available software and selected the one determined to be most appropriate for the application.

6. Cost/Benefit Analysis – As in nearly all projects in research laboratories and in industry, the project had some clear budget constraints and in there were a number of instances where the students had to contend with the tradeoffs between cost and benefit in selecting equipment and software. Two specific parts of the project where this was necessary was in the acquisition of various choices of photogrammetry software and in evaluating the costs of using the various available 3D printers and options for size and material used for the printed object.

7. Marketing the Capabilities of the UIC – One of the underlying motivations for the project was to showcase the capabilities of the UIC in the interest of its educational outreach mission and in development of new business opportunities. These considerations were a strong part of the consideration of the types of samples to select for analysis and modeling. They needed to be subjects that K-12 students and members of the public would find interesting, and also show the capability of the Center to make accurate CAD models of objects with complex geometry, and to produce quality models 3D models. The students addressed the marketing aspect in both their written and oral presentations for the course, and in the production of material to be shared with regional companies. For example the poster produced for the ET Undergraduate Research Conference was subsequently used in a UIC open house for industry.

This project also provided much valuable insight about how the ET Program and the UIC may work better on capstone project collaborations in the future. Much of this insight is applicable to a wide range of student projects involving collaboration with industry and research centers.

Common to projects where two or more students work together, there is often a challenge involved in regard to equitably distributing the project tasks among students, ensuring that each team member is engaged, and in assessing the contribution that each student made to the a project. In future collaborations it is planned to distribute project work assignments so that the accountability of the students is to a work group within the sponsor's organization, with less student-to-student dependence. Combined with continuing the already open communication between sponsor and faculty it should be possible to better monitor the progress that each student is making, and for the sponsor to engage faculty assistance where needed.

As discussed earlier, in undertaking this initial collaboration on the automating of the SEM imaging to 3D model process, the degree of difficulty that would be encountered was not easy to predict. While a certain degree of open-endedness and ambiguity is desirable in order to provide a realistic capstone experience, these aspects can overwhelm some students. Fortunately, this did not occur in the initial capstone collaboration. However, now that the challenges in the next steps in this project are better appreciated, it will be possible to give students more explicit scopes of work. This should give students a clearer definition of what is expected of them, while still giving them an appropriate amount of “real world” open-endedness and ambiguity.

One aspect that has been deemed successful in both this collaboration, and with ET capstone collaborations with some of the programs industrial partners has been involving the sponsors in the selection of students to work on their projects. With the UIC collaboration, this took the form of an informational session put on by the sponsors followed by the sponsors interviewing and selecting interested students whom they feel will be a good fit for their projects and organizational cultures. One of the program’s long-term industrial partners has begun to offer an internship in the summer prior to academic year in which the capstone project will be executed as a means of screening.

Conclusions and Future Work

The success of the initial collaboration has resulted in a decision by the UIC to continue and expand work on producing scaled 3D printed models of small and microscopic objects using SEM and other methods of imaging. Importantly, the sponsor found the collaboration under the ET capstone project structure to be fruitful, and intends to continue to involve ET capstone students in future work in this and perhaps other areas of the UIC. In the larger picture the intent is to create a UIC service offering based on this capability, while continuing to apply the technology to create models of increasing sophistication for STEM education purposes.

Major tasks envisioned for capstone projects includes:

1. Development and qualification of a compucentric Python script to further automate the photogrammetry and 3D modeling portion of the process.

2. Soliciting new ideas from K-12 educators for specimens that students would find inspirational, and would also serve the teachers in their teaching activities.

3. Evaluating the process for an expanded set of specimens and printing techniques. This would include tasks related to imaging and modeling specimens of varying geometric complexity and scale. For instance, one or more capstone projects could be devoted to incorporating the ability to reproduce the small features that had to be deleted from the pseudoscorpion and spider pedipalp cases. It would also involve evaluating which materials are most suitable for various types of models, and in creating more visually impactful models using multiple colors of plastic in a single printed part.

4. Expansion of the imaging portion of the process to include techniques in addition to SEM. These would include Confocal Microscopy and Micro Computed Tomography.

5. Integration of the process into the regular scope of services offered by the UIC. This would include such tasks as setting up a 3D printer acquired for the process in a lab space

within the UIC and creating a formal set of instructions that would become part of the UIC Document Control System (quality manual). Adoption as part of the service portfolio offered to external customers would also mean that the business aspects would have to be well understood. This would require developing the capability of reliably calculating the costs involved for various types of jobs and developing a corresponding price structure.

The first follow on to the initial capstone project is underway during the current academic year. If continued success in the collaboration is achieved, opportunity is seen to expand the involvement of ET capstone students in the research and commercial technical services business of the UIC.

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Benjamin T. Wood, Bachelor of Science, UNH Engineering Technology Program

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Biographical Information

T. SEAN TAVARES is an Assistant Professor in the Engineering Technology Program at the University of New Hampshire Manchester campus. Prior to his current faculty position, he spent more than 20 years in industry, working areas including fluid dynamics, thermodynamics, gas turbines, turbomachinery, and engineering software. He holds Bachelor's, Master's, and Doctoral Degrees from the M.I.T. Department of Aeronautics & Astronautics.

SHAWN C. BANKER is the Director of the University Instrumentation Center, a core series of core research facilities at the University of New Hampshire's Durham campus. Before joining the university, Shawn worked for Velcro USA Inc. where he held positions of Director of Engineering and Director of Manufacturing – Plastics. Shawn holds a BSMET and an MBA from the University of New Hampshire.

CHRISTOPHER D. LEBLANC is currently the Program Coordinator and Assistant Professor for the Engineering Technology program at the University of New Hampshire Manchester campus. Prior to his faculty appointment he spent 16 years at International Business Machines (IBM) as an Analog Mixed Signal design engineer.

JONATHAN FERGUSON earned a Bachelor of Science in Engineering Technology at the University of New Hampshire in 2018. He is currently a full-time graduate student at the University of Massachusetts studying Engineering Management and Entrepreneurship while moonlighting as an additive manufacturing and prototyping consultant for a number of startups.