

Development of Laboratory Learning Modules on CAD/CAM and Rapid Prototyping

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Abstract

As part of the 3D Modeling and Rapid Prototyping course, two new laboratory learning modules incorporating CAD/CAM and 3D scanning/3D printing methodologies have been developed. First module is to compare and contrast FDM (Fused Deposition Modeling) printing and CNC (Computer Numerical Control) milling. For that purpose, a custom desk organizer is designed in Fusion360. The part is exported as an STL to be sliced in Simplify3D and 3D-printed on a custom made 3D-printer. The part is also machined with a 3-axis CNC machine. The model is programmed in the integrated CAM environment in Fusion360. G-Codes for the CNC is exported and run via Grbl (an open-source firmware for CNC machines). The two processes are then compared and contrasted against several factors such as dimensional accuracy, processing time, and scalability.

The second module is to compare and contrast two different techniques of 3D scanning: fixed and hand-held scanning. In the former, the part is placed on a rotary table and the 3D scanner (EinScan Pro) is fixed in position on a tripod. Scanning large parts is not possible due to size restrictions of the rotary table. In such cases, the same scanner can also be used in a hand-held mode. During the scanning process, the software generates a point cloud, which needs to be optimized before generating a water-tight model in the STL format. In both cases, the parts are edited and scaled appropriately to prepare for printing. The parts are printed on a conventional FDM printer and results obtained are presented and discussed.

Through these hands-on learning modules, the students are trained in emerging/advanced manufacturing technologies such as CAD/CAM, 3D scanning/3D printing, rapid prototyping, and CNC machining. Some of the difficulties encountered, student learning outcomes, and the assessment results are presented and discussed.

1. Introduction

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. The term “3D printing” is increasingly used as a synonym for AM. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal. Instead of milling a workpiece from solid block, for example, AM builds up components layer by layer using materials which are available in fine powder form. A range of different metals, plastics, and composite materials may be used. AM is the process of joining

materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. The synonyms for AM are: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication¹⁻³. Additive Manufacturing is any of various processes for making three dimensional object of almost any shape from a 3D model or any other electronic data source primarily through additive processes in which successive layers of material are laid down under computer control⁴. The term Additive Manufacturing holds within such technologies like Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Layered Manufacturing, and 3D Printing. There are different 3D printing methods that were developed to build 3D structures and objects. The 3D printing technologies include: Stereolithography (SLA), Digital Light Processing (DLP), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electronic Beam Melting (EBM), and Laminated Object Manufacturing (LOM)¹⁻².

At Mercer University School of Engineering, as part of the innovation and entrepreneurship program, a new course on 3D Modeling and Rapid Prototyping (3 credits) was developed and is being taught to engineering students. The catalog description of this course includes: Product design, CAD and related software; basic principles, development, process chain of additive manufacturing; photopolymerization processes; powder based fusion processes; extrusion-based systems; printing processes; sheet lamination processes; beam deposition processes; direct write technologies; design for additive manufacturing; guidelines for process selection; software issues and direct digital manufacturing; medical applications; post processing; use of multiple materials, business opportunities and future directions; integrated 3D scanning and 3D printing lab experiments.

For this course, a low cost Rapid Prototyping Lab was developed with 3D scanners, FDM 3D printers, and mini CNC mills to provide hands-on experience to students on CAD/CAM, 3D Modeling, 3D Scanning, 3D printing, and reverse engineering. Two laboratory learning modules have been developed: 1. Comparative study module: additive and subtractive manufacturing processes to print the same part using a FDM (Fused Deposition Modeling) printer and a CNC mill and compare the two processes; 2. Reverse engineering module - use of a 3D scanner to scan small and large objects by fixed and hand-held scanning methods, edit, scale, and print the parts in a FDM printer and compare the parts for dimensional accuracy.

In addition, these laboratory learning modules are designed to fully/partially satisfy some of the ABET's student learning outcomes (1-7) that include:

2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors;
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives;
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

This course was offered in the Fall semester of 2018 that included the theory and the lab experiments. This is being offered as a senior level course open to all engineering and industrial management students as technical or professional elective. There were 21 students from mechanical, industrial, biomedical, and electrical engineering as well as from industrial management program in this class. The students attended theory classes and seven teams of 3-member teams participated in the lab modules developed.

2. Background

Additive manufacturing, the process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, is distinctly a different form and has many advantages over traditional manufacturing processes. Commonly known as “3D printing”, AM provides a cost-effective and time-efficient way to produce low-volume, customized products with complicated geometries and advanced material properties and functionality⁵. The generic AM process include the following steps: Conceptualization and CAD, conversion to STL, transfer to AM machine and STL file manipulation, machine setup, build, removal, post-processing, and application¹⁻².

There is consensus among both the research and industrial communities, and even the general public, that AM processes capable of processing metallic materials are a set of game changing technologies that offer unique capabilities with tremendous application potential that cannot be matched by traditional manufacturing technologies. Unfortunately, with all what AM has to offer, the quality and repeatability of metal parts still hamper significantly their widespread as viable manufacturing processes. This is particularly true in industrial sectors with stringent requirements on part quality such as the aerospace and healthcare sectors. One approach to overcome this challenge that has recently been receiving increasing attention is process monitoring and real-time process control to enhance part quality and repeatability. This has been addressed by numerous research efforts in the past decade and continues to be identified as a high priority research goal⁴.

3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. 3D printing is also considered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling (subtractive processes). A 3D printer is a limited type of industrial robot that is capable of carrying out an additive process under computer control⁶⁻¹².

While 3D printing technology has been around since the 1980s, it was not until the early 2010s that the printers became widely available commercially. The first working 3D printer was created in 1984 by Chuck Hull of 3D Systems Corp¹³. Since the start of the 21st century there has been a large growth in the sales of these machines, and their price has dropped substantially. According to Wohlers Associates, a consultancy, the market for 3D printers and services was worth \$2.2 billion worldwide in 2012, up 29% from 2011. The 3D printing technology is used for both prototyping and distributed manufacturing with applications in architecture, construction (AEC), industrial design, automotive, aerospace, military, engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic

information systems, food, and many other fields. One study has found that open source 3D printing could become a mass market item because domestic 3D printers can offset their capital costs by enabling consumers to avoid costs associated with purchasing common household objects⁵.

3. Methodology

3.1. Comparative Study on Additive and Subtractive Manufacturing Processes

CAD modeling

Regardless of the rapid prototyping technique chosen, the model can be created in any CAD software available. For this study Autodesk's Fusion360¹⁴ is chosen because of its versatility and support for CAM which will allow the user to program the CNC machine using the same software.

The desk organizer (Figure 1) has three features. The first feature is designed to hold Post-it® sticky notes. The sticky notes have a dimension of 3" x 3". A groove in the front of the model allows for easy access. The second feature is a slot for an iPhone 6s. A model was found online on GrabCAD¹⁵ to illustrate how the phone will fit into the organizer after it is completed. The slot is wide enough to fit a slim case. The last feature is a series of 16 mm holes which are designed to hold pens and pencils nicely hidden behind the phone. There are a total of 8 holes linearly patterned in two rows and four columns.

CAM programming

Before the desk organizer can be made on the CNC machine, the process needs to be programmed. In other words, most commercial CNC machines read in G-Code which is a programming language specifically made for any CNC machine as such any machine in which positions are controlled numerically with a computer (which includes 3D printers). Technically, one could program G-Code by hand which is fairly straight forward if there are only very few operations, but Fusion360 supports computer-aided manufacturing (CAM).

First, the stock needed to be cut to the correct external dimensions. The stock provided had outer dimensions of 167mm x 123mm x 50mm (L x W x H). The outer dimensions for the desk organizer were designed to be 167mm x 100mm x 35mm (L x W x H). Therefore, the height and the width needed to be trimmed. The height was reduced by using a facing operation as shown in Figure 2. For all operations, a 1/4" flat end mill with a cutting length of 1.5" was used. The operation removes 7.5mm of material. The operation is repeated on the other side. Each side takes about 15 minutes to complete given a feed rate of 254mm/min. This machining time could be drastically reduced by increasing the feed rate and using a face mill.

In the second operation, the sides of the block needed to be trimmed from 123 mm to 100 mm. Since the excess material exceeds the diameter of the end mill a simple contouring operation will not suffice. Therefore, an adaptive clearing method (Figure 3) was chosen. This method takes into consideration where the edge of the stock is located and removes material at a constant rate (i.e. it tries to keep a constant load on the cutter). To reduce the depth of cut, the operation was

completed in two steps. This operation was programmed to leave 1/2mm of stock. A second contouring operation was programmed to finish the edge. The estimated time for this operation is 9 minutes per side.



Figure 1. 3D Model of the desk organizer

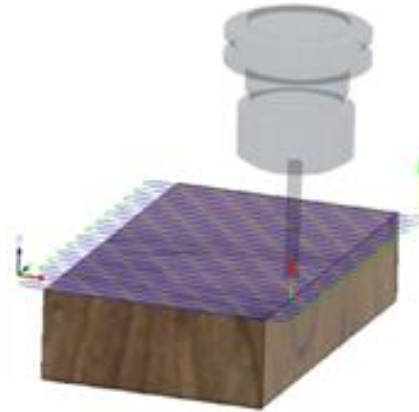


Figure 2. Facing operation

At this point, the stock should have the right dimensions and only the three features need to be cut into the top face as shown in Figure 4. A series of different operations have to be used to get the final product. For the pocket which holds the sticky notes, an adaptive clearing operation was chosen. It gradually moves into the material with a boring operation and when the full depth is reached it expands circularly to take full advantage of the long cutting length of the end mill. The iPhone slot was also cut using an adaptive clearing technique because the slotting operation is fixed to the width of the cutter which is smaller than the desired slot in this case. Lastly, the holes were cut using a standard boring technique. Fusion360 estimates the total machining time to be 45 minutes at a feed rate of 254mm/min.

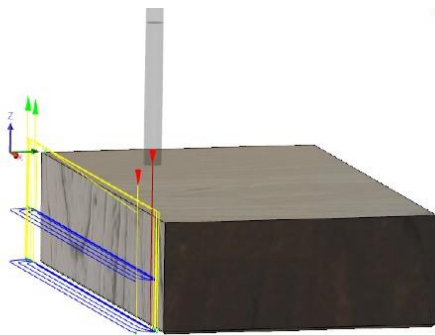


Figure 3. Adaptive clearing operation

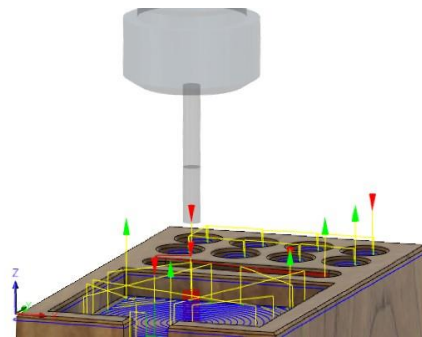


Figure 4. Clearing, slotting, and boring features

For a nice finishing touch, a chamfer is added to the model's top edges. A special operation exists for this feature in Fusion360 to make programming easy. The lower edge is selected and an additional 1mm offset is added so that the chamfer tool (1/4" shank, 90° cutting angle) tip is not engaged (which is good practice in CNC machining). The chamfer operation (Figure 5) takes about 1 minute.

FDM model slicing

In preparation to printing the model with a FDM printer, the model designed in Fusion360 needs to be exported as a STL file. This file can be imported into Simplify3D (S3D) simply by dragging and dropping. The part needs to be oriented most favorably. This means that the part orientation needs to be in such a way that there are a minimal amount of overhangs. The bottom surface will have the least appealing surface finish, so it was decided to place the model as shown in Figure 6. There are a multitude of settings which can be adjusted to receive the desired output. The material chosen was PLA (polylactic acid) due to its low cost and environmental friendliness as it is a bio-plastic. Long parts as such usually have a problem with warping due to part shrinkage. PLA has a much lower shrinkage rate than ABS (acrylonitrile butadiene styrene) which is another common plastic used in FDM printing. To avoid warping, a brim is added to the part which expands the boundary of the first layer to increase the layer adhesion near the edges which are prone to lift and warp. The printing speed/scan speed was set to 90mm/s which is about 50% faster than the norm. The extrusion temperature is set to 210°C. The nozzle diameter is 0.4mm. The total estimated time is 6 hours and 11 minutes. The infill is set to 25% to preserve material. The estimated material usage is 215g which is about \$4.72.



Figure 5. Chamfer operation

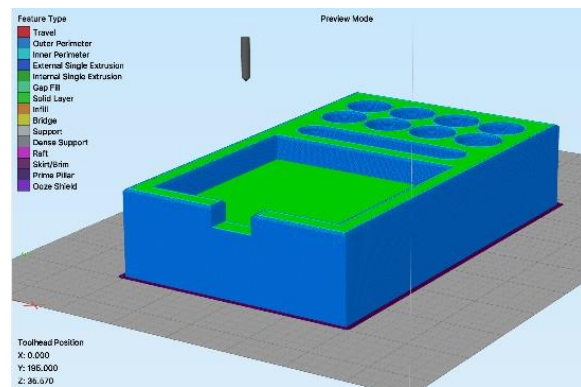
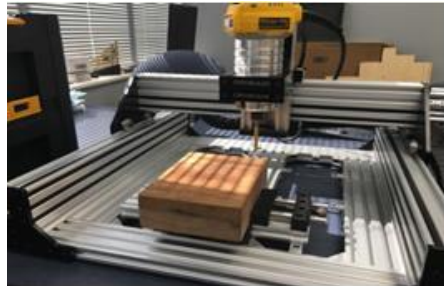


Figure 6. Printing simulation in Simplify3D

CNC machining

First and foremost, the stock needs to be fixed in the machine appropriately. Figure 7-A shows the fixture holding the stock. It can be extremely dangerous if the stock moves while being machined. The router is spinning at about 5,000-10,000 rpm and could possibly cause a fire in the case of an accident. Therefore, the machine should never be left alone. The G-Code programmed in Fusion360 now needs to be exported as a .nc file and the G-Code needs to be sent to the machine. In order to do this, a program called SourceRabbit is used. The CNC uses the XPro controller board which receives the commands and translates it to movements of the stepper motors controlling the movement of the router in three axes (x, y, and z). The XPro controller board uses Grbl as the firmware. Therefore, any G-Code sender which supports Grbl can be used. Grbl is open-source and available for free online. Within SourceRabbit, first the home position needs to be set. After an operation has been completed the router will return to this home position. Failing to set the home position correctly could mean that the router collides with the stock or cause other damage to the machine. Secondly, the stock coordinate system needs to be set. In other words, in Fusion360 the origin of the x-y-z coordinate system has been

set to the upper left corner as shown in Figure 7-B. The machine needs to know where this zero point is. Therefore, the user needs to manually position the end mill to this position as close as possible and reset the working coordinate system. Alternatively, a touch-plate or a probe can be used to set the zero-point more precisely.



(A): Fixture holding stock



(B): Setting the zero point

Figure 7. CNC machining

After the setup has been completed, the first operation can be sent to the machine. Figure 8-A shows the first facing operation in progress. The surface finish of the part feels very smooth to the touch. The stripped pattern as can be seen in Figure 8-B, is due to the small diameter of the end mill and a large stepover. A larger face mill would produce a higher quality surface finish, but this will certainly suffice. After the top surface has been completed, the part needs to be flipped and the other side needs to be machined as well to the final height of 35mm. As shown in Figure 8-B, the stock is also rotated 90°, to expose the side face because the machine cannot remove material on the side where the vise clamps the stock. In Figure 9, the second operation is shown in progress.

FDM printing

Fused Deposition Modeling (FDM) is a highly automated process. The slicer exports the G-Code which can be loaded on a SD card. The 3D printer is controlled by a modified version of an Arduino Mega which has been flashed with the Marlin firmware. Similar to the CNC machine running Grbl, the firmware interprets the G-Code and then moves the stepper motors or heats the extruder and the bed accordingly. Before starting the print, the build platform usually needs to be leveled, but this particular printer uses an autoleveling sensor to adjust the printing plate automatically. The z-offset also needs to be set so that the first layer is extruded at the appropriate thickness.



(A): Facing operation



(B): After facing operation

Figure 8. Facing operation

In this case, the layer height is set to 200 μ m and therefore, the z-offset needs to be set with the same accuracy. This calibration, however, only needs to be done once with automatic leveling. The build platform is also cleaned with isopropyl alcohol to ensure that the layer adhesion is optimal. All of these steps do not take more than 5 minutes. While, the printer is printing, one can leave the machine alone, because the risk of an accident is much lower than with a CNC machine. However, it is still advised to periodically check that the print is going smoothly. There are a number of issues that can happen randomly such as belt loosening or skipping a step which could ruin the print. Figure 10 shows printing in progress.

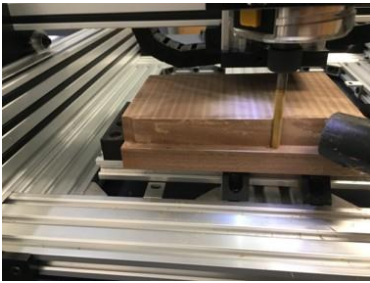


Figure 9. Trimming the sides of the stock

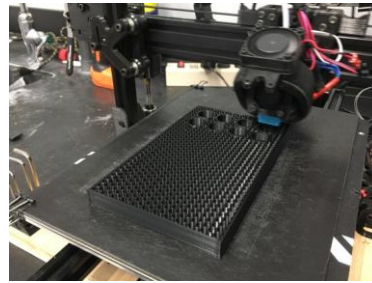


Figure 10. 3D Printing in progress

3.2. Comparative Study on 3D Scanning (Fixed and Hand-held Methods)

Part selection

The EinScan system (Fig. 11) projects a visible light pattern onto the object and measures the distortion of this pattern to determine the shape and distance between the camera and the object¹⁶. Each image has to be merged to form a 3D scan. The EinScan software uses feature tracking to combine individual scans. However, the software has its strengths and weaknesses. For example, parts that are symmetric are more difficult to scan than asymmetrical parts due to symmetrical features that mess up the software during the merging process.

Parts were selected that would provide a challenge to the software and the student team. The first part selected is a Tau Beta Pi bent (Fig. 12). Due to its flat geometry, it provides some unique challenges to the 3D scanning process because thin features are more difficult to detect for feature tracking. The second “part” selected is the forearm of one of the students in the team. Scanning an arm also provides certain challenges related to scanning such as scanning a moving object.



Figure 11. EinScan Pro 3D scanning system



**Figure 12. First object to be scanned:
Tau Beta Pi bent**

Fixed scanning

In fixed scanning, the object to be scanned is placed on a rotary table while the 3D scanner is fixed on a tripod. The software controls the rotation of the table and it has an easier time merging individual scans as it knows the rotation between scans. The 3D scanner is directly connected to the computer (Fig. 13) for real-time feedback about the scan quality.

Following the same concept, the Tau Beta Pi bent was placed on the center of the rotary platform with its flat surface placed flat on the table. Note that the rotary table (Fig. 14) has a distinct pattern which aids in recognizing the position of the table in relation to the scanner.



Figure 13. Stationary scanning process



Figure 14. Orienting part on rotary platform

As shown in Figure 15, the EinScan uses a pattern of visible light to measure the surface of the object. It does this by projecting a line pattern and measuring the distortion due to the object which can be used to calculate a point cloud. Note also that the bent is powder-coated to aid the process.

EinScan software

Meanwhile in the EinScan software, a 3D model is generated. Each time a scan is completed it is merged with the overall point cloud (Fig. 16-A). There is considerable noise and part of the fixture was also scanned. The EinScan software provides a tool which allows these parts to be easily deleted. In the final step, a water tight model (Fig. 16-B) is generated and a STL can be exported.



Figure 15. Alternative orientation of powder-coated part in fixture



(A) (B)
Figure 16. Point cloud to STL conversion

Meshmixer mesh editing

In Meshmixer¹⁷, a few modifications were made to aid the 3D printing process. One of these modifications includes reducing the mesh (Fig. 17) to 5% which still provides enough detail, but

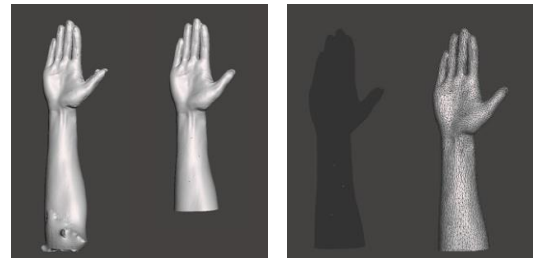
dramatically reduces the file size. This will help the slicer process the file much faster. Secondly, the back surface is cut with a plane so that it is perfectly straight. This is important for 3D printing so that the first layer is perfectly flat on the build platform.

Hand-held scan of forearm

For scanning an arm a different approach needs to be employed because obviously an arm cannot be fixated onto the small rotary platform. Therefore, the scanner needs to be used in its hand-held mode. This allows the 3D scanner to be moved around the arm to capture images continuously. This requires the scanner to continuously track the position of the scanner in relation to the arm. For smaller objects, like the bent, this would have been very challenging. As compared to scanning the bent, there were no complications in the scanning process. The scan, however, is not instantaneous, and due to human error, the hand moved slightly during the scanning process which took about 30 seconds. Ideally, a 3D image could be generated instantaneously to avoid the issue of moving objects, but this would require multiple scanners arranged 360° around the object. Of course, such systems are very expensive. The motion artifacts (Fig. 18) are visible at the proximal segment of the arm as well as the first digit of the hand. The artifact was minimal enough to be removed in Meshmixer. This is done using one of several smoothing brushes in Meshmixer. The arm is also cut to remove the entire proximal portion which was not desired in the final object. Due to the length (about 30s) of the scan, several million points were generated. The STL was also exported as a high detail model (Figure 18-B). This file includes more than a million nodes. In Meshmixer, the mesh is reduced to 10k nodes which provide sufficient detail for this application.



Figure 17. Mesh reduction in Meshmixer



**Figure 18. (A) STL editing;
(B) Mesh reduction in Meshmixer**

3D printing

The 3D printing process involves slicing the models as discussed previously. Note that the arm was scaled down to fit within the build platform of the 3D printer (Fig. 19). The model final scale was set to 50% which would allow for an easy comparison between the subject's hand and the model. Figure 20 shows the simulated G-Code. As shown by the color map the slicer (Simplify3D) automatically adjusts the printing speed when the layer printing time is reduced which creates a more even temperature gradient in the part. If this was not the case, especially the tips of the fingers would not have enough time to cool down before the next layer is printed which would result in a degraded part quality.

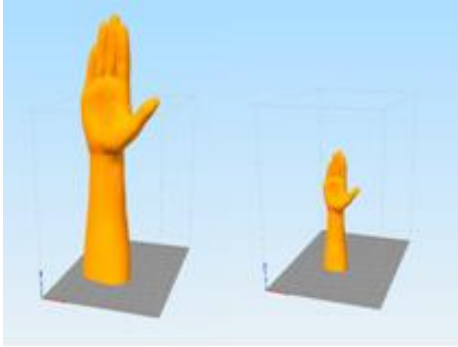


Figure 19. Before and after scaling

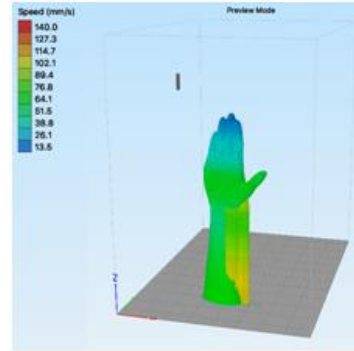


Figure 20. Color map of scan speed

4. Results and Discussions

4.1. Comparative Study on Additive and Subtractive Manufacturing Processes

The final model (Fig. 21) was tested whether all necessary components (pens, iPhone 6s, and Post-it® sticky notes) fit within it. The same was confirmed with the 3D-printed part. Both components fit all objects very well confirming the model dimensions were appropriate.

As a rough comparison between the parts, several measurements were collected with a digital caliper. As shown in Table 1, the FDM model was more accurate in most of the measurements. This is a result of programming mistakes made in Fusion360. Some operations by default will leave stock for a finishing pass. This setting should have been turned off, so that the machine cuts the part to the right dimensions in one operation. Hence, the CNC measurements do not provide us with the opportunity to judge its precision. However, it can be concluded that CNC machining is significantly more complex and it is far easier to make a simple programming error which will result in intolerances in the part.



Figure 21. Final CNC machined model

Table 1. Part measurements for the FDM and CNC part

	Overall width [mm]	Square pocket width [mm]	Hole width [mm]	Overall height [mm]	Slot width [mm]
CAD model	100	80	16	35	11
FDM	100.78	80.11	15.98	34.82	10.91
CNC	99.47	78.45	15.53	34.22	9.88

Comparing the quality of the final product, the surface finish of the CNC machined part looks almost like a production-level part. The 3D-printed part, however, has clear signs of layers (layer lines, Fig 22-A) which make the part look more like a prototype. The bottom surface of the 3D-printed part was very rough (Fig. 22-B) and had to be sanded significantly (Fig. 22-C).



Figure 22. Surface finish of FDM model and post-processing

Comparing the time required, the FDM model was printed in about 8 hours, while the CNC machined part was completed in just 3 hours. However, the setup for the 3D-printed part was complete in less than 10 minutes and for the remaining time, the 3D-printer did not require any more user interaction. Producing the CNC-machined part, the user needs to be present at all times, because an error, such as the stock coming loose in the vise, could happen at any time and the operator needs to be able to stop the machine quickly before significant damage occurs. Also, the operator needs to start each individual operation (the student team used 4 in total). Overall, for prototyping purposes FDM has a clear advantage because of the short setup time.

The main advantage of CNC machining is scalability. Once a program has been perfected and appropriately tested, the programmed part can be reproduced quickly. With further optimization, the part created in the lab could easily be produced in less than 1 hour by optimizing the feeds and speeds. If a thousand parts would need to be created, the process could be optimized even more by running multiple parts at the same time as the build volume on this particular machine could fit at least 5 parts next to each other. Hence, the production time could be reduced even further. For the thousand parts, the overall time could be roughly 400 machine hours. On the other side, FDM does not easily scale up. The time required to print one part cannot be optimized as much as its CNC counterpart. The 3D-printer was already running 50% faster than the general recommendation, so it's unlikely the 8 hour printing time could be significantly reduced more. Then, a thousand parts would take 8,000 hours of machine time which is 20x the time the CNC would need.

4.2. Comparative Study on 3D Scanning (Fixed and Hand-held Methods)

The final 3D printed part of the Tau Beta Pi bent is shown in Figure 23. The error of processing is discussed by comparing the overall dimensions of the 3D printed part to the original part in Table 2. Note that the percentage error includes the errors of the 3D scanner, Meshmixer adjustments, and FDM printer combined. Just looking at the images it is clear that the bottom part of the 3D printed part is cut off. During 3D scanning, the part was mounted in a vise and the vise grips covered this bottom portion, so the 3D scanner has no chance of seeing this surface.

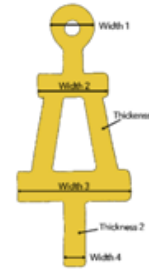
To capture the entire part, the part would have to be rotated and several other scans would need to be collected.



Figure 23. Original vs. 3D-printed part Figure 24. Final 3D-printed model of the arm

Table 2. Part measurements in mm

Part Dimension	Original Part	3D-printed part	% Error
Thickness 1	3.06	2.47	-19.3%
Thickness 2	5.40	4.12	-23.7%
Width 1	19.74	19.97	1.2%
Width 2	31.40	31.85	1.4%
Width 3	49.97	50.65	1.4%
Width 4	9.31	9.59	3.0%



The overall error of the 3D model ranged from 1.2% to 3%. Note that the thickness has much greater errors up to 23.7%. This is mainly due to performing the plane cut in Meshmixer and therefore this cannot be considered as the true error, but rather a processing error. The final 3D-printed model of the arm is shown in Figure 24.

Student Learning Outcomes and Assessment

The following ABET's student learning outcomes were fully/partially achieved by the student teams through these laboratory learning modules:

2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors: the student teams designed parts using Autodesk's Fusion 360 and produced parts using FDM 3D printing machine as well as CNC milling machine; they measured several dimensions of the parts made and compared the two processes (additive and subtractive manufacturing) with respect to dimensional accuracy, scalability, machining time, and final quality of the parts made.
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives: There were 21 students (seven 3-member teams) from mechanical, industrial, biomedical, and electrical engineering as well as industrial management program; multi-

disciplinary teams formed for the lab projects effectively functioned, planned tasks, established goals, and met the objectives of the lab work.

6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions: The student teams designed/scanned the parts, made the parts in FDM 3D printing machine and the CNC milling machine; measured and collected data; analyzed and interpreted the results by comparing the two processes (additive and subtractive manufacturing) and made conclusions and recommendations based on their experimental results.

Assessment made on these lab projects by student peers and the faculty member indicated that the seven student teams fulfilled their initial goals and objectives of these lab projects with an average score greater than 3.5 in the 5-level Likert scale (1 being the lowest and 5 being highest scores) in all three ABET's student learning outcomes 2, 5, and 6 considered for these hands-on lab modules.

5. Conclusions and Recommendations

FDM printing is a great option for preliminary prototypes, because the setup time is minimal and requires minimal user interaction during the printing process which means that prints lasting several hours can be done overnight. The surface finish is not as smooth as the CNC machined product and the plastic feels rather cheap, therefore, it is not ideal for producing finished products for sale without post-processing.

CNC machining takes a lot more user interaction to produce a part from programming to execution. Overall, the time required to produce one part is shorter than FDM, but this entire time the user needs to be physically present either on the computer programming or carefully watching the machine the first time it runs the code. Therefore, CNC machining is expensive for single prototypes. However, it is ideal if large quantities of parts need to be made. A tested CNC program will repeat precisely what it has done the first time around, so then the machinist does not need to be present during the entire time.

3D scanning is a useful tool for reverse engineering as parts can be scanned quickly within a reasonable error. FDM printing allows replicating these scanned models without much effort and little material cost. Being able to scale the model to any size with the click of a button also is a powerful feature especially when engineers have to test parts that are huge and cannot be easily prototyped at their 1:1 scale.

Through these two laboratory learning modules developed, the students were trained in using design tools such as Autodesk Fusion360, GrabCAD, CAM, and Meshmixer and emerging technologies such as CAD/CAM, CNC machining, FDM 3D printing, 3D scanning, and rapid prototyping as well as reverse engineering. They were able to print and machine 3D parts and scan, fix, and print 3D parts. They were able to measure the printed parts for dimensional accuracy and compare the results. One student team had difficulty in designing the part using the Autodesk Fusion360 and a few students had problems while tracking to combine individual scans and generating 3D printable water tight models using the EinScan system. The student

teams were evaluated using ABET's student learning outcomes 2, 5, and 6 considered for the hands-on lab modules developed and all seven teams scored above 3.5 in the 5-level Likert scale.

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