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Inexpensive Digital Light Processing 3D Printers in Undergraduate Engineering Labs

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Inexpensive Digital Light Processing 3D Printers in Undergraduate Engineering Labs

Abstract

While the Fused Filament Fabrication (FFF) 3D printers are now ubiquitous devices in many undergraduate engineering curricula, the Digital Light Processing (DLP) 3D printers just became affordable for widespread use in undergraduate engineering labs. This work has two objectives. It describes, for the first time, the similarities and differences between three inexpensive DLP 3D printers and one FFF 3D printer as evaluated by undergraduate students to help others develop DLP 3D printing labs. Furthermore, it provides the means necessary for student engagement and learning opportunities. While measuring various characteristics of three inexpensive DLP and one FFF 3D printer, students became more knowledgeable and accustomed to different additive manufacturing (AM) processes. In a two-hour lab session students created objects, measured process parameters, measured object characteristics, and discussed material properties. They were impressed with this new and affordable 3D printing process.

Introduction

The value of experiential learning in engineering education based on laboratory exercises and practice is well justified through the Kolb's experiential learning cycle theory [1-3] where active experimentation occupies a prominent role [4-7]. Additionally, Dewey's experiential education philosophy [8] fully supports hands-on activities in learning. Physical models and prototypes are important parts of the engineering design process and are addressed in many engineering texts [9, 10] and in engineering education literature [11-13].

3D printing is a form of AM whereby objects are created by adding material as opposed to subtractive manufacturing processes like machining whereby the objects are created by removing material. 3D printers were used in some engineering programs to create physical objects [14-19]. Originally, these 3D-printed objects were fairly costly because they were printed using expensive 3D printers with expensive materials. However, recently, a number of fundamental 3D printing patents expired and opened this technology to the rest of the world. New companies started producing inexpensive FFF 3D printers thus enabling their expansive use in engineering education [20]. Numerous undergraduate engineering 3D-printing laboratories with multiple 3D printers have been established [21-25]. The authors of textbooks added new chapters on 3D printing and AM [26, 27].

Generally, three groups of learning objectives can be defined in education: cognitive, affective (attitudes and values), and skill learning [28], where cognitive and skill learning objectives are mainly emphasized in engineering education. Furthermore, design emphasis (cognitive objective) and proficiency with 3D-printing processes (skill learning objective) are explicitly stated in ABET

General Criterion 3, Student Outcomes [29] (c) "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" and (k) "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."

Recently, companies started producing inexpensive DLP 3D printers. The DLP 3D printing technology is an extension of the stereolithography apparatus (SLA) 3D printing technology. While the SLA technology was the first 3D printing technology to be patented [30] and commercialized, the inexpensive SLA 3D printers became available just in the past two to three years. SLA 3D printing technology is based on lasers and photopolymers. Here, an object is created by repeatedly "drawing" object layers with lasers in a vat of photo-curable liquid resin thus selectively curing parts of each layer. As these layers are stacked together they form an object. Digital light processing 3D printing technology also works with liquid photopolymers, but curing is performed by digital light projectors that are capable of curing the entire layer at the same time. However, due to the digital nature of the projectors, usually, DLP 3D printers are not as precise as the SLA 3D printers. Both SLA and DLP 3D printing technologies are well described online [31]. Sirinterlikci *et al* [32] presented the development of a DLP 3D printer as a multi-year engineering capstone project.

The use of inexpensive DLP 3D printers in undergraduate engineering labs has not been described before in engineering education literature. In this work, students learn AM processes by comparing inexpensive 3D printers, three DLP (FlashForge Hunter, MoonRay S, and Phoenix Touch Pro Translating) and one FFF (MakerBot Replicator 2) 3D printer. These students' explorations of new 3D printing technologies exemplify "expansion," the fifth stage of the students' 3D printing expertise evolution [33].

Curricular Context

Even though 3D printers are used in many courses, the 3D printing lab/lecture modules are formally introduced in detail in a required one-semester, three credit-hours senior-level Computer-Integrated Manufacturing (CIM) course in two engineering programs: Bachelor of Science in Engineering with specialization in Mechatronics (BSE-Mechatronics) and Industrial Engineering (IE). During the lecture portion of the course students learn about various 3D printing technologies. In the lab, they create various small objects using nine FFF 3D printers [20].

An undergraduate research team of three students was formed to help in the development of a two-hour long lab module introducing the DLP 3D printing technology in the CIM course. The students used the three recently installed DLP 3D printers and one FFF 3D printer. For comparison purposes, the students created tensile test specimens, prisms (3cm x 3cm x 1cm), and objects with many intricate geometric features (e.g., an Eiffel tower from Thingiverse [34]) using the four 3D printers. Then, they compared the processes (variables: environmental impact and hazards, printing speed, and additional post-processing work required to obtain the final part), the objects (variables: surface structure and smoothness, object's dimensional precision, and object's mechanical characteristics), and materials (variables: environmental impact and cost). Based on the experiences of these students a set of lab requirements and procedures were improved and implemented in the CIM course.

Sixteen students that were enrolled in the CIM course were divided into groups of four. Each group sequentially conducted 3D printing experiments described here. The three undergraduate researchers acted as lab coordinators/assistants explaining the process, helping with the software environments, and instructing the CIM students in the use of measuring instruments. It is expected that this lab module will become a permanent part of the AM laboratory experiences.

DLP 3D Printer Characteristics

The three DLP 3D printers used in this study are shown in Figure 1. Phoenix Touch Pro Translating is an $8,000 3D printer manufactured by Full Spectrum Laser, MoonRay S is a $4,000 3D Printer by SprintRay, and (c) FlashForge Hunter is a $3,500 3D printer by FlashForge Corp. Special photo-curable liquid resin was included with each DLP 3D printer. Figure 2 depicts a Helix Cure 60 UV curing chamber by Strategic 3D Solutions. The UV curing chamber allows DLP 3D printed objects to fully cure after printing. The printers' specifications claim 20 – 100 µm layer thickness and relatively fast built times.

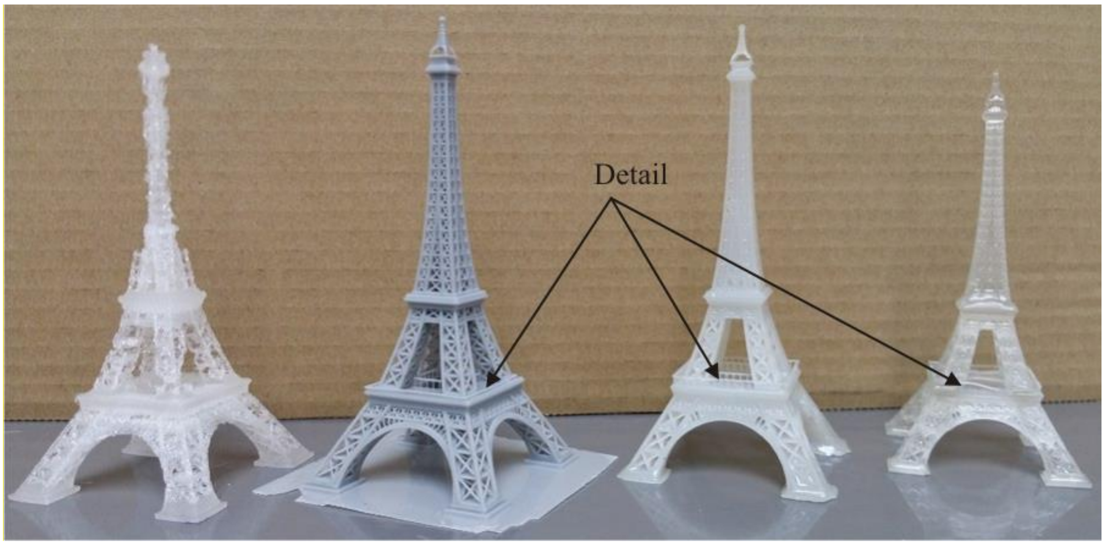
a b c

Figure 1. DLP 3D Printers: (a) Phoenix Touch Pro Translating, (b) MoonRay S, and (c) FlashForge Hunter

Figure 2. UV Curing Chamber

Dimensional and Mechanical Testing of Printed Objects

Details. Figure 3 shows four objects with intricate detail built by the four 3D printers. All the print files were created from the same .stl file imported into the printers' proprietary software packages. The created objects are of different colors because the resin used with each DLP 3D printer was the resin included with the original purchase (gray for FlashForge Hunter, light gray for MoonRay S, and transparent for Phoenix Touch Pro Translating). The object created by the Phoenix 3D printer was somewhat smaller than the other objects due to the object size limitation of this printer. From observations of Figure 3 (a) it can be concluded that, in this case, the FFF 3D printer failed to produce an acceptable object using polylactic acid (PLA) filament. Observing the other three objects, (b) is missing an observation fence, while that fence is distorted in (d). Only (c) the MoonRay S 3D printer has produced acceptable observation fence detail.



a b c d

Figure 3. Comparison of Print Details: (a) MakerBot Replicator 2, (b) FlashForge Hunter, (c) MoonRay S, and (d) Phoenix Touch Pro Translating

Dimensional Accuracy. Four rectangular prisms (3x3x1 cm) are created. Their dimensions are measured using a caliper. The dimensional readings were mostly within +/- 0.04 mm. The Phoenix 3D printer was an exception having the height of the prism of 1.096 cm.

Surface Roughness. This surface characteristic is measured in micro inches using a pocket surface roughness instrument, Pocket Surf, by Mahr Federal Inc. The top surface, and a side surface (along and against the grain) are measured. The DLP-created top surfaces had surface roughness averaging between 10.6 and 18 µin while the average top surface created by the FFF 3D printer was 190 µin.

Surface Hardness. Surface Hardness is measured with two durometers using the ASTM D2240 standard and “A” and “D” scales. For the “A” scale, surface hardness was in the high 90’s range (full scale: 0 to 100), thus only the “D” scale is used for comparison. For DLP prints, the hardness was measured before and after curing. Curing of DLP parts increased their hardness on the “D” scale from 76 to 82 while the FFF-created PLA prism had surface hardness of 82 on the “D” scale.

Tensile Strength. Tensile strength test was performed using an Instron 1123 Universal Testing System recently upgraded with a National Instruments LabVIEW data acquisition system. The tensile strength test displacement data were read from a crosshead and an extensometer. Figure 4 shows the experimental setup and a screenshot of the software while running the test. Figure 5 is a photograph of some tensile test samples before testing. The sample in Figure 5 (d) was printed on a side and is still showing supports that were removed just before the tests. All samples had comparable tensile strengths.

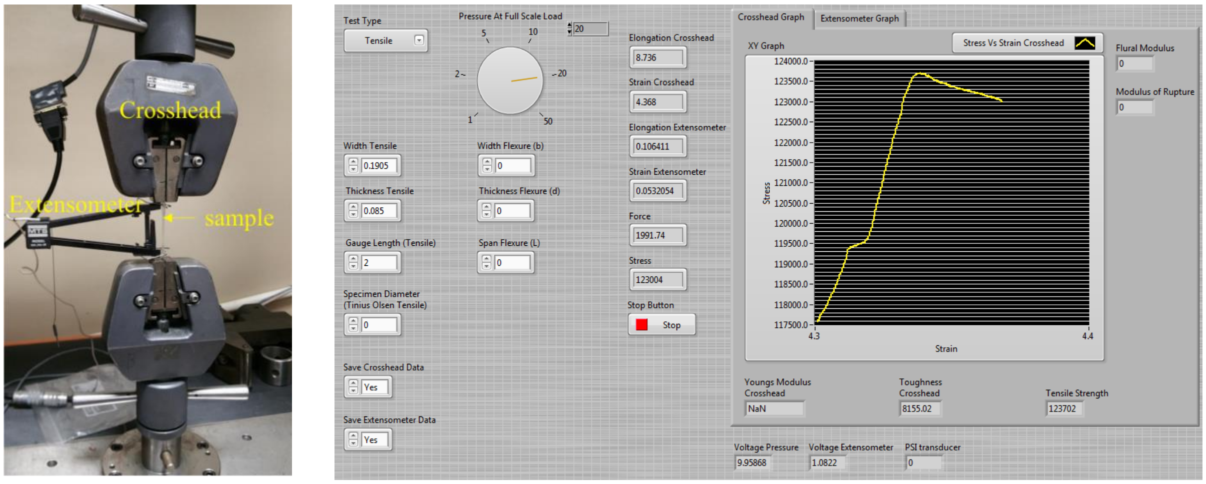
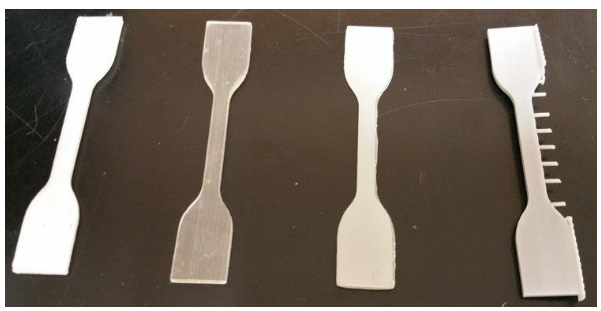


Figure 4. Tensile Test Setup and Screenshot of the Software



a b c d

Figure 5. Tensile Test Specimens: (a) MakerBot Replicator 2, (b) Phoenix Touch Pro Translating, (c) MoonRay S, and (d) FlashForge Hunter (printed on a narrow side)

Student Knowledge, Skills, Perceptions, and Attitudes

There are about 150 students enrolled in BSE-Mechatronics and IE programs. All undergraduate engineering students are required to use 3D printers in many of their engineering courses. Three undergraduate engineering research students of different academic standings and fourteen out of sixteen students enrolled in the CIM course participated in this study. To evaluate the pedagogical success of DLP 3D printing lab activities and 3D-printed objects, an assessment tool measuring students' knowledge and skills is developed, administered, and reviewed. Also, an attitudes and perceptions questionnaire is delivered and evaluated.

After the students entered their measurements in an Excel file, they analyzed the data. From the data analysis they were able to evaluate the different 3D printers. Figure 6 shows the comparative evaluation form with comparative rankings where 5 means "the highest ranking." The form includes two tables: one table dealing with the quality of the 3D printed objects and another dealing with the quality of the 3D printing processes. The students (n = 17) arrived to the final comparative evaluation results based on their analyses and discussions. The surface finish quality of the FFF

3D printer was significantly inferior to the DLP 3D printers while its dimensional accuracy was a bit better. The surface hardness tests didn't show a difference between the four 3D printers.

The 3D printing processes are evaluated based on printing speed, post-processing time, and environmental impacts and hazards. The printing time of the prisms was recorded. In the printing programs, the best print quality was selected for each 3D printer while all other settings were left at their default values. Print times ranged from one hour for the MakerBot Replicator 2 3D printer to two hours and four minutes for the MoonRay S 3D printer, an unexpected result. Upon closer observation, it was discovered that all DLP 3D printers lift their platforms after each layer is cured and then immerse them into resin again. The post-processing time for DLP 3D printers involves submerging either the whole platform or just the object into isopropyl alcohol for 10 to 15 minutes and curing the part in the UV curing chamber for about 30 minutes to achieve the maximum strength. For MakerBot Replicator 2 this was a quick process since this 3D printer has a removable bed that allows quick removal of the objects. The prism was removed from the bed and cleaned (the raft, a thin layer of material printed to ensure that the part adheres to the printing platform, was removed) within one minute. Finally, the used 3D printing materials are evaluated for toxicity. All photopolymers used are mild skin irritants, so one should use gloves when handling them. In contrast, PLA is biodegradable organic thermoplastic. Finally, PLA filament is about two times less expensive than DLP liquid resin.

Question 3 asked about possible applications of 3D printers. Students' answers included making figurines, jewelry, small objects for fundraising, parts for mechanical testing, replacement parts, plastic household items, idea demonstrations, and testing design iterations.

Students' Evaluation of 3D Printing Technologies (DLP and FFF)

Q1: Evaluate the objects printed using the following printer types (use ranking 1-5 to show the lowest to the highest evaluation value)

3D Printer	Surface finish quality	Dimensional accuracy (precision)	Surface hardness	Tensile strength
FlashForge Hunter DLP	5	3	5	4
MoonRay S DLP	3	4	5	5
Phoenix Touch Pro T. DLP	4	2	5	3
MakerBot Replicator 2 FFF	1	5	5	2

Q2: Evaluate the printing process of the following printer types (use ranking 1-5 to show the lowest to the highest evaluation value)

3D Printer	Printing speed	Post-processing time	Environmental impact and hazards
FlashForge Hunter DLP	3	3	2
MoonRay S DLP	1	2	2
Phoenix Touch Pro Translating DLP	2	2	2
MakerBot Replicator 2 FFF	5	5	5

Note: Include in a separate document experimental results supporting your findings.

Q3: List two possible applications for DLP and FFF 3D printers in your daily life

1-

2-

Figure 6. Students' Evaluation of 3D Printing Technologies: DLP vs. FFF (n = 17)

Students' 3D Printing Attitudes Survey

Please rate the following four questions.

1. Working with DLP 3D printers was ____________.
   1 = really boring, 2 = somewhat boring, 3 = neither boring nor exciting, 4 = somewhat exciting, 5 = very exciting
2. From this lab I learned ___________ about different 3D printing technologies.
   1 = nothing, 2 = very little, 3 = something, 4 = much, 5 = very much
3. By operating 3D printers and performing experiments I became ___________ with different 3D printing technologies.
   1 = less proficient, 2 = somewhat less proficient, 3 = neither less nor more proficient, 4 = somewhat proficient, 5 = very proficient
4. Mechanical tests of 3D printed objects were __________ in my understanding of materials used in 3D printing.
   1 = unhelpful, 2 = somewhat unhelpful, 3 = neither unhelpful nor helpful, 4 = helpful, 5 = very helpful

Please comment on your experience with DLP and FFF 3D printers:

5. What is it that you liked the most about these 3D printers?
6. Which part of the 3D printing process (3D printing software use, material preparation, actual 3D printing, post-processing, etc.) was the easiest/hardest for you?
7. What is it that you think can be improved in these 3D printing processes?

Figure 7. Students' 3D Printing Attitudes and Perceptions Survey (n = 17)

Figure 8 shows the results for the first four questions of the students' attitudes survey of Figure 7 (n = 17). Since the probability distribution functions are not Gaussian, the results are reported qualitatively. There were no negative responses. All students agreed that working with DLP 3D printers was exciting. Most of the students agreed that they learned much about different 3D printing technologies and that mechanical testing helped them understand materials used in 3D printing. Question 3 results were a bit puzzling. Seven students reported no gain in proficiency from operating 3D printers and performing the experiments. There are two simple explanations that could account for this result. Either the undergraduate student assistants were too helpful in explaining the process and assisting the CIM students in operating the 3D printers, or the CIM students are already so proficient in using FFF 3D printers that the use of DLP 3D printers did not present a significant gain in their proficiency. In the future, this question will be changed to only address DLP 3D printers and the student assistants will be instructed to help only when asked by the CIM students.

Question 5 of the survey was purposefully written in a positively biased form. It was not meant as an assessment tool but as a motivational tool. While self-reflections are important parts of experiential learning experiences [1 - 4], positive self-reflections are important parts of the theory of motivation and self-efficacy [35]. When answering Question 5, the students liked "*the process of seeing and creating parts from scratch*," "*how much detail the MoonRay can print," "objects rising like Phoenix," "upside down grown parts," and "the quality and accuracy of the process."*

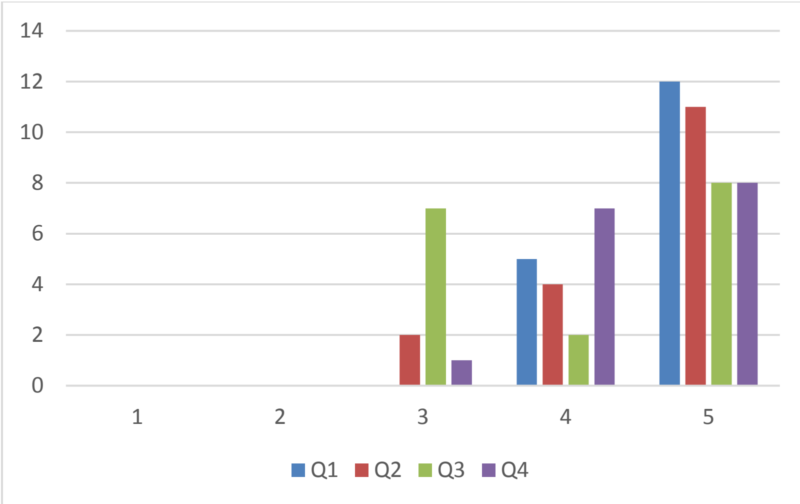


Figure 8. Students' 3D Printing Attitudes and Perception Survey Results: Questions 1 – 4 (n = 17)

To further assess students' attitudes, questions 6 and 7 were presented as open-ended questions. The students appreciated how easy it was to use specific printing software for each 3D printer, as well as how easy it was to perform the pre-printing process. They all agreed that for DLP 3D printers post-processing was not easy (removing objects from the printing platform was challenging). The final question on improving DLP 3D printers resulted in a number of general suggestions like "*standardize the printing software between 3D printers*," "*quicker build time would be nice,*" and *"automate the post-processing."* Also, there were some printer-specific suggestions like *"FlashForge's rigid base made it hard to remove structure,"* or *"On the Phoenix software one should be able to scale parts in the x y z direction separately."*

Summary and Conclusions

This work describes the development and implementation of a two-hour undergraduate engineering lab session with currently available inexpensive DLP 3D printers. A group of undergraduate engineering students was instructed in measuring the relevant characteristics of DLP 3D printers and in performing a comparative analysis of different 3D printer technologies. The measured object characteristics were objects' geometric details, dimensional accuracy, surface roughness, surface hardness, and tensile strength, while the measured process characteristics were printing time, post-processing time/difficulty, and environmental impacts and hazards. DLP 3D printers created sample objects slower than the FFF 3D printers, but the DLP 3D printed objects were smoother, and exhibited more details than the FFF 3D printed objects. Students gained practical knowledge of inexpensive DLP and FFF 3D printing technologies while they were building and testing objects. Their attitudes towards 3D printing (DLP and FFF) were positive. The DLP 3D printing lab module is implemented as a part of a regular CIM course. It is worth mentioning that students are fascinated with the engineering profession when they see tall solid objects emerge from shallow vats full of liquid.

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