The Innovation of Using 3D Printing Technology in Mechanical and Manufacturing Engineering

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Abstract. One of the main challenges that the educator faces in integrating 3D printing technology in a traditional engineering course in the capability of introducing and merging the 3D printing technology at the right educational material. The paper aims to present the challenges and the achievements of integrating 3D printing technology in teaching design and manufacturing courses in the mechanical engineering department to enhance the students' skills and engagement with the course material. One of the course experiments was nominated to introduce the 3D printing technology, where the students were asked to use the systematic design method as well as design matrix procedure to explore different options to come up with a solution to hold a mechanical component for quality control task. Besides, the students had to design an engineering measurement procedure to achieve the assigned mission of the experiment, where the mechanical part was described to present the main dimensions needed for the measurement sequence. Different groups submitted innovative ideas that were evaluated initially and discussed individually before submitting the final design and the holder prototype. The students presented a functional 3D printed prototype with a full report that clarifies the engineering procedure adopted to achieve the goal of the experiment. The innovation in the addressed solution revealed the importance of 3D printing technology to enhance the students' skill and engagement with the course material and help them to encounter challenges to come up with creative engineering solutions.

1. Introduction
Additive manufacturing, or what is named 3D printing technology has a significant contribution to the world in many directions because of the remarkable advantages to the industrial sector. It has a substantial impact on other fields [1,2]. Moreover, this revolution has been extended to other applications, like in prototyping, simulations, and failure mechanism [3,4], whereas the aerospace sector is one of the promising areas due to the vast and numerous applications that could be adopted of using 3D printing technology [5]. However, the 3D printing technology started being embraced in schools [6] for the learning purposes, as well as implemented in different university levels [7]. At the university level, vocational, technical institutes, and universities throughout the world have long been offering courses related to technical drawing, engineering graphics, and computer-aided design (CAD) at various levels of different programs. 3D printed prototypes are very common in the arts, animation, and fashion studies as well. 3D printing can provide a simple tool for illustration and visualization for students allowing them to grasp the concepts of their coursework [8] quickly. Not only in the design and prototyping courses where students print static prototypes but also in other classes involving the complex
movement of certain parts such as compressors and linkages where students suffer from visualizing the action at different instances. Hence, a 3D printed prototype with details involving these parts can solve this problem by providing a real-time simulation of the actual movement. Moreover, some courses, such as structural design and mechanics of materials, involve specific testing of materials and structures subjected to different loads. 3D printing can translate the problems discussed on the board by the instructor or even presented in the student’s textbooks into a live model that can be experienced by the students allowing them to see the behavior of these structures under specific loads. The printed model can even be tested in the laboratory for tension or compression, bending, buckling, or under a sophisticated type of mechanical loading. This work will be focused to discuss the application of 3D printing in the following courses:

A. Mechanics of Materials
B. Manufacturing processes

2. Innovation of Using 3D Printing Applications in Mechanics of Materials: Case Study

In general, students sometimes face a particular sort of difficulty in perceiving the mechanics of material cases, where understanding the actual behavior of the structure is not easy. Therefore, by translating the case study into physical structure would enhance the student’s grasp to overcome the imagination problem. Besides, engaging the students in assembling and disassembling the prototype will be a significant advantage to minimize the possible deficiency, uniquely combining both the 3D printed prototype with the actual bolts, nuts, and washers used in the structure. A problem from the mechanics of materials textbook [9] was selected as a case study in the course to be considered in this practice, where it is anticipated many lessons will be achieved through this case. Uniquely it blends many theoretical backgrounds like dealing with free body diagram, statics analysis, trigonometry, tensile and compressive stresses, types of the supports, etc. There is much commercial software available to be used for design purposes, like Autocad, Solid Works, CATIA, Fusion 360, and the online Autodesk Free software Tinkercad. Besides, STL, OBJ, AMF, and 3MF are the four most common 3D printer file formats, but there are many others [10]. The case was designed and printed by the instructor of the course [11]. A group of students that finished the geometric modeling course MECH 315 was nominated to develop and to build by 3D printing the case under the instructor’s supervision. The theoretical analysis of the case is depicted by the prototype made, it term of the geometry and the shape matching, and this helped the students to perceive the solution since it involves trigonometric analysis to find the angle of the rotation that will be used to calculate the extensions of the axial members at points A and C. Figure 1 illustrates a comparison between the theoretical case nominated from the mechanics of materials textbook and the 3D printed prototypes that show the similarity in the design.

![Figure 1. Comparison between the hypothetical case and the 3D printed prototype.](image)

Where:
- \( F_C \): Axial tensile force caused due to elongation of the vertical member connected with joint C.
- \( F_A \): Axial compressive force caused due to the shortening of the horizontal member connected with joint A.
- \( F_{Bx} \): Horizontal component of the force reaction in joint B.
- \( F_{By} \): Vertical component of the force reaction in joint B.
- \( v_C \): Vertical displacement of joint C.
- \( v_A \): Horizontal movement of joint A.

Structural components that are subjected only to tension or compression are known as axially loaded members. Bars with straight longitudinal axes are the most common type, although cables and coil springs also carry axial loads. Examples of axially loaded bars are truss members, connecting rods in engines, spokes in bicycle
wheels, columns in buildings, and struts in aircraft engine mount [12]. Axially loaded bars elongate under tensile loads and shorten under compressive loads. Unfortunately, most of the two-dimensional drawings don’t represent the real case studied, and this may cause difficulties to the students to grasp the idea behind the practice and sometimes causes confusion and leads eventually to a wrong solution. As an example, a hollow, brass circular pipe ABC supports a load P1 acting at the top [12]. A second load P2 is uniformly distributed around the cap plate at B. The diameters and thicknesses of the upper and lower parts of the pipe are d_{AB}, l_{AB}, d_{BC}, and l_{BC}. In contrast, the modulus of elasticity is E. It is observed from this case that the geometry details are not apparent to the students, especially if they did not take the engineering drawing yet. However, a 3D printed object that represents the case was constructive to overcome the confusion. On the other hand, some analyzed bars consisted of prismatic segments that may have different axial forces, different dimensions, and different materials. As an example, a non-prismatic cantilever bar has an internal hole of d/2 from 0 to x, so the net area of the cross-section for Segment 1 is (3/4)*A, as shown in Figure 2-a. The bar is subjected to an axial tensile load P at x, and another axial compressive load P/2 is applied at the end of the bar. The bar has a modulus of elasticity E that is constant along with the member. The problem was again to identify the geometry details, especially the depth of the bar. A designed model that represents the actual geometry was printed using 3D printed and used in teaching that was reflected positively on the students’ grasp. This is illustrated in Figure 2-b.

![Figure 2](image.png)

**Figure 2.** A non-prismatic axially loaded cantilever bar that contains a hole (a), 3D printed design for the bar (b).

A composite structure system that contains embedded elements, like reinforced concrete and other applications, is another challenge that is usually faced in teaching the mechanics of materials. As an example, a cylinder and a tube are compressed between the rigid plates of a testing machine by compressive forces P [12]. The steel cylinder has cross-sectional area A and modulus of elasticity E, the copper tube has area A and modulus E, and both parts have length L. In order to solve the problem, the student must imagine the free body diagram of the composite structure, which is a difficult task since the imagination level varies from a student to another. Therefore, printing a 3D model by the 3D printer, this will diminish the imaginary weakness of some students. Besides, the students will have better images to deal with the deformation of the composite system, since they are going to test the experience of assembling and disassembling of the composite structure themselves. Accordingly, at the next stage of the solution, they will have to imagine how both elements will have the same axial shortening. This structure is classified as statically determinate since the numbers of the unknowns are more than the equations available. To analyze such arrangements, we must supplement the equilibrium equations with additional equations pertaining to the displacements of the structure. A knuckle joint is used to connect two rods that are under the action of tensile loads (Figure 3). However, if the joint is guided, the rods may support a compressive load. A knuckle joint may be readily disconnected for adjustments or repairs. It has many applications such as it may be found in the link of a cycle chain, tie rod joint for roof truss, valve rod joint with the eccentric rod, pump rod joint, tension link in bridge structure and lever and rod connections of various types [13]. The knuckle joint example is a typical case that is used in the machine design course since it has many failure modes that students need to understand them one by one. Due to the complexity of the knuckle joint, students always encounter difficulties in imagining the failure mode of the individual components; moreover, how the forces transfer through parts to cause the failure. Both the 3D printed model, as well as figures, are necessary to convey the concept of the failure mode to the student. An open-source website [14] was selected to get and to print the parts from a 3D model of the knuckle joint, as illustrated in Figure 3. The students later asked to participate in the assembling process of the elements and to practice the assembly process that had a positive impact on the students’ understanding.
3. Innovation of Adopting 3D Printing Applications in Machine Design Course

A new assembly training approach based on 3D printing technology was proposed since the assembly is an essential aspect of the manufacturing process. An efficient operation would be achieved through suitable assembly training. Al-Ahmari et al [15] proposed an approach to compare existing assembly training methods, including conventional drawing and virtual reality. A 3D printing approach was adopted of a product to evaluate and validate the suggested product. The training performance is assessed for 25 participants using the three-assembly training plan, and it was estimated based on the completion time of assembly task, number of assembly errors, number of frustration points during the job, and completion percentage. It was observed that the 3D printed model performed better than the other two conventional methods. The results also illustrate that there is no significant effect from the 3D model scale variation on the assembly training performance. Teaching mechanical engineering course can be enhanced through using 3D printing capabilities, where students become more excited and enthusiastic when allowed to use 3D printing technologies freely in their course work [16], therefore it is the instructors’ responsibility to integrate 3D printing in their course through engaging the students into different activities, starting from research and ending with dealing with open-source 3D printers [17-19]. For teaching machine design and manufacturing lab Mech440, an innovative approach was adopted to stimulate the students toward using 3D printing technology prior the midterm, where a pre-midterm task was delivered to them to design and to build a fixture that can be used to hold and to measure the dimensions a manufactured part. The main objective of the exercise is to consistent repeatability of the measurement since it is essential to calculate the process capability of a traditional milling process as well as CNC milling machine, where the students will collect the measured dimensions to estimate the process capability of the manufacturing process statistically. The evaluation criteria were simplicity, accuracy, measurements repeatability. Students were given two weeks to complete the task. The first stage was to use brainstorming to address innovative solutions that would match the task requirements. Then a detailed explanation should be presented for the prototype that has been done by using CAD software. This part was designed as a holder, it's the base of the product which aim to hold the Vernier caliper into the two small triangles with depth of 10 mm, and the desired piece the can be fit in three inserts in the square shape with 10 mm depth also so that the part can be measured as efficiently as possible, as per instructions, The holders were designed in Y-shape with two different sizes, that should match with the base holder in the same place of the Vernier caliper by keeping a good clearance to maintain accuracy. However, both have the same function to perform the measurement, where the most significant size holder is used to measure the highest point, whereas the smallest holder for measuring the lower parts. The inserts in Figure 4 are designed in three shapes with depth 5 mm to fit the workpiece in all directions so it can be measured to get the right dimensions of the piece, where the insert is going to mount by the base holder part.

Figure 3. Disassembled knuckle joint (a), Assembled 3D printed knuckle joint (b).

Figure 4. 3D printed holder with the inserts that used for measuring the dimensions.
4. Conclusion
The revolution of the 3D Printing technology has been implemented in the educational sector since the technology has been launched in the market. Although adopting 3D printing technology is fast as the development in the industrial area due to many reasons, but significant efforts have been made to implement the technology through the learning process for different levels. One of the educational applications where 3D printing technology has been implemented in mechanical engineering courses to highlight the contribution to integrating 3D printing technology for the courses in the mechanical engineering department of the UAE University covering the main experimental procedures where they integrated and implemented the 3D printing technology in the educational process. Eventually, by incorporating the 3D printing in the educational process would enhance the educational process including the intellectual properties [20-21] through building a functional 3D printed prototypes that would be tested and proved before manufacturing the full-scale system.

5. References
[1] Ahmed W and Yarub Al-Douri 2020 3D Printing of Ceramic Powder Technology Metal Oxide Powder Technologies: Fundamentals, Processing Methods, and Applications (ELSEVIER) Chapter 17.
[2] Ahmed W and Al-Douri Y 2018 Additive Manufacturing Technology for Nanoscale Applications: The Revolution of 3D and 4D Printing Technology in Nanoscale Applications Meeting on Nanotechnology: Principles and Applications University of Malaya (UM) KL Malaysia.
[3] Aldarmaki A et al 2019 Designing and Developing Innovative Structural Engineering Failure Experiment Using Additive Manufacturing Technology Advances in Science and Engineering Technology International Conferences 1-6, doi.org/10.1109/icaset.2019.8714208
[4] Al-Shamsi A et al 2019 Assessing Commercial 3D Scanners to Reproduce Structural Elements Advances in Science and Engineering Technology International Conferences Dubai, United Arab Emirates.
[5] Awad A et al 2019 Designing an Innovative CubeSat Payload to Investigate Material Properties for UAE Space Missions Advances in Science and Engineering Technology International Conferences, Dubai, United Arab Emirates doi: 10.1109/ICASET.2019.8714273
[6] Ahmed W and Alhamad I 2018 3D printing innovations in UAE: Case study: Abu Dhabi summer challenge 2017 Advances in Science and Engineering Technology International Conferences, Abu Dhabi 2018 doi: 10.1109/ICASET.2018.8376924
[7] Alhamad I et al 2019 Boosting Teaching Experience in Mechanical Engineering Courses Using Additive Manufacturing Technologies Advances in Science and Engineering Technology International Conferences (ASET) Dubai, United Arab Emirates.
[8] Coakley M and Hurt D 2016 3D Printing in the Laboratory Journal of Laboratory Automation, 21(4) 489-495. doi: 10.1177/2211068216649578
[9] Philpot T 2013 Mechanics of Materials: An Integrated Learning System (3rd e.). Wiley.
[10] Girroir J 2018 3d-printing file formats must evolve with the industry Machine Design.
[11] Ahmed W 2019. Retrieved from https://eng.uae.ac.ae/en/departments/eru/profile.shtml?email=w.ahmed@uae.ac.ae
[12] Gere J and Goodno B 2009 Mechanics of materials (7th ed) Cengage Learning.
[13] Khurmi R and Gupta J 2005 A textbook of machine design. New Delhi: Eurasia Publishing House.
[14] Open Source STL files 2020 Retrieved from https://grabcad.com/library/knuckle-joint--1
[15] Al-Ahmari A et al 2018 Evaluation of 3D printing approach for manual assembly training. International Journal of Industrial Ergonomics 66, 57-62. doi:10.1016/j.ergon.2018.02.004
[16] Alhamad et al 2019 3D Printing Applications in Mechanical Engineering Education 3D Printing Applications in Mechanical Engineering Education. Leiden, The Netherlands: Brill | Sense. doi: https://doi.org/10.1163/9789004451513_006.
[17] Mansour A et al 2020 Evaluating the 3D Printing Capabilities Oral Case Studies International Conference on Industrial Engineering and Operations Management (IEOM) Dubai, 2020.
[18] Ahmed et al Open Source 3D Printer: A Case Study International Conference on Industrial Engineering and Operations Management (IEOM) Dubai UAE.
[19] Al Khawaja H et al 2020 Investigating the Mechanical Properties of 3D Printed components, Advances in Science and Engineering Technology International Conferences (ASET) Dubai, United Arab Emirates.
[20] Ahmed W and Aziz M 2020 Educational system and method for teaching mechanical failure US Patent and Trade Marks Office US10580322B1.
[21] Ahmed W 2019 Toothpaste cap with dental care tools US Patent and Trade Marks Office US10399747B2.