Enhancing Mechanical Engineering Education with an Integrated 3-D Printing Approach

Jingyu Wang, University of Oklahoma

PhD candidate at OU

Noah C. Golly, University of Oklahoma

undergraduate research assistant, School of Aerospace and Mechanical Engineering, University of Oklahoma

Mr. Blake Herren, University of Oklahoma

I am a first year Ph.D. student in mechanical engineering at the University of Oklahoma. I graduated magna cum laude with a bachelor's degree in aerospace engineering in May 2018 from OU. I currently work as a TA and RA in a new additive manufacturing lab lead by my advisor, Dr. Yingtao Liu. As I start my career in research, I hope to enhance my creativity and learn to identify and solve problems within my field.

Mr. James Ian Macdonald, University of Oklahoma

Mr. Macdonald is a recent graduate with a bachelors in Mechanical Engineering from the University of Oklahoma's School of Aerospace and Mechanical Engineering.

Prof. Zahed Siddique, University of Oklahoma

Zahed Siddique is a Professor of Mechanical Engineering at the School of Aerospace and Mechanical Engineering of University of Oklahoma. His research interest include product family design, advanced material and engineering education. He is interested in motivation of engineering students, peer-to-peer learning, flat learning environments, technology assisted engineering education and experiential learning. He is the coordinator of the industry sponsored capstone from at his school and is the advisor of OU's FSAE team.

Prof. Yingtao Liu, University of Oklahoma

Dr. Yingtao Liu is an assistant professor in the School of Aerospace and Mechanical Engineering at the University of Oklahoma (OU). Before joining OU, he was an assistant research scientist in the AIMS center at Arizona State University from 2012 to 2014. His research expertise include the development, advanced manufacturing, and application of lightweight composites and nanocomposites, smart structures, non-destructive evaluation, structural health monitoring and prognostics.

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Abstract

Recent advances in additive manufacturing have allowed the integration of multiple mechanical engineering fields including design, materials, mechanics, and manufacturing, for enhanced experiential learning and education. This paper reports the education projects and programs being developed at the University of Oklahoma to improve undergraduate mechanical engineering education using 3D printing technologies and systems, emphasizing three core topics: design, solid mechanics, and manufacturing. The interaction of design, materials, solid mechanics, and manufacturing is carried out at two different stages: the coupon level and product level. At the coupon level, mechanical testing samples, such as dogbone samples, are 3D printed using the filament deposition modeling (FDM) method following ASTM standards. Nanoparticles, such as zinc oxide nanoparticles, are integrated within the 3D printed filament so that the mechanical properties of raw materials are tailored. By controlling the 3D printing parameters, the manufactured samples have various microstructures and mechanical behaviors. Standard mechanical tests following the ASTM standards are carried out to verify the variation of mechanical properties by controlling material formulation and 3D printing parameters. Students obtain hands-on experience in 3D printing and enhance their understanding of the relationship of manufacturing on structural properties and solid mechanics concepts. At the product level, students practice designing mechanical engineering systems by creating novel and complex engineering structures, such as artificial prosthetic hands, visualize their design by 3D printing, and finally assemble the printed parts into a final product. The design of parts and the selection of critical design parameters, such as tolerances, are critical to determine the 3D printability, ease of assembly, and functionality. The 3D printing parameters, such as nozzle size and printing direction, impact the quality and mechanical performance of the manufactured products. The testing of manufactured products provides detailed feedback to the design and 3D printing, which are useful for the design optimization and improvement in the following design and manufacturing cycle. Two groups of students are currently working on the artificial prosthetic hands and joints. This paper reports students' learning outcomes from both mechanics and component level and the interactions at both levels.

Introduction

Mechanical engineering education includes broad topics and courses, such as materials and mechanics, design, manufacturing, control, thermodynamics, and fluid dynamics that traditionally serve to prepare a large number of students. Currently, these topics and courses are taught separately in most mechanical engineering programs, in most instances, without demonstrating the connection of concepts and applications. Students can often learn to solve textbook problems, without deeply understanding the connection between various courses and fundamental engineering concepts. Therefore, although engineering curricula are well-designed and highly structured, a few research studies have reported that students who successfully completed the engineering education still faced challenges during the college to career transition [1, 2].

The advances of additive manufacturing technologies have provided a unique platform to integrate multiple mechanical engineering topics and courses to enhance both graduate and undergraduate education. Three-dimensional (3D) printing technology has been well-accepted as an additive manufacturing approach for fabricating a wide range of materials and structures in complex geometries directly from 3D models. Since 3D printing technology was first developed by Charles Hull in 1986 using the stereolithography (SLA) method, various additive manufacturing technologies have been developed, such as digital light processing (DLP), selective laser sintering (SLS), fused deposition modelling (FDM), material jetting (MJ), and contour crafting (CC) [3-10]. A broad range of materials can be employed by various 3D printing platforms. The most common materials include thermoplastic polymers [11, 12], continuous fiber reinforced composites [12, 13], nanoparticles reinforced composites [14, 15], ceramics [16, 17], and metals [18, 19]. Additionally, 3D printing involves almost all the key elements in undergraduate mechanical engineering education, including modeling and design, materials and equipment, and manufacturing and testing. Therefore, early introduction of 3D printing technologies to undergraduate engineering students and continuous involvement in 3D printing-related activities through in-class projects and undergraduate research projects can provide unique opportunities to improve students' understanding of abstract engineering concepts and improve problem-solving capabilities, resulting in enhanced problem-solving capability through experiential learning. Students are expected to be better prepared for the college to career transition.

In the School of Aerospace and Mechanical Engineering at the University of Oklahoma, faculty members are developing a series of in-class projects and undergraduate research opportunities to involve undergraduate engineering students in 3D printing related projects. All the projects are carried out at two different scales: the coupon level and product level. At the coupon level, students design and 3D print nanocomposite materials and testing coupons by integrating various nanomaterials and polymers. The students gain hands-on experience through processing materials, manufacturing FDM filament, designing 3D models for testing coupons, 3D printing all the coupons, and testing and analyzing experimental results following the ASTM standards. Students are able to gain experience in key mechanical engineering fields, including solid mechanics, materials, processing, and 3D modeling. Both sophomore and junior students are suitable for 3D printing projects since there are direct connections between the mechanics projects and their ongoing courses. The product level projects are prepared for senior students as individual undergraduate research projects. Clear design objectives and technical requirements are first given to students. Students have the opportunity to develop concepts and perform preliminary design using 3D modeling software, then optimize their design through an iterative design process by 3D printing the designed parts for assembly and testing. Although various design ideas, such as ground vehicles or four-propeller drones, can be used in the product level study, our current work is focusing on the design, 3D printing, and optimization of prosthetic hands using the underactuated mechanism for finger structures. Each project has been created to achieve certain educational goals. The overall schematic of these approaches is shown in Figure 1. Specific instructional objective of this research is to improve students' understanding of key mechanical design, mechanics, and materials and manufacturing concepts by 3D modeling and 3D printing of practical mechanical structures and products.

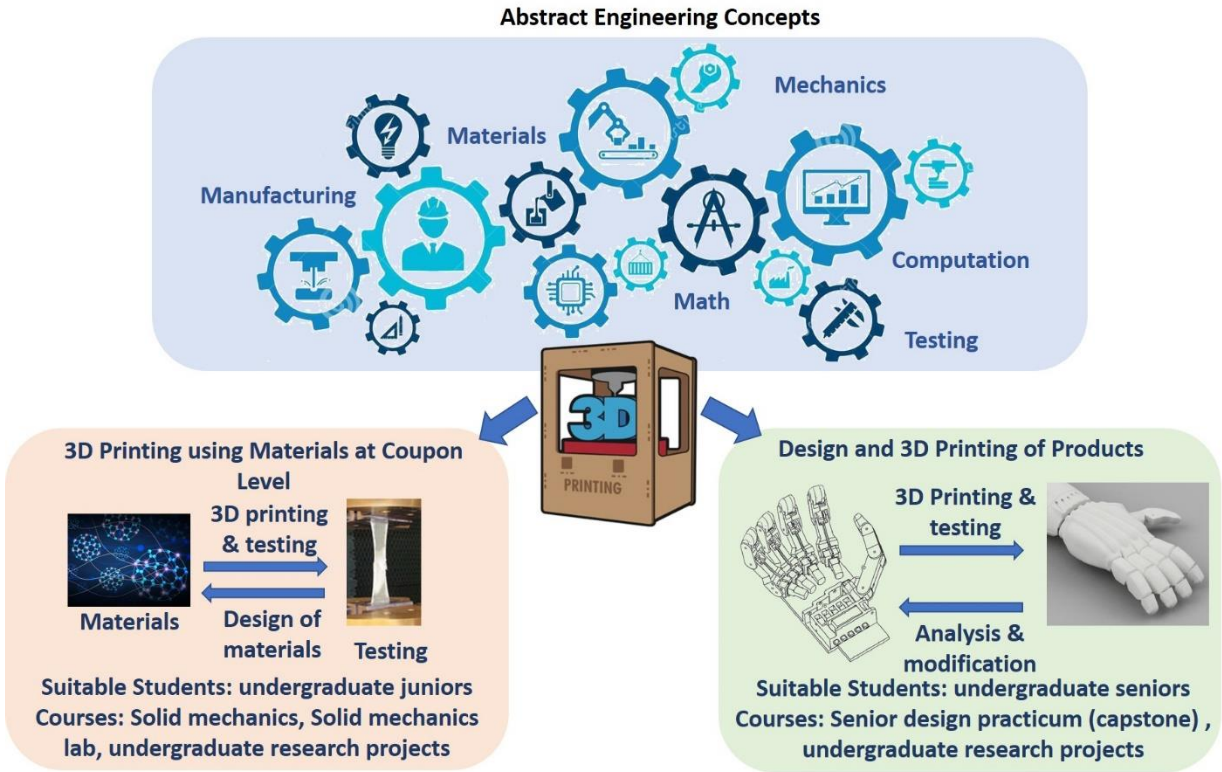

Figure 1. The schematic of mechanical engineering projects with integrated 3D printing approach for manufacturing and testing at coupon level, and for design and manufacturing at the product level.

Enhanced mechanics education integrating materials and 3D printing approach

Materials and solid mechanics are critical subjects for successful undergraduate mechanical engineering education. Current curriculum in mechanical engineering has provided adequate training through learning to solve textbook problems. Students are tasked with memorizing and understanding equations to know how to use the equations to solve given problems. However, engineering practice can be dramatically different from any textbook problems. Engineers need to know how to summarize a real engineering challenge into a series of questions and prepare solutions through subtasks. Integrating materials, manufacturing, and testing provides a unique opportunity for students to gain such experience. Since most engineering structures need to be built by materials with certain mechanical properties, students can encounter real challenges when trying to use certain materials to meet the given technical requirements. Through material processing, manufacturing, and testing, they can gain real experience to understand solid mechanics behavior and their relationship with materials processing procedure. The specific learning objectives are: (i) integrate materials' properties and advanced manufacturing methods to strengthen key mechanical properties of materials and products; (ii) improve understanding of key solid mechanics concepts.

In our study, we first design the 3D printing and nanocomposite materials testing as undergraduate independent research project. Faculty and students worked together to integrate polymers and nanomaterials, materials processing and manufacturing, and experimental solid mechanics in a 3D printing centered project. The goal is to provide hands-on experience to young undergraduate mechanical engineering students to enhance their understanding of materials, modeling, and testing. Therefore, the project objective given to the participating students is to identify the optimal nanocomposite formulation using thermoplastic polymers, including PLA and ABS, and zinc oxide (ZnO) nanoparticles. Students need to design a series of experiments to find which ASTM standards they should follow, what polymer and nanocomposites can be manufactured into FDM filament and efficiently 3D printed into coupons, and how to design 3D testing models and convert the models' geometries to G-code for 3D printing. Three junior undergraduate students participated in this project in the Fall 2018 semester as their guided undergraduate research projects. The three students worked together as a team to practice their collaboration and communication skills during the project period, as well.

The material fabrication procedure developed by the undergraduate students is shown in Figure 2. First, the selected thermoplastic polymers, including ABS and PLA, are ground into fine powders within a liquid nitrogen cooled environment. Since the glass transition temperatures of ABS and PLA are both low, the liquid nitrogen can efficiently cool the polymer to facilitate the grinding process. ZnO nanoparticles are mixed with the ground polymer powders and extruded into a filament for manufacturing testing coupons using an in-house modified FDM 3D printing system. Students solved several critical technical challenges during the materials preparation and 3D printing process: (i) identify an efficient way to grind large polymer pellets into fine powders; (ii) build an FDM filament extrusion system for filament fabrication and identify appropriate filament extrusion parameters; (iii) optimize 3D printing parameters to reduce visible voids in 3D printed testing coupons.

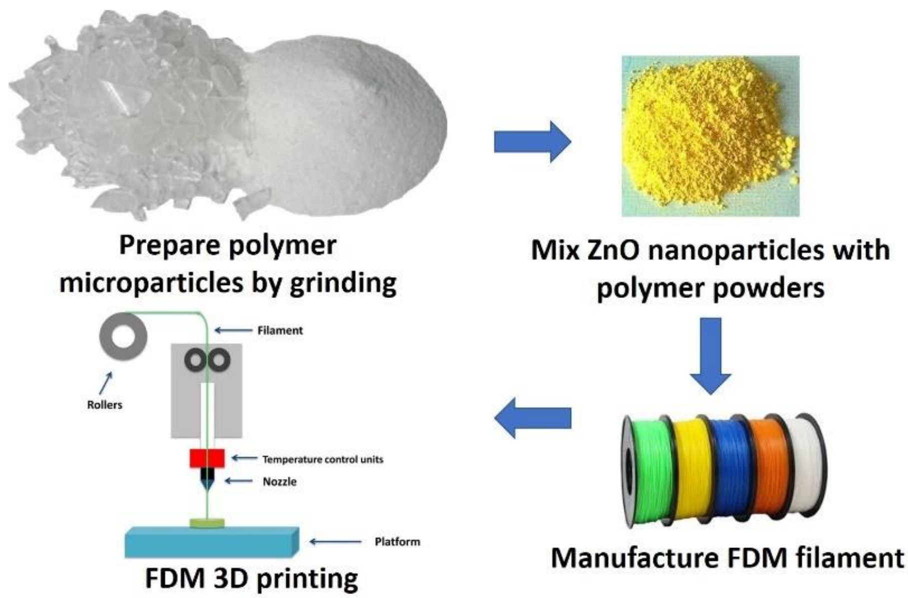

Figure 2. Schematic showing the material preparation and 3D printing process for the fabrication of nanocomposite testing coupon

Under the guidance of their faculty advisor, the students quickly learned how to identify the appropriate ASTM standard for 3D modeling of 3D printed testing coupons. ASTM D638

(Standard Test Method for Tensile Properties of Plastics) was followed by the students for the 3D modeling of coupons and identifying the exact testing procedure, including load rate and testing data processing procedure. The created 3D coupon model was used during the 3D printing process, as shown in Figure 3 (a). Students printed pristine testing coupon using pristine PLA and ABS filaments purchased online and in-house prepared nanocomposite filament. The 3D printed coupons are shown in Figures 3 (b and c).

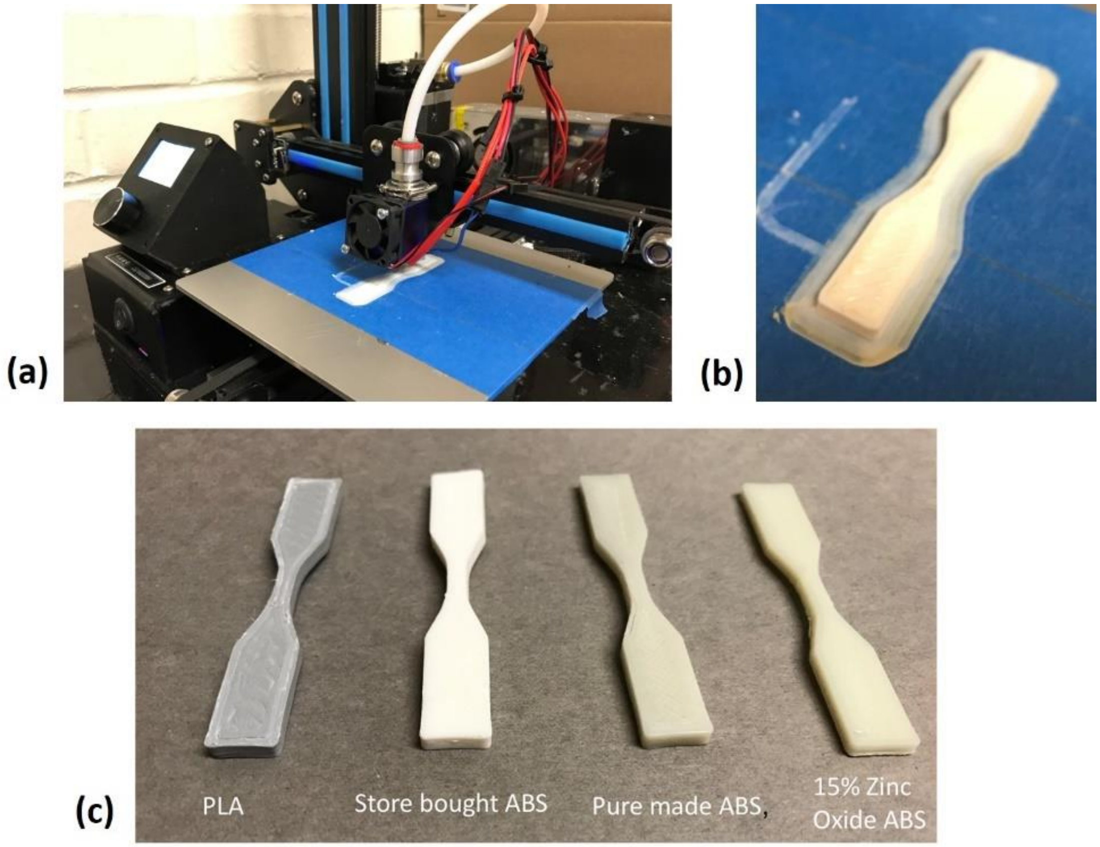

Figure 3. 3D printing of ASTM dogbone coupon: (a) 3D printing process using an FDM 3D printer; (b) 3D printed dogbone coupon; (c) 3D printed dogbone coupon using PLA, ABS, and ZnO nanoparticle enhanced ABS.

The mechanical testing and materials characterization were carried out following the selected ASTM standard. As shown in Figure 4, all the tested samples were clamped on an Instron dual-column mechanical tensile fixture and tested under uniaxial tensile load until fracture. All the samples were tested under quasi-static tensile load until fracture at the load rate of 3 mm/min. The obtained mechanical behaviors of the four types of materials are shown in Figure 5. Students learned to process all the testing data by converting recorded force and displacement into stress and strain relationship. Using their knowledge of mechanics, they were able to identify key mechanical parameters, such as ultimate strength, Young’s modulus, and the elastic and plastic range of the 3D printed coupons. The project results were closely related to their mechanics courses, such as Solid Mechanics and Design of Mechanical Components. Therefore, positive feedback was received from the students. More details will be discussed in the assessment of students’ learning outcome section in this paper.

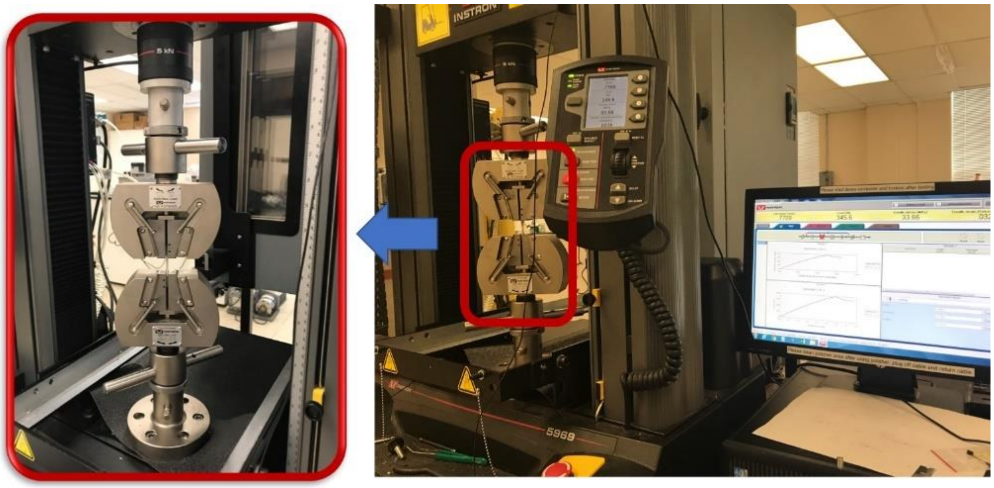

Figure 4. Mechanical testing of 3D printed dogbone coupon.

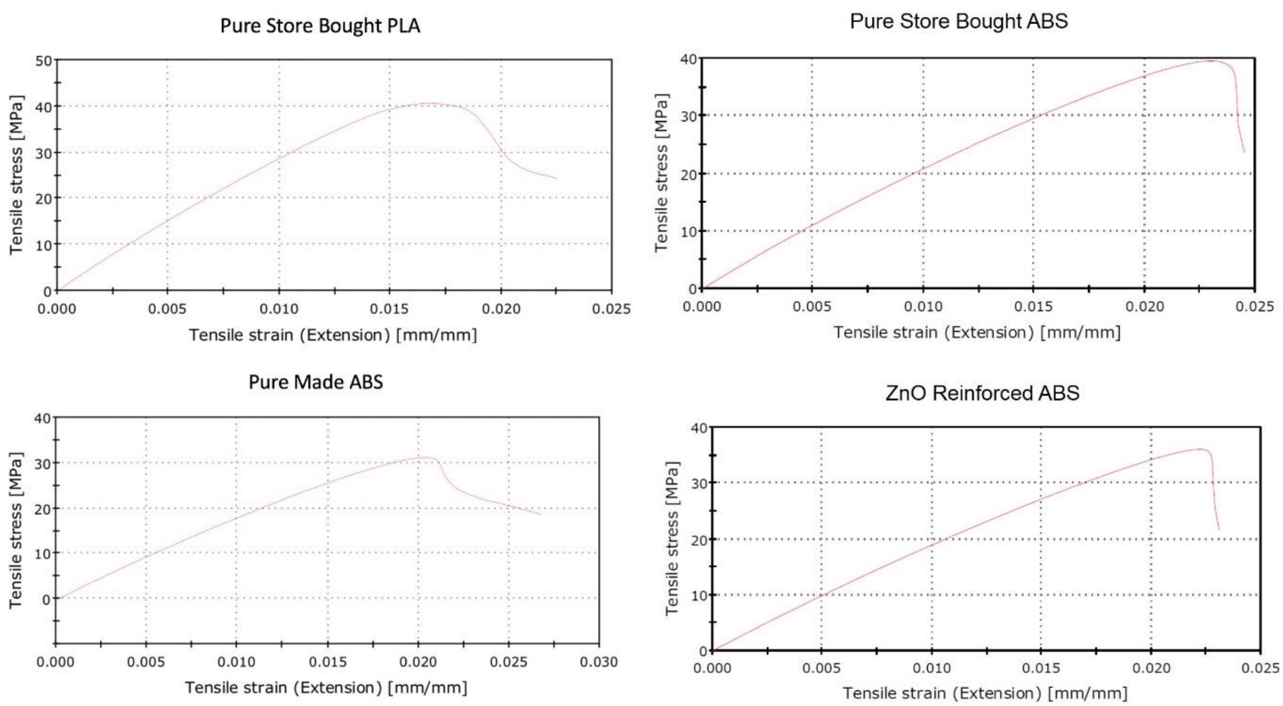

Figure 5. Mechanical testing results of four types of 3D printed coupons.

As shown in Figure 1, the 3D printing and materials testing project is suitable for junior undergraduate students when they study critical mechanics courses and as an independent undergraduate research project. In the last two years, the project has been carried out as independent undergraduate research projects for the senior students working in the authors' research laboratory. Under the detailed guidance, the undergraduate students were able to establish a solid understanding of the 3D printing process, and effect of nanoparticles on the overall materials' mechanical properties. In addition, the experience in mechanical testing following ASTM standards emphasized the solid mechanics knowledge the students learned in their junir year. Three students have participated in the reported undergraduate 3D printing and materials testing research. Positive feedbacks were given by the students in the final class evaluation and survey.

In order to benefit a broader range of undergraduate students and enhance mechanics education, the authors plan to integrate the reported 3D printing into his Solid Mechanics courses in Fall 2019. Except of using nanoparticles enhanced 3D printing materials, the low-cost pristine PLA and ABS filaments will be used for the 3D printing of samples following the ASTM standards. The authors plan to adjust key 3D printing parameters, such as printing direction, to tailor the strength and stiffness of the printed materials. Since both standard mechanical testing methods and theories are introduced in Solid Mechanics and Solid Mechanics Lab courses, the testing of 3D printed samples, such as dogbone samples under tensile loads, will imporve the students' understanding of critical solid mechanics concepts, such as stress, strain, and fracture. In addition, the relationship of 3D printing parameters and the characterized mechanical properties can be established, so that the students will have opportunities to obtain hands-on experience in solid mechanics and advanced manufacturing.

Design, 3D printing, and product development

Senior mechanical engineering students are heavily involved in mechanical and product design, particularly in their capstone projects. Well-trained senior mechanical engineering students should be able to sufficiently conduct complex engineering design and meet all the required design criteria. In our study, we created a design project focusing on the artificial prosthetic hand. The participating students were required to (i) design an under-actuated prosthetic finger with three degrees of freedom and one actuator; (ii) design a five-fingered prosthetic hand with 15 degrees of freedom and one actuator; (iii) provide reasonable grasping speed and force; (iv) 3D print, assemble, and validate the grasping functionality of the developed prosthetic hand. Four senior students completed the initial design, 3D printing, and testing of the underactuated prosthetic hand in a Senior Design Practicum (Capstone) project. Thereafter, one more student participated in this project in the Summer and Fall of 2018 as his undergraduate independent project. In Spring 2019, two more senior students are currently working on this project to create a new and improved version of the prosthetic hand as their senior guided undergraduate research project.

The concept of under-actuation mechanism was new to all the students in this project. The reason for employing under-actuation concept into the prosthetic finger and hand design is to simplify the finger and hand mechanical structures, but still providing a reasonable grasping function of the developed hand [20, 21]. Although multiple mechanisms including linkages and strings, can be used for finger design, the student first decided to use the combination of rubber bands and wires to obtain the under-actuation function of the finger. The first version of designed fingers and hand is shown in Figure 6. Rubber bands were installed at the backside of the finger and plastic wires were embedded in the fingers. Once the wire was pulled by the actuator, the finger was able to bend and enclose the objective. After the removal of the actuation load, the rubber band was able to pull the finger straight. Although the initial design met all the given design criteria, the students suggested that the rubber band be embedded into the finger to ensure the long-term performance. After more than 10 revisions, the student adopted the new under-actuation mechanism using torsional spring and plastic wire. All the springs and wires were finally able to be embedded into the designed fingers. Five identical fingers were connected to the palm of the prosthetic hand. The finalized hand was 3D printed and shown in Figure 7.

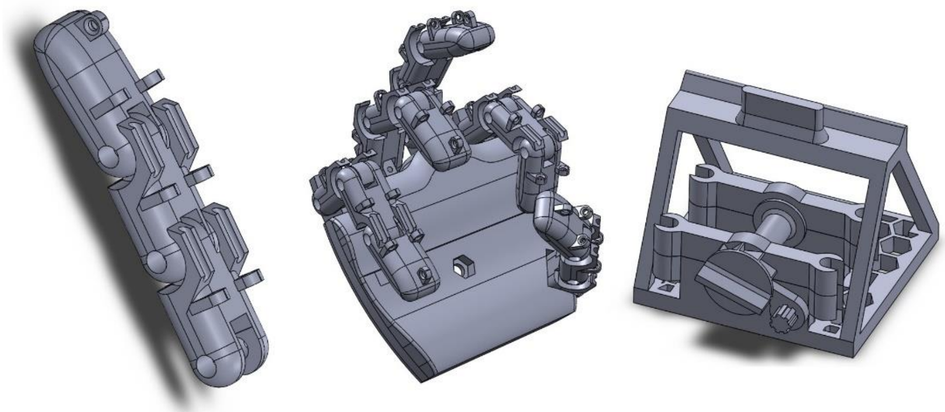

Figure 6. 3D model of the initial finger, hand, and base design

Figure 7. 3D printed prosthetic finger, hand, and string-driven bent fingers.

Preliminary testing of the 3D printed prosthetic hand demonstrated the grasping function of the designed hand. As shown in Figure 7, the fingers of the prosthetic hand were able to be controlled independently and used to enclose a given object. Even when the object had complicated shapes, the five fingers were able to fully grasp the entity and each finger was able to bend to various angles. Electrical motors can be installed to the base of prosthetic hand for accurate control of each finger.

Since Spring 2018, the design, 3D printing, and testing of prosthetic hands project has been offered both as senior design practicum (capstone project) and independent undergraduate research projects, and seven students have participated in these projects. The preliminary design of the prosthetic hand was completed by a capstone team of four students in Spring 2018. The capstone team first reviewed the most recent prosthetic hands published in the literature and proposed their own approaches. Various initial design concepts and preliminary finger structures were 3D printed, assembled, and tested before finalizing the design concepts, as shown in Figure 8 (a&b). The capstone team was able to summarize their design based on the product functionality, shape, materials and production (FSMP) plan. As written in their final report, "*the material and manufacturing process for the Underactuated Prosthetic Hand will follow the form of FSMP. This means that priority is given to product functionality when selection the materials and production method. Before the materials are selected, a product analysis for the Underactuated Prosthetic Hand was performed.*" This study outcomes closely matched with teaching goal of this project that was focused on the integration of design, materials, and fabrication in a single project to enhance the product development capability of senior undergraduate students.

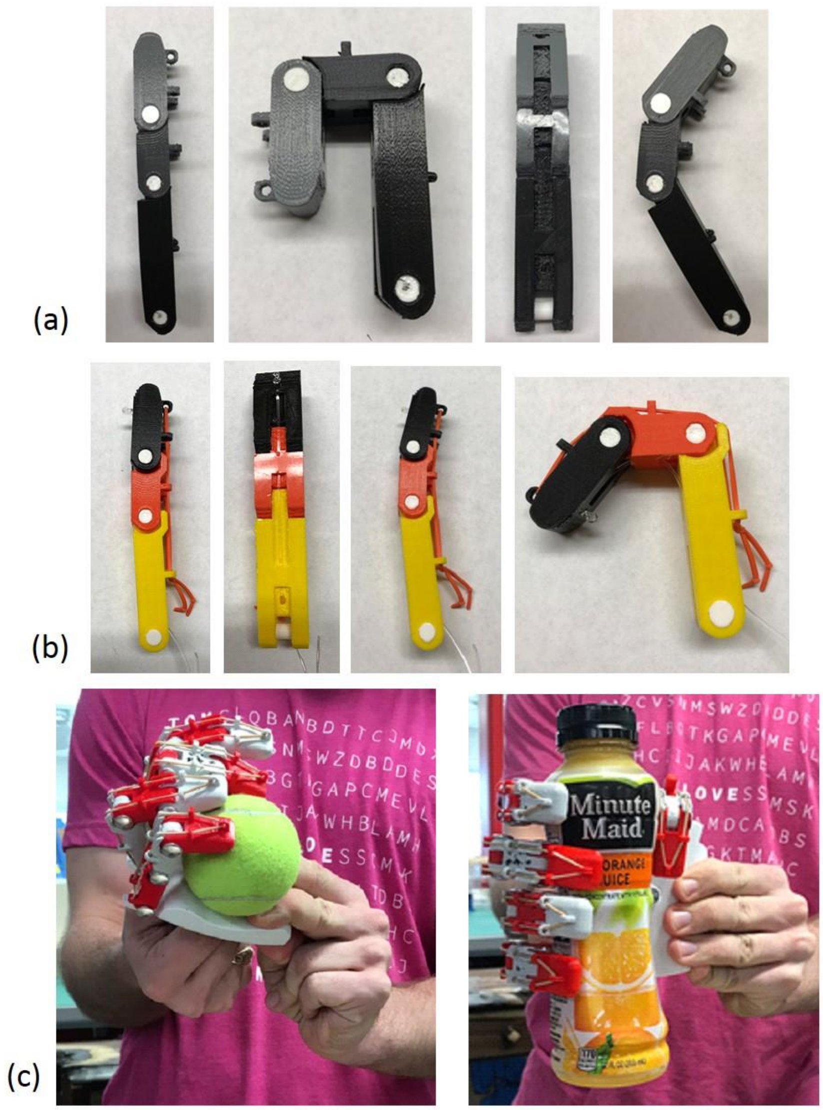

Figure 8. The various versions of 3D printed finger structures and grasping tests during capstone project, (a) the initial designed and 3D printed finger, (b) the optimized finger structure, (c) the testing of grasping capability of 3D printed hand.

The prosthetic hand design and 3D printing project was continued as independent undergraduate courses after the successful completion of the capstone project. Three senior students worked on the project during summer and fall 2018 semesters, and the modified hand designs were shown in Figures 6&7. Two new undergraduate senior students joined the project in Spring 2019. The students are currently modifying the thumb structure to optimize the initial position of the thumb to better mimic the bone and joint structures of a real human hand. The authors plan to work with undergraduate students to improve the hand design and enhance the grasping capability of the prosthetic hand. In addition, the project will be revised to better fit into students background and enhance the their learning outcomes.

Assessment of student learning outcomes

Evaluation and assessment of students' learning outcomes are critical for 3D printing related undergraduate research. Students learning outcomes should articulate what are the new skills the students learned during the research and training process. Although external evaluators are more appropriate, the current research and learning outcomes are still limited by internal and self-evaluation due to the lack of financial support.

All the assessment of student learning outcomes is evaluated by using: (i) bi-weekly reports submitted by students during the entire research period; (ii) final reports provided by the students after the end of research period; (iii) comparisons of generated experimental results with the published data and papers. Because learning objectives were given to the students at the beginning of the project, students were able to address each objective and discuss what are the new skills and experience they gained by the end of their project.

For the 3D printing of nanocomposites project, the final student reports showed that the students were able to use all the knowledge learned in a broad range of courses, including solid mechanics, modeling, and solid mechanics lab, to design experiments and analyze data. This experiential learning opportunity allowed the students to review a series of courses they took in the last two years and emphasize the fundamental concepts of each course.

With regard to the prosthetic hand design project, the student's reports showed a strong knowledge of mechanical design, particularly related to the 3D modeling using commercially available software. The 3D printing system used in this project allowed the students to quickly manufacture the designed parts and realize the drawbacks to improve their design through iteration. The cover page of the final report submitted by the 2018 Spring Capstone team is shown in Figure 9. Through more than 10 revisions to improve the quality of the designed hand, the students achieved good grasping capability with the developed hand. More complicated and reliable external assessment of students' outcomes will be carried out once a higher number of students participate in the two undergraduate research projects.

ISE 4393 / AME 4553: Capstone - Spring 2018

Underactuated Prosthetic Hand

Authors: David Doshier, Modi Elisa, Samantha Tran, Jacob Welch

Company: OU AME Department

Company Sponsor: Dr. Yingtao Liu

Faculty Advisors: Dr. Chris Dalton, Dr. Shivakumar Raman

May 3rd, 2018

Figure 8. Cover page of final report submitted by 2018 Spring capstone team.

Conclusions

This paper presented the projects and program being developed at the University of Oklahoma to enhance mechanical engineering education by integrating 3D printing technologies. The overall goal of this approach is to enhance students understanding of fundamental concepts in materials, mechanics, modeling, and manufacturing by providing hands-on opportunities to undergraduate students, aiming to improve their problem-solving capabilities. Two types of projects have been developed focusing on different education topics. With regard to materials and mechanics, the 3D printing and characterization of nanocomposite materials following ASTM standards were assigned to junior undergraduate researchers as a team project. Students were able to independently identify materials processing procedures and experimentally characterize the key mechanical properties of the 3D printed samples. Self-assessment of the students indicated that they were able to link their materials knowledge to solid mechanics knowledge and implement the relation of the two fields into their project. To provide a unique design opportunity, a prosthetic hand project was developed to allow students to create a novel under-actuated hand structure. One student completed the first version of the prosthetic hand design using a torsional spring and plastic wire mechanism. The 3D printed hand demonstrated the functionality of a hand but still left potential opportunity to further improve the hand's function by optimizing the thumb joint. Self-assessment of the learning outcomes indicated the effectiveness of this study to enhance mechanical education. Once the dataset of student learning outcomes is large enough, we will look for a more reliable external evaluation of our study.

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