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MAKER: A class project on the design and fabrication of a 3D printer for delivering food at the point-of-care for addressing food insecurity – Manufacturing for social purpose

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MAKER: A class project on the design and fabrication of a 3D printer for delivering food at the point-of-care for addressing food insecurity – Manufacturing for social purpose

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Abstract

This paper presents the results of the project-based education method adopted as a part of an undergraduate level additive manufacturing class for applicability towards a social problem. Additive manufacturing or 3D printing is a technology that allows the manufacturing of parts layer-by-layer in a bottom-up approach that has advanced to manufacture parts using various types of materials including metals, ceramic, and polymers. A relatively recent and still emerging area of research is to explore 3D printing techniques for food manufacturing or 3D food printing (3DFP), which was the focus of this project assignment.

Over the past few years, food insecurity is a widely recognized challenge across US college campuses. USDA defines food insecurity as "limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways". Various reports indicate that about 20-40% of students face food insecurity and hardship during an academic year in 2-year and 4-year colleges with affordability and accessibility of nutritious meals being one of the primary reasons. Through the principles of additive manufacturing, 3D Food printing could offer a possible solution to food insecurity across the college campuses through 1) customization of nutritious food, and 2) ability to provide on-demand, on-site delivery of ready-to-eat food at point-of-care.

The class project specifically focused on the design, development, and prototype testing of a 3D food printer. The class was segmented into four groups with 5-6 students per group. Students were given detailed guidance in terms of a project rubric that discussed the motivation behind the project and outlined the boundary conditions that the food printer design should abide by. These included constraints such as print size, the requirement of an all-mechanical design (no electrical components), and a limit on the number of parts to be designed. Almond butter-based nutritious ink composition was the food ink to be printed for delivery. To encourage student engagement within the groups, each student oversaw a specific component of their group's food printer design. Students were encouraged to utilize 3D printing resources on campus to print their designs and build a working prototype of their designs. After the formulation stage (by the end of six weeks), one lecture period per week was dedicated to the discussion of the class project where every group presented their progress update and receive appropriate feedback from their peers and the teaching team. The final presentation was in the form of a PowerPoint presentation along with an open house demonstration of the prototypes. Student feedback was collected mid-semester and at the semester end through surveys and questionnaires. The project was successful in delivering the hands-on component of the class where students applied their knowledge of additive manufacturing, material properties, and mechanical design (part of a course curriculum) for a societal benefit, through a hands-on experience.

1. Introduction:

Manufacturing subject is an important aspect of a mechanical engineering undergraduate curriculum. As the manufacturing techniques have advanced over the years, the curriculum has also evolved to include many special topics and elective courses focusing on covering advanced manufacturing, design, and materials research. This includes courses focusing on rapid prototyping, non-traditional machining, nano and micromachining, microelectromechanical systems, nanotechnology and nanomanufacturing, and in recent years various aspects of additive manufacturing [1]. These topics are essential for exposing undergraduate students to advancements within the field and building their necessary skillset for their future careers. Due to the cutting-edge nature of many of these topics, a hands-on project experience is important to complement classroom-based learning for retention of knowledge and at the same time addressing a social cause. This paper presents the results of a semester-long class project as a part of an additive manufacturing and research credit class in Fall 2021. Specifically, the project was aimed at increasing student awareness of an important social problem of food insecurity while also allowing students to learn about 3D food printing under severe resource constraints to challenge creativity in a structured class through the principles of frugal engineering. Frugal innovation/frugal engineering can be understood as a solution developed under severe resource (space, time, capital, etc.) constraints to enable affordable and accessible product/solutions for wider dissemination and equity [2]–[4]. This is especially relevant after the COVID-19 pandemic, where severe disruptions challenged the resiliency and sustainability of supply chains and consumer products [5]–[7] and put social challenges such as food insecurity to the forefront.

Food is one of the three basic needs of life and yet several families and especially students across college campuses are increasingly going hungry. USDA defines food insecurity as *"Limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways"* [8]. Recently, several reports focused on 2-year and 4-year college students reported about 20-40% of the students face food insecurity across the US college campuses [9]–[13]. Lack of affordable/nutritional options coupled with the rising college fees results in students choosing between tuition and food [14]. US Government Accountability Office (GAO) report [9] also highlights the fact that in several cases, either due to ignorance or due to psychological roadblocks, students often do not utilize the benefits available to them on the college campuses such as a food pantry service or Supplemental Nutrition Assistance Program (SNAP). Food printing (also known as 3D food printing) offers a possible engineering solution to tackle the problem in a form of customized, nutritional, ready-to-eat food. These food options can be delivered asynchronously, on-demand, and at a point of care and were the overarching theme of the class project. The following section discusses the structure and execution of the class project followed by the discussion of student feedback and instructors' reflections. The uniqueness of this exercise was at the nexus of traditional additive manufacturing/3D printing class, increasing awareness of a social cause on-campus/peers, and experiential learning through the application of frugal engineering. The following sections discuss the details of the class and the hands-on project along with results and discussion.

2. Details of the class and the project:

Class framework

The additive manufacturing (AM) class was an elective course consisting mainly of students in mechanical engineering at the sophomore/junior level. The goals of this class were – 1) to develop foundations for materials, additive process fundamentals, and testing, 2) develop an understanding of processes and equipment for AM, and 3) implementation of AM for product applications. The first two goals were addressed using classroom discussions, weekly quizzes, and exams. The class covered a variety of topics relevant for AM including details of various AM processes, design for AM, materials-process-properties relationship in addition to guest lectures covering application-specific recent developments within the field. During the instructor's prior experience with teaching an AM class, it was observed that retaining the knowledge was challenging especially with virtual and hybrid modes of learning as a result of the COVID-19 pandemic. A hands-on project (as an experiential learning method) was thus implemented in this class to allow students an opportunity to work as teams on a specifically targeted problem on the theme of social innovation related to food insecurity, as college campus citizens.

The project was structured around three key aspects – 1) increasing awareness about food insecurity among college students, 2) engineering and design approaches for food printing as a possible solution towards addressing food insecurity, and 3) creating a 3D food printer prototype under severe boundary conditions. Food printing is a relatively recent and still emerging area of research for food additive manufacturing [15]. A common way of 3D printing food involves the use of food in the form of slurry that can be extruded through a syringe-type mechanism on a platform to create various shapes and sizes as desired [16]–[20]. The project was chosen to incorporate aspects of AM processes towards a common goal while at the same time encouraging students to innovate their creative designs/approaches within the specified boundary conditions as discussed below.

Project details and execution:

The class project contributed to 20% of the student's final grade. The class was segmented into student groups with 5-6 students per group. A detailed rubric was provided to students as a 'guidance' for project planning for execution and final report submission. Table 1 shows the scoping and details of the timeline for the project. The project was introduced to students during weeks 2 and 3 of the semester. The discussion during the initial weeks was to introduce the subject area, the motivation behind the project/introduction to food insecurity, group formations, and logistics. From then onwards, one class period per week was dedicated for the discussion relevant to the project for advancement towards timely completion. Student groups were asked to present their weekly progress update during this period and were given feedback for directions and improvement. During weeks 7-8 (about halfway), students were asked to submit a mid-semester project report. The purpose behind this report was to get everyone aligned on their project outline and to avoid last-minute changes and rush. Additionally, this report served as a working document towards their final presentation. The final project report was submitted at the end of week 15 for grading. During the same week, student groups demonstrated their prototypes in an 'open house' session for food printing. Details of the engineering design framework of the project are discussed below.

Table 1: Project scoping and timeline

Week	Project schedule
Week 2	Project: Introduction
Week 3	Project: topic identification
Week 4	Project: Topic literature review
Week 5	Project: Project statement and task-timeline planning
Week 6	Project: Design and Materials
Week 7	Project: Mid-semester project report submission
Week 8	Project: Materials and process(s), evaluation of reports for feedback
Week 9	Project: Fabrication and testing
Week 10	Project: Fabrication and testing
Week 11	Project: Fabrication and testing
Week 12	Project: Fabrication and testing
Week 13	Project: Improvisation and optimization
Week 14	Project: Writing Report (ppt) writing
Week 15	Project: Final ppt report submission and presentations with demo
Week 16	Project evaluation and related project grades will be posted

Figure 1 outlines the key project parameters including the project objective, intended goals, and boundary conditions. To account for the fact that such a solution can be potentially applied at remote point-of-care locations where electricity may not be readily available/easily accessible, the students were asked to make their design fully mechanical and not rely on electrical power/motors. This also helped to reduce the number of interfaces that students must design. The rationale behind reducing the number of critical interfaces was to increase the simplicity and robustness of the design, aligning with the frugal engineering principles for operating under severe resource constraints. Furthermore, this also ensured that each student from the group actively participated in the project, as the number of components was ideally set at 6 (one design component per student). The final assembly of the prototype was expected to demonstrate the extrusion of almond butter ink on a cookie substrate within the specified dimensions. During the weekly updates, each group brainstormed the ideas for their design (specifically the mechanism of extrusion and substrate translation concerning the nozzle) for discussion, improvements, and execution. The components were built using FDM 3D printers available on campus and assembled to create the final working prototypes. During the last week of classes, each student group submitted the final project reports and presented those to the class (20 min presentation + 5 min Q/A). The class projects were graded based on the depth of the presentations and the completeness of the final project reports. Even though not counted towards grading, all four student groups demonstrated their final assembled prototype mechanisms during the open house session, attended by a wider audience.

GIVEN PROJECT PARAMETERS (BOUNDARY CONDITIONS)

- Subject: Design 3D food printer for ready to consume food at the point-of-care
- Addressable societal problem: Food insecurity on college campus
- Project to be conducted in a team of 6 students in the class (exception needs approval by the instructor)
- Printer and printed parts specifications:
  - Printer assembly will be of minimum 6 and no more than 7 parts
  - Each part will be designed and prototyped using a plastic 3D printer by separate individual teammate from a group of 6 students.
  - Assembly will be performed and tested by the team
  - Parts of the printer: dispenser (print head), substrate table (printer platform), delivery mechanism (remove printed sample away from dispenser for delivery) and cleaning dispenser.
  - Operation: completely manual mechanical only (no electricity required)
  - Material to be deposited: Almond butter base ink
  - Substrate (a cookie): a minimum 3.5-4 inches
  - Capacity: Print on 2 and maximum 3 cookies in one fill of dispenser ink nozzle.
  - Design to print: “P” (minimum height 1.5”)
  - Evaluation criteria for printer parts: creativity, simplicity of design, and tolerances of printer assembly for functionality
  - Evaluation criteria for printed parts: Uniformity of printed ink in x-y dimensions, surface smoothness of a printed trace and continuity and integrity of printed letter

Figure 1: Project specifications and boundary conditions.

3. Results and discussion:

Prototypes and instructor’s feedback

Figure 2 shows the prototypes created by the students that were used for printing during the open house sessions. Three out of four groups (images 2(a)-2(c)) completed their final prototype assembly with ink extruded on the surface of the cookies while one group (image 2(d)) demonstrated the extrusion mechanism without the full assembly. The key operating principles of the prototypes are succinctly discussed below:

Figure 2(a): The prototype included a syringe-shaped nozzle to hold the ink that was extruded through a food-safe stainless-steel nozzle (shown by II in the picture). The group made use of a piping bag inside a 3D printed nozzle to ensure that the food does not come in direct contact with the plastic during dispensing. The food was extruded through the movement of the plunger in a nozzle controlled using the lever on top (shown by me in the

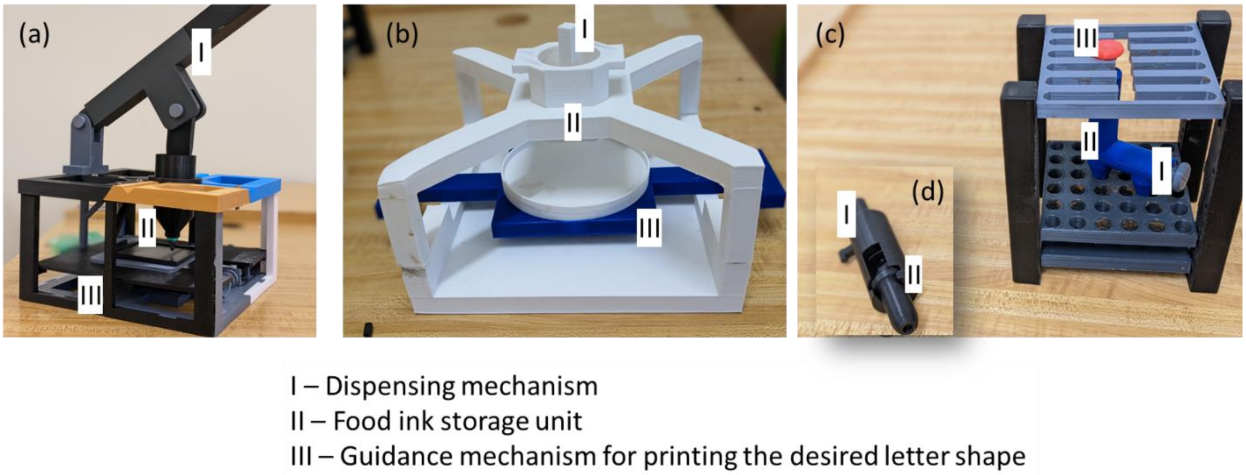

Figure 2: All-mechanical food printer prototypes.

picture). The bottom assembly (III in the picture) had the guidance track in the shape of 'p' (not visible in the picture) housed with a string. The movement of the substrate was achieved through an interaction of the rotating arm with the guidance string.

Figure 2(b): This prototype included a spider-like frame to support the extruding mechanism and the nozzle. The food ink was contained in a cylindrical container (II) fitted with a circular steel nozzle at the bottom. The plunger (I) on the top was pressed to extrude the ink. The blue arms (III) on the bottom were used to move the cookie placed on the circular substrate holder which was placed in a 'p' shaped guidance track.

Figure 2(c): This prototype utilized a concept similar to a dot matrix printer to achieve the desired shape. The blue-colored hollow tube (II) was used to periodically fill and dispense food ink by using the piston assembly. The assembly was lifted and moved along the dots using the guidance tracks (III) placed on top of the frame. Once the assembly was moved to the desired spot, the piston was pressed to dispense the ink onto the cookies kept underneath the dotted frame.

Figure 2(d): The dispensing mechanism for this partial prototype included a series of threaded screws to translate the rotational motion from the top (I) to drive the piston within the circular tube (II) to dispense the ink. This unit was intended (not assembled in the final prototype) to be housed in a guidance track on the outside frame to move the nozzle for printing the desired shape.

Through the completed report, presentations, and demonstration, the instructors evaluated that the student groups invested desired time and worked well as teams for the completion of the project. Additionally, all the teams took different approaches to develop the extrusion and guidance mechanism for their prototypes, as discussed above. Overall, it was observed that the students followed the timeline, used the feedback to improve their final designs, and submitted a well-formulated project report. It was also observed that the student teams appreciated the importance of 'design for additive manufacturing using design iterations to include lattice structures for weight reduction, use of infill percentage during a 3D printing operation to save print time, and need to tolerancing to ensure the effective assembly of parts. It was also noteworthy that during their final presentations in class, all the student groups spent time discussing food insecurity on college campuses. At the end of the semester, students were asked to fill out a survey to reflect on their learning from the class with specific questions targeted towards analyzing the roles of a class project in the class. The results of this survey are discussed below.

Student's feedback

At the end of the semester, students were asked to provide detailed feedback on the class structure, overall learning, and their experience with the project. The questions were disseminated through a class survey and the questions were formulated to have short responses as opposed to multiple-choice or Likert scale questions. The reason behind this was to receive constructive feedback as well as criticism from the students for future improvements to the class project. The survey was completed by 20 students from the class of 23. Specific to the class project, the questions gauged different aspects of students learning/feedback as discussed below:

1) Student's learning through hands-on project work in terms of technical and soft skills:
   - The question asked students to list 2 technical learning/skills and 2 soft skills each. Hands-on experience with 3D printing, CAD software, and design for AM, tolerancing of parts were the most common responses for technical skills. While for soft skills, working as a part of a team, coordination, time management, and planning, presentation skills were the common responses.

2) If and how the project helped them to retain AM knowledge:
   - For this question, the majority of students responded positively with working with 3D printers, designing for 3D printers and assembly were the most common responses.

3) If and how the project complemented the structured classroom learning through simple designs for frugal engineering:
   - Overall, a majority (15/20) of the responses indicated that the class project satisfied the purpose of complementing classroom learning. While few students (3/20) mentioned felt the project did not meet the expectations in complementing the classroom learning. The remaining two responses were mixed/neutral. Some of the representative responses from these categories are listed in Table 2.

4) Awareness about food insecurity on college campuses:
   - The question asked students about highlighting one or two real facts about food insecurity on college campuses and students responded with a few relevant statistics as well as their personal experiences to indicate their awareness of the problem. Some of the common responses included 2019 statistics based on the report [11] published by the HOPE center. Few student responses provided food insecurity statistics in the state of Indiana based on the report and based on the

on-campus food pantry resource. Some students reported observing food security closely (either personally or through their classmates).

Table 2: Selected student responses related to the complementary nature of the class project

Met the expectations	Neutral/Mixed	Did not meet the expectations
"The in-class time really gave us time to set out to find what exactly what we want, and the more and more time we got to spend understanding how 3D printers work, we were able to find how best to design our parts to get the functionality we wanted while being compatible to easy printing/"	"This project helped me to apply the various control methods of printers that we learned about in class with the added challenge of being fully mechanical. There was a disconnect while learning the academic material because of the expensive and complex nature of the machines we had been learning about. By making a simple and cheap machine I was better able to understand the class material."	"The structured classroom learning allowed me to learn the different kinds of AM and the benefits of each. I was able to use the knowledge of AM limitations to better design parts. Also, I learned that designing simple parts often eliminates many assemblies and decreases later manufacturing costs. However, most of the processes that we learned about in the lecture did not directly correlate to many aspects of our specific design project. So, we learned supplemental information on top of the project."
"I believe that this project helped realize and visualize like the real-life application of the theory part that we learned in class. Instead of just having knowledge, we were able to actually experience."	"I feel that our team struggled a ton with minimizing the number of parts and fasteners that we had, but I feel happy with the final product we achieved. I feel this is a useful design frame of mind to have."	"The class learning material was based on the entire AM industry while our project just focused on using one type of printer and material which also happened to be the most commonly used printer and material. Meaning we did not get to experience a new AM process through this project."
"This project forced me to think in ways I had not for previous projects to come up with a solution that fit the simple and frugal criteria. The knowledge initially taught during lecture helped compliment the project development and serve as a source for ideas."		"I felt like there was a disconnect with this topic. We spent much more time in class talking about the other AM topics besides the PLA extrusion that we used for our project. I would have appreciated more discussion on the FDM process and even some more in-depth instruction on the specifics of operating the available printers.

Additionally, students' feedback on the overall course and course objectives was collected through the semester-end course evaluations and students shared positive responses for the overall objectives of the class, class projects, and assignments/tests as suggested by the statistics presented in Figure 3 below.

The assignments aid me in achieving the class objectives.					
Response Option	Weight	Frequency	Percent	Percent Responses	Means
Strongly Agree	(5)	5	23.81%		3.90
Agree	(4)	10	47.62%		
Neither Agree nor Disagree	(3)	5	23.81%		
Disagree	(2)	1	4.76%		
Strongly Disagree	(1)	0	0.00%		
				0 25 50 100	Question

Response Rate	Mean	STD	Median
21/23 (91.30%)	3.90	0.83	4.00

The projects or laboratories aid me in achieving the class objectives. [where relevant]					
Response Option	Weight	Frequency	Percent	Percent Responses	Means
Strongly Agree	(5)	8	38.10%		4.14
Agree	(4)	10	47.62%		
Neither Agree nor Disagree	(3)	1	4.76%		
Disagree	(2)	2	9.52%		
Strongly Disagree	(1)	0	0.00%		
				0 25 50 100	Question

Response Rate	Mean	STD	Median
21/23 (91.30%)	4.14	0.91	4.00

Figure 3: Project and assignment-related questions from the course evaluation results.

4. Summary and conclusions:

A hands-on class project was implemented in an introductory level additive manufacturing (AM) class. The intention was to complement the in-class learning with an exercise that students can learn, build and implement 3D printing to fabricate a 3D food printer prototype. The project was based on a socially conscious concept to introduce students to the growing problem of food insecurity on college campuses as motivation while delivering a potential solution to address the issue as a point-of-care solution that operates solely on mechanical power. The project was conducted in teams where students also learned to implement project planning, teamwork, and communication skills (through the class presentations and reports). Through the presentations and feedback, the class project achieved its objectives of introducing the subject of food insecurity to students and allowing them an opportunity to implement simple designs in their prototypes. The restriction of having no electrical parts as a boundary condition specifically resulted in innovative and frugal engineering design concepts as observed during the demonstrations. The feedback received from the students will be useful in further improving the structure and organization of the class projects in future semesters for enabling socially conscious frugally engineered designs.

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