3D Food Printing Insights and Opportunities: A Capstone Design Case Study

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Abstract

Additive manufacturing currently plays a key role in driving the expansion of the maker movement and has contributed to the development of 3D printers capable of unique food preparation and design. While most applications of 3D food printing are concentrated on single serving, novelty food prototypes, there is an opportunity to explore design variations for a commercial, production grade 3D printer capable of creating of consistently replicable food items for mid-range production facilities, such as schools and hospitals. This paper outlines preliminary research conducted by an interdisciplinary capstone design team of mechanical and electrical engineering students at California State University, Fullerton (CSUF) during the 2016/2017 academic year. A detailed overview of the capstone design course requirements and the team's design method is presented. The team was broadly tasked with reverse engineering and manufacturing a 3D food printer and identifying limitations and future research opportunities. After successfully designing and constructing a working extrusion-based Cartesian prototype, the team created a preliminary 3D food printing design database based on a series of experiments. This database is populated with design variables (including syringe pressure), quantitative results (such as material print height), and qualitative observations (photographs,

written descriptions). A two-sided t-test was used to understand the prototype's sensitivity to changes in key variables that impacted the printing performance. The 3D food printing design database provides valuable insights and baseline values for future 3D food printing research. Finally, scalability challenges are identified, with recommendations to meet these challenges.

Introduction

Continuous improvements in additive manufacturing technologies have expanded the breadth of possible applications for 3D printing (Wegrzyn, Golding, & Archer, 2012; Wei & Cheok, 2012; Millen, Gupta, & Archer, 2012; Lipson, 2012; Leach, 2014; Petrick & Simpson, 2013). In addition to printing items from plastic and metal, opportunities now exist to print food. In 2012, Systems and Materials Research Consultancy was awarded a NASA small business innovation research grant; the company had identified a practical need for 3D food printing in extreme environments, such as space, stating a need for a wide array of foods to be printed using different combinations and types of inputs, such as ingredients (Systems, 2012). NASA's vision for this research was to enable astronauts to design and manufacture a variety of food options with a finite set of inputs, while having customizable control over portion size and personal taste. However, this concept has multiple challenges. Primarily, most 3D food printing is performed by extrusion-based methods that limit the food type and consistency to primarily homogenous mixtures (pastes or gels) and is unable to accommodate other types of food consistencies (Sun, Zhou, Yan, Huang, & Lin, 2018; Cornell University, 2014; Cohen, Lipton, Cutler, Coulter, Vesco, & Lipson, 2007; Cohen, Lipton, Cutler, Coulter, Vesco, & Lipson, 2007; Seraph Robotics, 2015). Subsequently, an opportunity exists to examine new methods for depositing other heterogeneous food types.

This paper illustrates the efforts of undergraduate capstone design students from CSUF, who were broadly tasked with reverse engineering and manufacturing an extrusion-based 3D food printer and identifying limitations and future research opportunities. Capstone design refers to an engineering course, often taken during the senior year, that aims to bridge the gap between engineering theory and practice (Dutson, Todd, Magleby, & Sorensen, 1997). A key objective for the team was to broaden the practical applications of existing 3D food printing technologies by specifically focusing on the creation of consistently replicable foods for mid-range production facilities, such as schools and hospitals. For example, could several homogeneous or heterogeneous key ingredients (sauce, dough, cheese) be interchanged strategically to produce different food items (pizza, calzone)?

In terms of undergraduate research via capstone design, examining methods related to 3D food printing has multiple benefits. First, this work combines key elements of CSUF's mechanical and electrical engineering curriculum, such as CAD, system-level thinking, and additive manufacturing. Next, many capstone students, typically engineering seniors, are familiar with 3D printing through previous channels: high school, extracurricular hobbies, or other courses (Irwin, Pearce, Anzalone, & Oppliger, 2014). Finally, capstone design is well studied in the literature as a mechanism for teaching engineering design and promoting creative thinking (Dutson et al., 2014; Dym, Agogino, Eris, Frey, & Leifer, 2005; Wood, Jensen, Bezdek, & Otto, 2001).

The following research was conducted by a student capstone design team from the two-semester Mechanical Engineering 414/419, “Senior Design,” during the 2016/2017 academic year. Their work focused on identifying challenges for design scalability while considering manufacturing costs and applicable retail and commercial markets. This research was proposed and internally funded by CSUF, based on the university’s strategic plan for improving instructional processes that lead to increased student success. It addresses these processes directly, focusing on the implementation of high-impact practices in the classroom (Kuh, 2008; Carpenter, Morin, Sweet, & Blythe, 2017). A primary component of the senior design course is to collaborate with an industry sponsor/mentor who will benefit from the merits of this research. Ideally, these partners/collaborators would support (both financially and technically) this project for multiple years, and the students’ designs will improve iteratively. Another benefit of this research is the interdisciplinary nature that requires the mechanical engineering design team to collaborate with other disciplines. For this project, these areas include electrical engineering (electronic hardware design), computer science (programming), and business (market analysis, cost modeling, supply chain management).

Background

3D printing is a technological process where an object is created layer by layer from a file created by CAD software. The technology of additive manufacturing has existed since the early 1980s. Until the open-source release of the 3D printer Fab@Home by researchers at Cornell University in 2006, the printers were industrial scale and expensive (Lipson & Kurman, 2013). The Fab@Home Model 1 could be used in the production of a variety of forms and materials, including, for the first time, food (Lipson & Kurman, 2013).

The basic principle for 3D printed food is solid free-form fabrication, the ability of food material to hold and produce a solid structure without deformity (Lipton, Arnold, Nigl, Lopez, Cohen, Norén, & Lipson, 2010). Currently, there are four types of 3D food printing techniques: extrusion-based printing, selective laser sintering, binder jetting, and inkjet printing (Godoi, Prakash, & Bhandari, 2016; Sun, Zhou, Huang, Fuh, & Hong, 2015; Liu, Zhang, Bhandari, & Wang, 2017). Extrusion-based printing is the most commonly used technique and is typically used for hot-melt extrusion of chocolate or for the extrusion of room temperature soft materials like frosting, processed cheese, and sugar cookies (Lipton et al., 2010; Periard, Schaal, Schaal, Malone, & Lipson, 2007). Several extrusion-based food-printing machines are commercially available to print materials such as chocolate, dough, and pasta (Sun et al., 2018; Liu et al., 2017). The technique works by continuously extruding the material out of a moving nozzle, and the material fuses to preceding layers due to the material properties. The second most commonly used food printing technique is selective laser sintering, which works by fusing powder particles with high sugar content to form the solid layers. This technique has allowed for the creation of complex structures (Sun et al., 2015; Liu et al., 2017). Binderjet printing is the process of alternating between depositing layers of powder and spraying a liquid binder agent. This technique has resulted in the printing of complex structures, including structural cakes (Izdebska-Podsiadły & Żołek-Tryznowska, 2016). Inkjet food printing works like a standard inkjet printer for paper. The ink, however, is a low-viscosity food material dispensed in droplet form. This technique is limited to decoration or surface filling.

3D food printing allows food products to be designed and fabricated to meet personal and/or nutritional requirements and to create custom designs. Printing food allows for freedom of design regarding 3D shape and the composition, texture, structure, as well as taste (Sun et al., 2015). In addition, this process is capable of creating unique goods and structures that require specialized human skills or cannot be made by humans. 3D printing food additionally allows for the customization of the nutritional content (Wegrzyn, Golding, & Archer, 2012; Sun et al., 2015; Severini & Derossi, 2016; Severini, Derossi, Ricci, Caporizzi, & Fiore, 2018; Yang, Zhang, & Bhandari, 2017). Therefore, personalized food can be created based on a person's dietary restrictions, allergies, or health goals.

The accessibility of additive manufacturing technology has contributed to innovative advances in 3D food printing for both academic and commercial applications (Sun et al., 2015). However, current techniques need further investigation. There are many limitations including accuracy and precision (Liu et al., 2017). Once these challenges are overcome, wider application is expected.

Methodology

For this research, the following key performance metrics were provided to the capstone design team, each applicable to their 3D printer prototype:

- **Functionality:** Does the machine perform its intended function of printing multiple and different edible foods?
- **Scalability:** Can this design scale to mid-level production applications (schools)?
- **Robustness:** Will this design produce consistently replicable and reliable food prints?
- **Cost:** Is this design financially competitive with existing 3D food printing products?

Since most applications for 3D food printing are concentrated on single serving, novelty food prototypes, the team was asked to consider challenges for designing and manufacturing a commercial, production grade 3D printer capable of creating of consistently replicable food items for mid-range production facilities, such as schools and hospitals. Creating a 3D printer capable of producing a variety of standardized food products for mid-level production could significantly improve food health and increase distribution efficiency, while minimizing waste and reducing costs. This work has broad reaching applications in the domains of mechanical engineering, additive manufacturing, and food science. Another benefit of this research is its compatibility with the capstone design course series (either CSUF's or another institution's), which is formatted to allow annually reoccurring research projects on the same topic.

The team's method is based on Ullman's four stages of product design including project definition, product definition, conceptual design, and product development (Wang & Shaw, 2005). An outline of the team's method is shown in Figure 1. The capstone design team worked within the constraints of the course, during CSUF's 2016/2017 academic year. This limited the team to two 15-week semesters to complete their prototype, and their budget could not exceed $1,000. In addition, the team was required to track all design, manufacturing, and testing activities in a cloud-based document-sharing platform (Google Drive), to pass information on to next year's team. Table 1 provides an outline of key course requirements and justification, to help guide the students' design.

Project/Product Definition

The capstone design team student selection was based on students who were interested in additive manufacturing but did not necessarily have experience in this domain. As described above, the project definition and key objectives were already outlined by the capstone design advisor. Subsequently, production definition was the first component of the team's method.

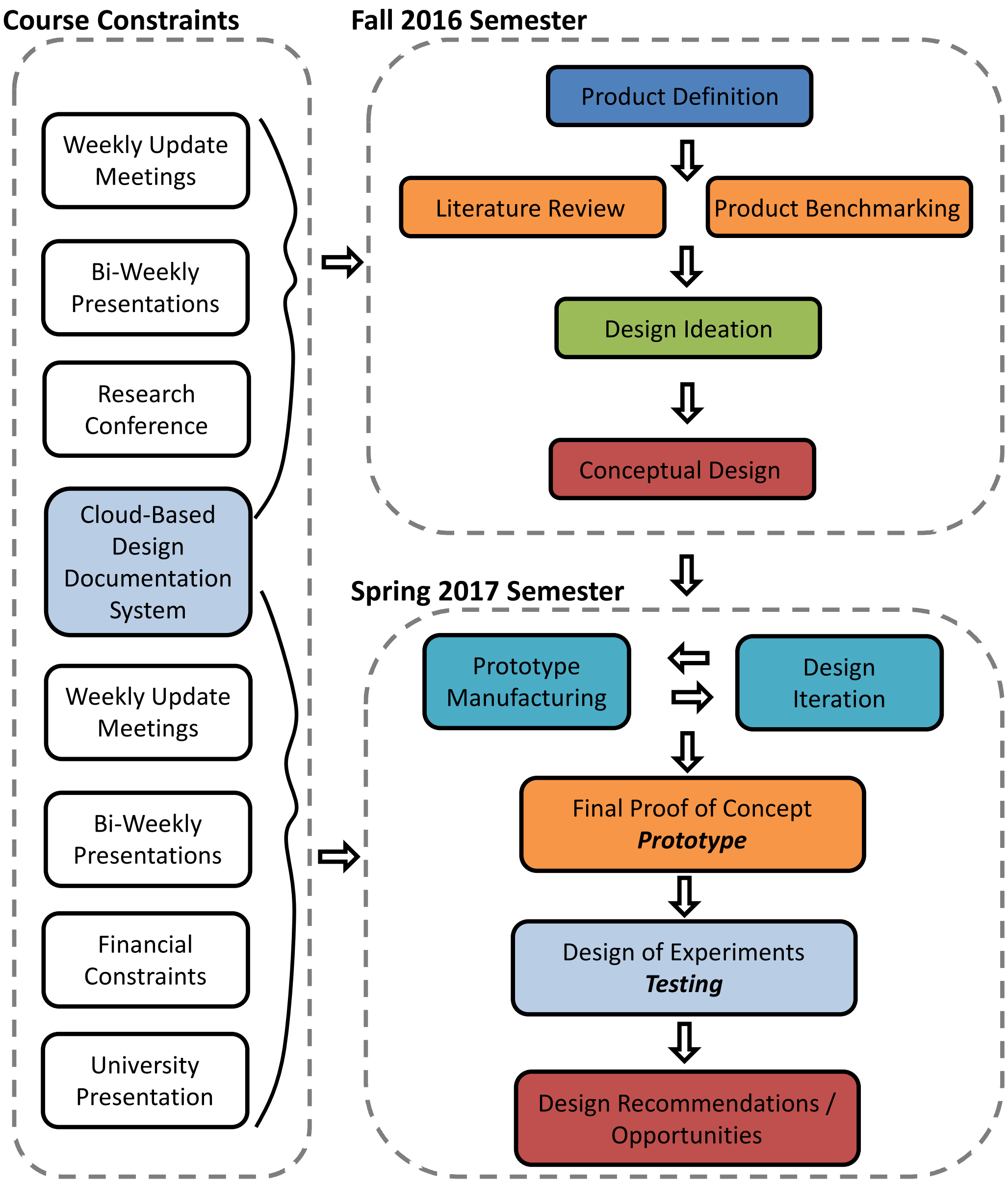


Figure 1. Student team design method.

An examination of the literature and existing technologies was performed, where the students found current work relating to both the fundamental science of additive manufacturing and commercial applications for 3D food printing. This review helped guide them during the design ideation phase and identify potential 3D food printing methods that could be replicated, given the temporal and financial constraints of the course. The team selected the extrusion-based food printing method, motivated by opportunities defined in the literature (Sun et al., 2018).

Table 1. Key course requirements and justification.

Design Task	Justification
Create Gantt chart	Track critical deadlines and responsible individual
Perform literature review	Explore state of-the-art research and product benchmarking
Begin cloud-based research documentation system (Google Drive)	Archive and document research to pass on to future researchers
Attend weekly update meetings with instructor	Receive feedback on design and manufacturing choices
Present bi-weekly 10-minute research update to class	Gain critical evaluation from peers
Submit project abstract to undergraduate research conference (2016 Southern California Conference for Undergraduate Research [SCCUR])	Expose students to peer review research process
Create abstract based research poster	Understand how to concisely present work with limited time/space
Present research at undergraduate conference (such as SCCUR)	Opportunity to disseminate work, and receive feedback from the research community
Give 20-minute research update to class	Gain critical evaluation from peers
Display final prototype and poster at university-wide event (2017 CSUF Student Project Showcase)	Opportunity to disseminate work, and receive feedback from peers outside of department
Submit final research report	Allow students to practice technical writing

Conceptual Design

The conceptual design phase was guided by project definition requirements and the course design task requirements listed in Table 1. A functional decomposition of several extrusion-based food printers was performed, to help identify potential design alternatives. The most common method for depositing food to the build surface is via a syringe, activated either pneumatically or with an electromechanical power screw. This syringe is then coupled with a mechanism for translating three different axes. Design trade-offs were examined between each of the multi-axis food printer approaches (Cartesian, Delta, Polar, Scara) identified by Sun et al. (2018).

For the syringe, the team created a functional prototype of a pneumatic extrusion system using a purchased 38.1mm diameter syringe with a custom 3D printed ABS plastic air input (Figure 2). The nozzle diameter was tested at 3mm, based on extrusion techniques by Wang and Shaw (2005). From this design, they made several attempts to extrude different foods, corn bread mix and frosting. This initial testing was performed at room temperature (~32º C).

Figure 2. Preliminary conceptual design for extrusion testing.

Since the expanding market for 3D printing technology is driving related component costs down, the team investigated the benefits of purchasing a 3D printer to harness the multi-axes translating function, instead of designing and manufacturing one themselves. For their final conceptual design, the team chose to purchase a Prusa i3 3D (Cartesian coordinate) printing kit (Irwin et al., 2014; Prusa, 2018) and modified the printing head mechanism to accept the customized pneumatic syringe used for testing. An initial challenge was to modify the Prusa's original microcontroller and coding to activate a pneumatic valve that would let pressurized air enter the syringe and subsequently start the food-extrusion process. The Prusa printer head contained a stepper motor, a heater, and a fan; all were removed from the unit, leaving three "empty" outputs on the microcontroller. The team utilized a pneumatic valve that could be activated by the original 5V stepper motor output (Figure 3). All activities leading up to the conceptual design were performed during the fall 2016 semester.

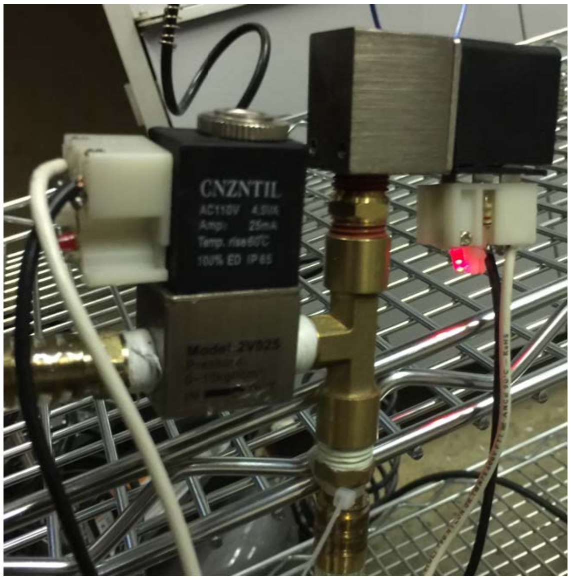


Figure 3. Pneumatic pressure inlet and pressure relief valves.

Product Development

After completing the conceptual design, the team began to finalize their design and manufacture a final product that could “print” different foods, by pneumatically extruding the food material from the syringe onto the build platform of the printer. The product development stage occurred during the Spring 2017 semester. Figure 4 shows the Prusa 3D printer with the original filament print head removed and a custom-designed syringe mount installed. The modified syringe and 3D printed air inlet from the design phase (Figure 2) was replaced with a commercially available Uxcell 300ml Luer Lock 40mm diameter syringe and air inlet with a 6mm barb fitting.

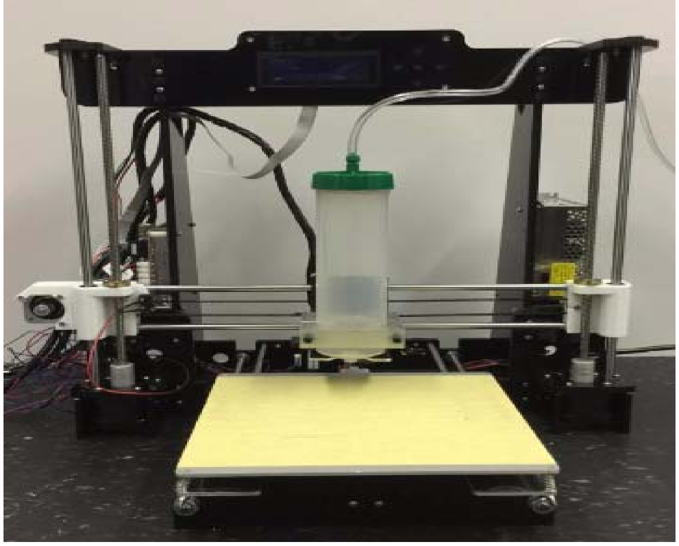


Figure 4. Initial product conceptual design.

Next, initial testing began to validate the team's conceptual design by attempting to print a $50mm^2$ square using frosting. The syringe pressure was set to $43.7kPa$ based on the initial syringe testing results. As seen in Figure 5, the square was successfully printed; however, the syringe continued to extrude after the pneumatic valve was closed due to remaining pressure in the cylinder. Subsequently, a second valve was added to relieve pressure after the air inlet valve was closed (Figure 3).

Figure 5. Pressure release testing for $50mm^2$ square shape.

Testing Configuration

After the product development phase was complete, the team selected a two-sided t-test to understand the prototype's sensitivity to changes in key variables that impacted the printing performance. Due to the temporal constraints of capstone design, the team chose to vary print geometry, material type, and syringe pressure (Table 2).

Table 2. Outline of design variables and performance metrics.

Design Variables	**Quantitative Performance**	**Qualitative Performance**
Material type	Material height	Geometry accuracy
Print geometry		
Syringe pressure	Material width	Ability to layer

Printer performance was measured quantitatively with material height and material width. Qualitative evaluations were also recorded (documented with photos) that included geometry accuracy (Did the food print in the intended shape based on input variables?) and ability to layer (Was solid free-form fabrication visually apparent based on input variables?).
The design variables and performance metrics identified in Table 2 would allow the team to perform two-sided t-tests once the experimental data were collected.

Results

Based on the testing configuration outline, the team chose Betty Crocker Rich and Creamy Chocolate Frosting and Jiffy Corn Muffin Mix as their material types. A circle and star pattern were used for the print geometry. Discrete syringe pressure values were set at $43.7kPa$ and $87.3kPa$, drawing from preliminary syringe pressure tests. Nozzle height (distance from the print bed) was initially set at 5mm, based on initial extrusion testing. For all of the experiments presented, 4 layers of material were printed, with the syringe nozzle moving 5mm distance upward after each layer. Material height values were recorded for each discrete layer.

To organize the experimental data, the team created a preliminary 3D food printing design database, which is populated with the design variables, the quantitative and qualitative performance metrics, and a photograph of the print from each experiment. In total, 39 individual layers were printed and analyzed. Table 3 displays a relevant subset of the database.

Results Interpretation

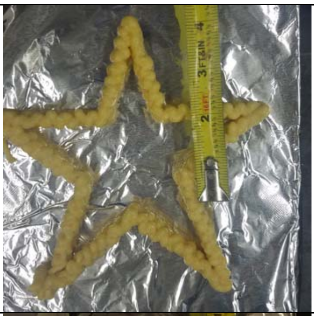
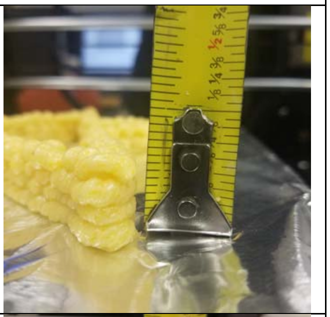
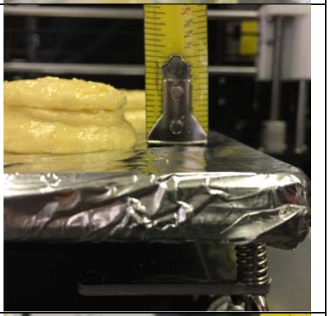
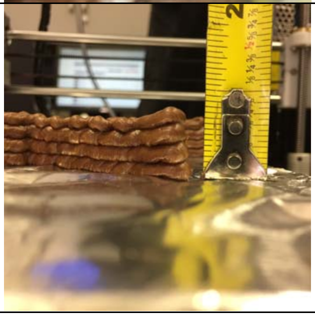
Two-sided, two-sample unequal variance t-tests were performed to help identify which design variables (material type, print geometry, syringe pressure) have a significant impact on the quantitative design performances measured (material width, material height). The number of samples (N), mean (M), standard deviation (SD), and t-test results, including the t-value ($|t|$), degrees of freedom (df), and the significance level (p) are given in Table 4.

Table 4. T-test results.

Design Variables		**N**	**Printed Material Width (mm)**					**Printed Material Height (mm)**				
			M	**SD**	**$\|t\|$**	**df**	**p**	**M**	**SD**	**$\|t\|$**	**df**	**p**
Material Type	Chocolate Frosting	22	9.1	2.9	2.36	22	0.027	5.2	0.9	0.79	27	0.434
	Corn Muffin Mix	17	12.6	5.6				4.9	1.3			
Print Geometry	Circle	17	9.2	2.8	1.90	33	0.067	4.6	0.7	2.21	34	0.034
	Star	22	11.7	5.4				5.3	1.3			
Syringe Pressure	$43.7\ kPa$	31	9.0	1.9	3.64	7	0.004	4.7	0.8	4.39	9	0.002
	$87.3\ kPa$	8	17.0	6.7				6.6	1.1			

For material type, the t-test results show that there is a significant difference ($p<0.05$) in the printed material width between chocolate frosting and corn muffin mix. But there is no significant difference in printed material height between the two materials. For different printed geometries of circles and stars, there is a significant difference in printed material width but no significant difference in printed material height. As for syringe pressure, there is a significant difference in both printed material width and height between the syringe pressures of $43.7kPa$ and $87.3kPa$.

Table 3. Outline of design variables and performance metrics.

Material Geometry Pressure	**Qualitative Description** (from team)	**Width/ Layer** (mm)	**Height/ Layer** (mm)	**Geometry Accuracy**	**Ability to Layer**
• Cornbread • Star • 43.7*kPa*	Sine wave shape probably due to height	L1- 11.9 L2 - 10.3 L3 - 11.1 L4 - 11.1	L1 - 3.2 L2 - 3.2 L3 - 4.8 L4 - 4.8		
• Cornbread • Star • 87.3*kPa*	Flattens first layer	L1 - 25.4 L2 - 20.6 L3 - 25.4 L4 - NA	L1 - 7.9 L2 - 4.8 L3 - 6.4 L4 - NA		
• Frosting • Circle • 43.7*kPa*	Began to print out sine wave shaped lines	L1 - 4.8 L2 - 7.9 L3 - 7.9 L4 - 7.9	L1 - 4.8 L2 - 4.8 L3 - 4.8 L4 – 4.0		
• Frosting • Circle • 87.3*kPa*	Print becomes smoother as the printer head prints closer to printing surface	L1 - 14.3 L2 - 12.7 L3 - 13.5 L4 - 14.3	L1 - 8.8 L2 - 9.5 L3 - 7.9 L4 - 7.9		
• Frosting • Circle • 43.7*kPa*	Began to print out sine wave shaped lines	L1 - 9.5 L2 - 9.5 L3 - 9.5 L4 - 6.4	L1 - 4.8 L2 - 4.8 L3 - 4.8 L4 – 4.0		

From these results, syringe pressure has emerged as a critical design variable that impacts printer performance and subsequently should be considered as a key design parameter going forward with a new/updated design. Additionally, a more detailed study should be conducted to determine if there is a relationship between the viscosity of the material and the printed material width. Overall, these preliminary results indicate that more tests should be carried out with more material types, printed geometries, and syringe pressures for more insightful conclusions. For this future testing, quantitative measurements for geometry accuracy and ability to layer (instead of the qualitative measures used here) should be developed and implemented.

Discussion and Future Opportunities

This paper presents a case study of undergraduate research conducted by an interdisciplinary capstone design team of mechanical and electrical engineering students broadly tasked with reverse engineering and manufacturing a 3D food printer. Creating the framework for the 3D food printing design database is a significant contribution for research at the undergraduate level and provides valuable insights for future 3D food printing research. In addition, the team was able to address each of the four key performance metrics provided at the beginning of the capstone design course:

- **Functionality**: The team's conceptual design resulted in successfully printing two different foods.
- **Scalability**: The current conceptual design is a proof-of-concept prototype and would be difficult to scale for mid-level production applications. However, the material loading challenges discussed in the next section provide insight into design attributes that will be required for mid-level production.
- **Robustness**: Since only 39 individual layers were printed, it is difficult to conclude if this design will produce consistently replicable food prints. Additional experiments will be performed in future work to examine printing performance variation.
- **Cost**: Based on the proof-of-concept design presented, this design primarily used commercially available components and very few custom parts. Subsequently, it could be financially competitive with existing 3D food printing products.

Another future research opportunity is exploring the impact of post processing (packaging, freezing, baking) the final product for large volume applications is a. Specifically, how does post-processing impact the printed material (physically, aesthetically)?

Material Loading Challenges

One of the unexpected challenges the team faced was the time and effort required to load the various food types into the syringe. While low viscosity foods like corn muffin batter could be poured directly after mixing, higher viscosity foods like frosting had to be forced in (or loaded) with a spoon or spatula. Another issue with loading the food was the formation of air pockets throughout the column of the syringe, which resulted in discontinuity during a print. Cleaning the syringe and nozzle also took more effort with high viscosity foods.

In an effort to save time loading material and potentially reduce the presence of air pockets, and improve the syringe cleaning process, the students experimented with the idea of "prepackaging" the food before it was inserted into the syringe. Prepackaging was performed by enclosing 200 ml of frosting in either wax paper ($12\mu m$), foil ($16\mu m$), or plastic wrap ($10\mu m$). Each package was inserted into the syringe, and a small hole was poked through the nozzle opening. The syringe was then pressurized to $87.3kPa$ until the material had been completely extruded onto the build platform, without a coordinate change. Of the three packaging types tested, foil performed the best using qualitative observation (Figure 6). The foil extruded the largest volume of material, while minimizing the presence of air pockets and cleanup effort.

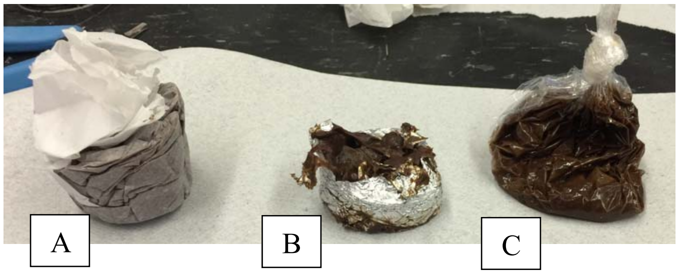


Figure 6. Prepackaging tests: A. wax paper, B. foil, C. plastic wrap

This preliminary qualitative experiment highlights an additional opportunity for future research, toward the goal of creating consistently replicable food items from pre-packaged containers (similar to Keurig coffee cups), and represents a key contribution of this work. At the time of this publication, there are plans to continue this research at the University of West Florida with another capstone design team for the 2018/2019 year.

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