ADVENTURES IN SOFTWARE-BASED COOKING

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Abstract

Additive manufacturing (AM) of food has great potential but in its current state, lacks the ability to create fully cooked printed food products. While food printers have the ability to create tailored nutritious meals, precision *cooking* appliances to selectively cook printed food layers do not yet exist. This has driven our exploration of laser cooking, a novel software-controlled heating technique that targets heat from lasers—via mirror galvanometers—to cook thin-layered foods. By varying laser parameters such as power, speed, and cooking pattern, we develop a software-generated three-course meal for consumption. We use a blue laser (445 nm) and a near-infrared laser (980 nm) to cook printed food products. Here, we show a few applications of digital cooking techniques, which we believe will give chefs and makers the ability to create novel and creative food products and shift the way we currently think about meal generation.

Keywords: additive manufacturing, food printing, precision laser cooking, tailored meals, software-based cooking, digital food

Introduction

Meal prep is an unavoidable part of every person's daily routine. Depending on the person, average cooking and preparation times vary widely from 30 minutes [1] to more than 2 hours [2]. Our current method of cooking and preparing meals is a time sink due to the fact that is inherently an analog process. Cooking appliances are open-loop; they require constant human interaction throughout the process to achieve desired results (e.g. sautéing vegetables in a wok, searing fish on the stove, baking a cake in the oven, charring chicken on a grill, etc.). Using software-controlled lasers we can leverage additive manufacturing (AM) to tailor the cooking process for various food products for the individual [3].

Meal preparation is implicitly an additive process. Chefs combine ingredients like water, flour, salt, pepper, oil, and protein to create delectable meals for consumption. AM can be applied to food—referred to as food layered manufacture (FLM)—and it allows us to physically fabricate and generate unique food combinations much the same way a chef would. Plated foods are the result of a combination of ingredients and not just one single ingredient. FLM must therefore accommodate a vast range of ingredients and not just one single material, as is the case for plastic or metal AM.

Figure 1 shows an assortment of printed structures with various types of liquid-based fillings. These hexagonally-shaped structures were printed on our food printer and could not be recreated by hand. They also stand to show the current limitations of food printing technology. They are crafted from pre-cooked carrots and other spices and common additives a chef might use in the kitchen. Each layer was additively constructed and, as such, could have featured alternating ingredients throughout the piece. While food printers have the ability to deposit materials to mm-scale resolution, they don't yet have the ability to cook foods to this same degree of resolution. The current system doesn't allow us to print a layer of chicken, cooked to perfection, amidst the layers of carrot purée, or interlace beef with various levels of doneness, or a crusted interior texture with no cooking on the outside. Integration of a precision heating system onboard a food printer offers a new modality for food designers that allows for more creative food combinations and taste profiles to be experienced.

Figure 1: Printed hexagonal structures made from a carrot purée with various fillings.

We investigate the feasibility of printing and cooking food in tandem. We craft three multi-ingredient recipes that include ingredients such as dough, tofu, tomato paste, cheese, graham cracker, cream cheese, and miso paste. Each food object is constructed on our custom food printer, and cooked using our selective laser broiling apparatus. These two systems are separate from one another but easily have the potential to be integrated into one functioning machine.

Background

While commercial food printers do exist, they are somewhat limited in their abilities to combine cooked foods. Food printing was first introduced at Solid Freeform Fabrication Symposium in 2007 [4], and has since slowly burgeoned as a commercially viable application of AM. Current food fabricators being developed in industry include machines that can print customized pasta geometries [5], chocolate structures [6], pizzas for separate oven baking [7], user-inputted multi-material food products [8], [9], and other confectionary sugary treats [5], [10]. All of these printers have the ability to combine one or—in some cases—more ingredients in a single printed object, however, they are limited by a lack of onboard heating. Hertafeld *et al.* [11] investigated multi-material printing with *in situ* cooking via an infrared lamp on a food printer. This sort of simultaneous high-resolution heating is necessary on a food printer in order to achieve more complex recipe combinations.

Heat is a transformative process that affects the aroma and flavor development of foods [12]. Doughs and starch-containing products develop different microstructures and nutritional profiles when subject to heat and other prerequisites [13]–[15]. Perhaps more familiar to most are the color and textural changes associated with protein denaturation, which is a common process undergone by animal proteins in the presence of sufficient heating [16], [17]. Another recognizable heat-driven process is non-enzymatic Maillard browning, which greatly affects the flavor development and aesthetic of heated foods [18], [19]. These chemical processes, which are typically achieved using conventional heating appliances [20], can also be achieved via the use of diode and gas lasers [21]–[24].

Prior work with regards to laser cooking is quite limited. Fukuchi *et al.* [25] cooked the fat portion of bacon on a laser cutter. A few patents exist around the use of lasers for cooking [26]–[28], but none properly parameterize in detail the requirements for proper cooking of food items. Our prior work investigates precision software cooking as it applies to lasers as a heating source [21]–[24].

We used two different laser apparatuses in this study: 1) a stationary blue (445 nm) laser beam redirected by a set of mirror galvanometers and 2) a movable near-infrared (980 nm) diode laser mounted to a Cartesian gantry. The blue laser was used to crust parts of the cheesecake and to brown the tofu mix, while the near-infrared (NIR) laser was used to cook the dough and melt the cheese on the pizza. Through multiple iterations and trials, we successfully printed and cooked three different recipes that were edible and tasty.

Experimental

Printing food

We retrofitted a 3-axis Cartesian gantry with a custom extrusion mechanism that allowed us to pick-and-place ingredients for printing. Ingredients were packed into separate plastic syringe barrels, each outfitted with a tapered nozzle for controlled material deposition. We used Repetier-Host [29], an open source firmware, to interface with the machine and upload recipe files for printing. We generated custom printing and cooking files via a custom script that was formulated in Matlab.

Our script allowed us to vary parameters such as print speed, extrusion rate, and geometry of the printed object. Parameters such as number of ingredients, sides, size, height, and twist angle could be tailored in our G-code generator. **Figure 2** shows example geometries and ingredient combinations that are currently capable of being printed using our system. The variance in shape of the four structures can be attributed to five variables: number of sides (s), diameter (d, mm), number of layers (h), twist (t, °), and number of ingredients (i). Polygons of different size and shape were created by interpolating points along a circle. For simplicity, further mention of these variables to characterize the shape of an object will be in the form of the matrix [s,d,h,t,i].

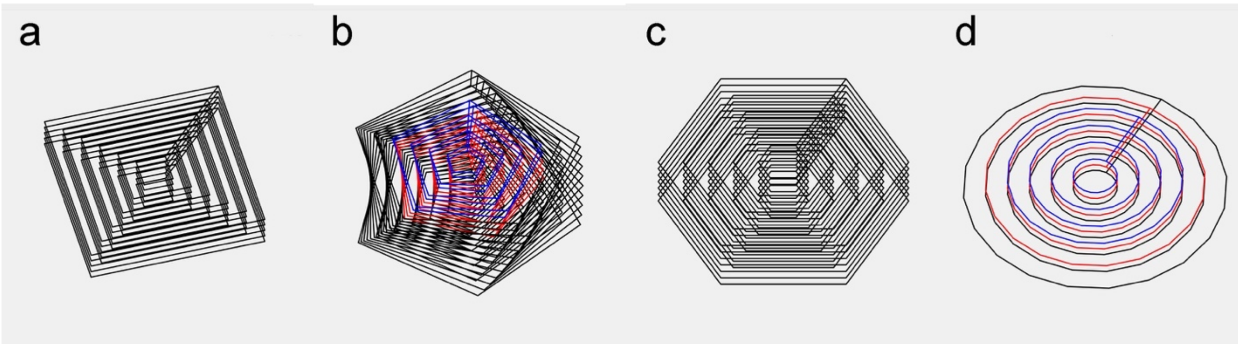

Figure 2: Print paths that were generated via Matlab. The modeled food objects can be characterized in terms of number of sides (s), diameter (d, mm), number of layers (h), twist (t, °), and number of ingredients (i) in the form [s, d, h, t, i]: **a** [4, 36, 5, 0, 1], **b** [5, 36, 10, 3, 3], **c** [6, 30, 10, 0, 1], **d** [20, 36, 3, 0, 3].

Food recipes

Three recipes were used in this software cooking study (Table 2). Recipe 2 took inspiration from a pizza recipe and combined dough sauce and cheese into one fully-cooked pizza pie. Granted, this laser-baked pizza was about the size of a Bagel Bite, it proves the ability to preliminarily bake dough and melt cheese via a NIR laser. Recipe 1 features a tofu bite that was laser-crusted on its top surface by the blue laser after printing. Lastly, Recipe 3 was inspired by a cheesecake dessert recipe and is the sweetest of three multi-ingredient objects. The dessert was also laser-crusted on the surface by the blue laser. All of the ingredients and food products for this three-course meal were combined and heated entirely using software cooking methods.

Recipe #	**Ingredients**	**Preparation**
1. Laser-crusted tofu bite (appetizer)	1 block (14 oz.) Medium firm tofu 6 oz. Tomato paste 1 tbs. Dehydrated mushrooms 1 tbs. Dried onions 1 tsp. Salt 1 tsp. Black pepper 2 tbs. Miso paste 6 oz. Water 2 tsp. Guar gum	Tofu mix: first process the dehydrated mushrooms and dried onions until they become a fine powder. Then, drain the medium firm tofu. Process the mushrooms, onions, tofu, tomato paste, salt and pepper until a creamy, even consistency is achieved. Miso glaze: dissolve the miso paste in warm water. Then, using a cheesecloth or some kind of sieve, strain and discard the larger particles. Slowly stir in the guar gum. Let sit and congeal.
2. Laser-baked pizza (entrée)	½ cup All-purpose flour ½ cup Water 1.5 oz. Tomato paste 1.5 oz. Ricotta	Dough: mix or process the flour and water until an even consistency is achieved. Sauce: Add basil salt and paprika to tomato paste and mix for uniform consistency.

	½ tsp. Basil salt ½ tsp. Paprika	Cheese: depending on consistency of ricotta, process for a few seconds in Cuisinart for uniform consistency.
3. Laser-crusted cheesecake (dessert)	8 graham cracker sheets (approx. 31 g) 1 tbs. Butter 2 tbs. Powdered sugar 2 oz. water 8 oz. plain cream cheese 4 tbs. Citron preserves 4 tbs. Black currant preserves ½ orange, juiced 1 tsp. Vanilla extract	Crust: crush and process the graham cracker sheets until they become a fine powder. Then, mix the powdered sugar with 2 oz. cold water until it becomes a paste. Blend the crackers with the sugar paste. Melt the butter, and pour it into the graham “dough”. Filling: first heat up the citron preserves so that the liquid separates from the solid. Blend the cream cheese, vanilla extract and orange juice together until it reaches an even consistency. Then, add the liquid from the citron preserves. Glaze: heat up the black currant preserves and then separate the solids from the liquid.

Table 2 – Preparation techniques for three recipes used in experiments.

Laser cooking apparatuses

Figure 3 displays the two heating apparatuses used in our heating experiments. Setup 1 (Figure 3, left panel) directs the energy from a blue laser using a set of mirror galvanometers. Setup 2 (Figure 3, right panel) utilizes motion from a 3-axis Cartesian gantry to move an NIR laser diode, which is vertically mounted. The gantry used in the second setup is the moving extrusion head on our food printer. We designed a mount for the NIR laser that allows it to mounted and dismounted for ease of use.

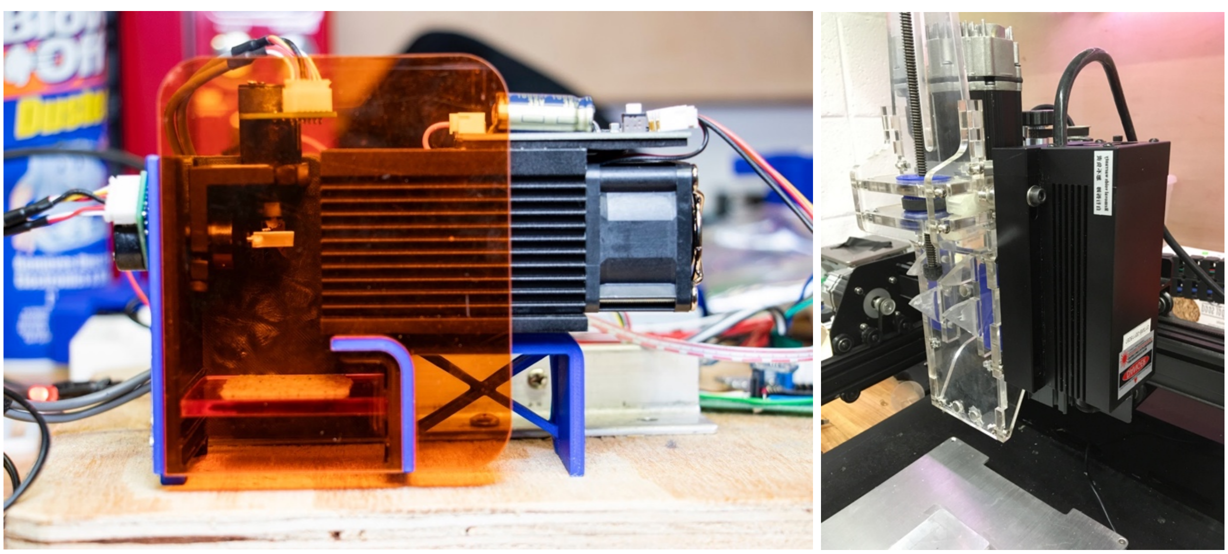

Figure 3 – Laser systems used in cooking trials. **Left**: Stationary blue diode laser with energy being redirected by dual axis mirror galvanometers. **Right**: Near-infrared diode laser mounted to a 3-axis gantry, which provides motion.

Table 1 lists out the pros and cons for each of these laser setups. While Setup 1 is more compact, integrable to other cooking appliances, and provides more versatile cooking patterns; it's slightly more limiting in terms of cooking area and software fixes need to be implemented to prevent distortion effects from mirrors. Conversely, Setup 2 provides a much larger cooking area with an easier system to upload cooking patterns, yet it's inefficient in terms of the mounting of the laser and as a result less compact. Ideally, we would have used galvo mirrors with both lasers but light from the NIR laser gets fully absorbed by the optical mirrors on our galvo setup, hence we needed to mount it to a movable platform.

Setup 1: Blue laser		**Setup 2: NIR laser**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
- More compact - Higher laser speeds - More complex cooking patterns - More integrable	- Limited cooking area - Mirror distortion affects - Inconsistent beam diameter - Efficiency loss to mirror heating	- Larger cooking area - Quicker setup time - More intuitive motion profile	- Large moving mass on end effector - Less compact - More safeguarding needed

Table 1 – Advantages and disadvantages for both laser heating systems.

Laser heating parameters

Satisfactory cooking of food via laser energy requires proper calibration of the cooking patterns and laser parameters. Similar to printing, specific adjustments were needed for different edible materials. With prior knowledge of laser-induced dough baking and browning [21], [23] and initial benchmarking, we operated the NIR laser at slower initial speeds to allow for sufficient heat to build up in the dough sample and gelatinize the starch granules.

Fabricating a pizza on our machine involved a series of steps: 1) printing a first layer of dough, 2) cooking the first layer of dough, 3) printing the next layer of sauce, 4) printing the next layer of cheese, 5) melting the top layer of cheese and sauce. We used a spiral cooking pattern that spanned across the 30 mm diameter of the printed dough. The spacing between each successive spiral was 3 mm and the total time for each pass of the pattern was just shy of 6 minutes. The pattern was run for six successive passes with the NIR laser operating at 8.5 W. After the sauce and cheese were deposited on the laser-heated dough, the same spiral heating pattern was run three more times in succession to melt the cheese.

Unlike the pizza, the tofu bite and the cheesecake could have been eaten raw but we chose to heat parts of it with the laser to showcase the spatial and temporal control of our software-controlled laser cooking system. For these two food objects, we used our 5 W blue laser to crust parts of the exterior. A trochoid heating pattern was used since it was proven by Blutinger *et al.* [23] to be an efficient heating pattern.

We printed the tofu bite onto a cracker for ease of transport to the laser cooker and to show another use case of our printing setup. Once the tofu ingredients were printed, we traced a trochoid cooking pattern along the same path of the material deposition for two consecutive passes. The total cook time with the laser was 4 – 5 minutes. After heating, the miso glaze was printed inside of the tofu structure to create a two-ingredient final product.

A similar trochoidal cooking pattern was used to cook the crust and filling of the printed cheesecake. The cheesecake was printed with a single-ingredient base structure of crust layered with a crust rim and filling in the center for successive layers. Initial cooking trials involved a trochoidal path that followed the printing path and traverse the entire top surface of the printed structure, which included filling and crust material. Another test was also conducted to just assess the laser heating effects on just the crust. Each of these trials took somewhere on the order of 5 – 7 minutes depending on the shape of the printed layer.

Results and discussion

Appetizer: laser-crusted tofu bite

Due to the fact that our blue laser was a separate system from our food printer, we used a laser oven tray to transport printed foods from one machine to the other. For this appetizer, we used a cracker as a vehicle to transport the printed structure between our printer and cooker (**Figure 4**). Printing and cooking onto a premade structure like a cracker also shows the ability for these processes to be integrated with preexisting materials.

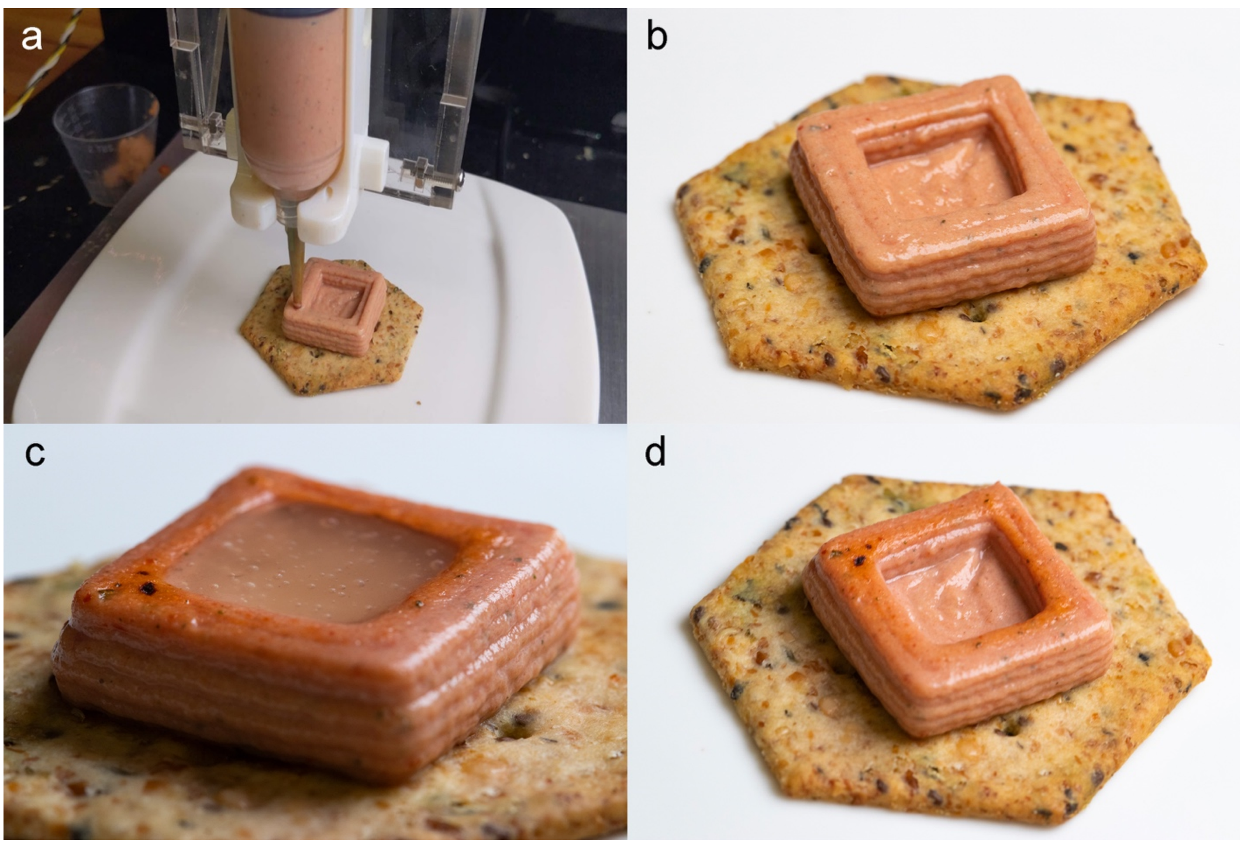

Figure 4 – Printing and cooking of the tofu bite. **a** Printing of tofu mix base structure and wall. **b** Printed tofu mix on cracker prior to laser heating. **c** Final-cooked tofu bite. **d** Printed tofu mix on cracker after laser heating.

This structure was designed to capture the miso paste within the tofu mix. We printed the tofu mix that had two solid layers of material and a 2-layer thick wall that spanned four layers high (**Figure 4a**, **4b**). We then transferred the print, supported on the cracker, to the laser cooker for further processing. **Figure 5** shows the tofu mix during laser heating. The 5 W blue laser was used to cook the top portion of the food sample. Clear moisture evaporation can be visualized from **Figure 5** from the droplets of water vapor that are shown in the path of the beam. This stream of vapor followed the beam as it propagated along the surface of the food, further drying out the food from the blue laser energy [30]. By drying out the sample, the laser is developing a scenario that is more conducive to non-enzymatic browning development [31].

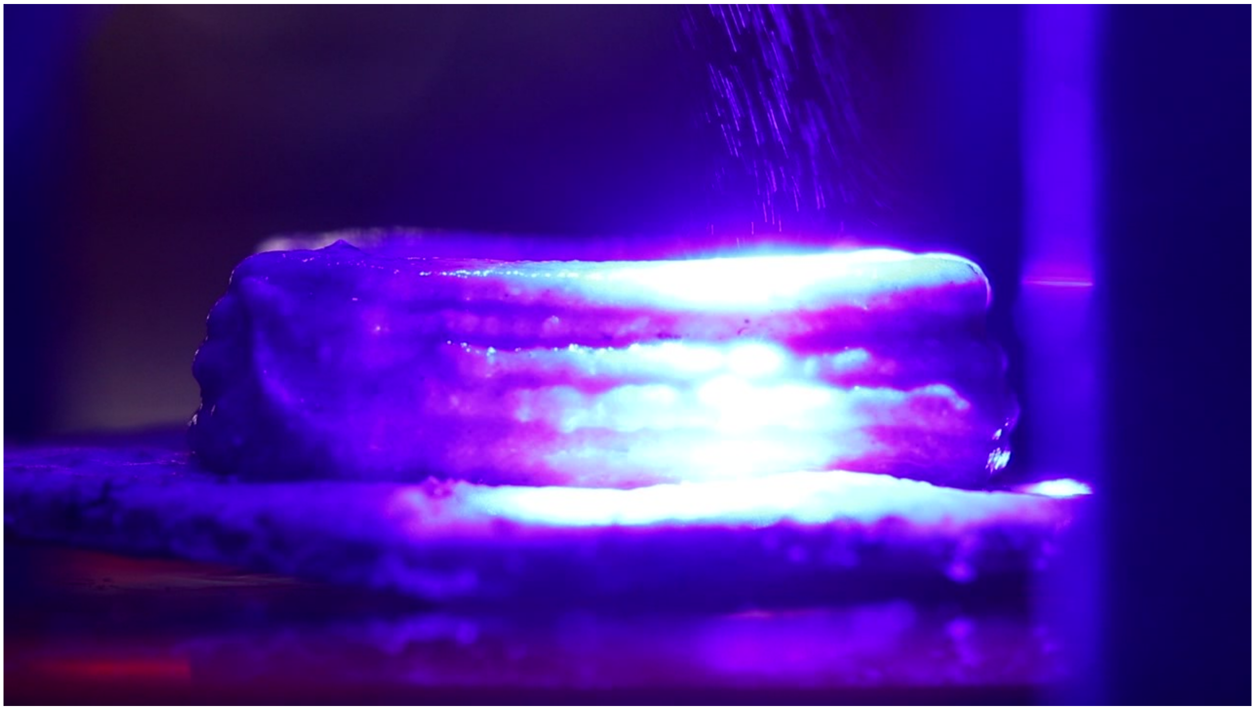

Figure 5 – Side view of tofu mix during blue laser exposure.

The final cooked sample was sampled by two unbiased individuals [32]. Upon biting into the sample, one affirmed that "it actually tastes really good," continuing with "I wasn't expecting that." The other taste-tester then responds in agreement: "Yeah. I was not expecting it to taste so good." They—like many—may have had reservations about eating printed and laser-cooked foods, when in reality we use the same ingredients as what you'd cook with in your home.

Entrée: laser-baked pizza

The bottom dough layer of the pizza was intended to be 30 mm in diameter. Due to the consistency of the dough mixture, the material leveled off and spread to an area slightly larger than its original intended size. This meant that the pass of the laser did not adequately cook the perimeter of the dough (the outermost 4 mm). As the dough is heated and transitions from raw to cooked dough, it darkens and becomes more translucent then starts to crumb and develop a lighter color shade [33]. This dough color transition can be visualized in **Figure 6**, which shows the color progression of the printed dough sample during the initial pass of the NIR laser. The crumb that forms in the middle of the sample spreads to other parts of the dough sample with each consecutive cooking pass, which can be visualized in **Figure 7a**–**7c**.

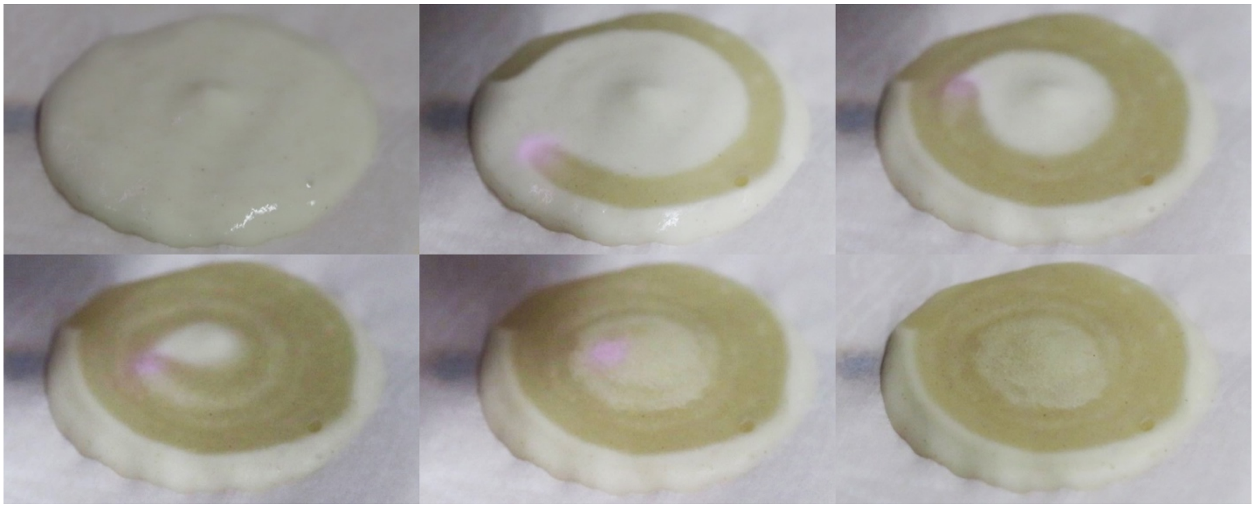

Figure 6 – Initial spiral heating pass of NIR laser on printed dough.

To cook the dough most effectively, the laser needed to be moving at a slow enough rate to build enough latent heat to cook the surrounding areas. With the NIR laser operating at 8.5 W, we found this optimal speed to be roughly 40 mm/min. With each successive spiral pass of the NIR laser, more crumb develops along the surface of the dough, with the center of the dough developing spots of browning. This browning progression in the center of the sample can be seen in **Figure 7a–7c**.

During the third and fourth passes of the laser over the dough, we noticed bubbling in the dough, suggesting that the laser energy was permeating the dough and causing evaporation. By the end of the fifth round, there was a clear spiral marked on the dough by the focused laser. This was a result of using a different lens on the laser for the sixth heating cycle, which focused the beam and created a more concentrated heating along the spiral path.

During heating of the cheese and sauce toppings, a significant amount of water vapor could be seen bubbling from the cheese and being expelled from the sample. The pizza appeared to be steaming with water vapor release and started to show significant more bubbling and melting of cheese on the second and third passes of the laser. Ultimately, browning was achieved with the laser-heated cheese and dough samples (visible in **Figure 7c**, **7h**).

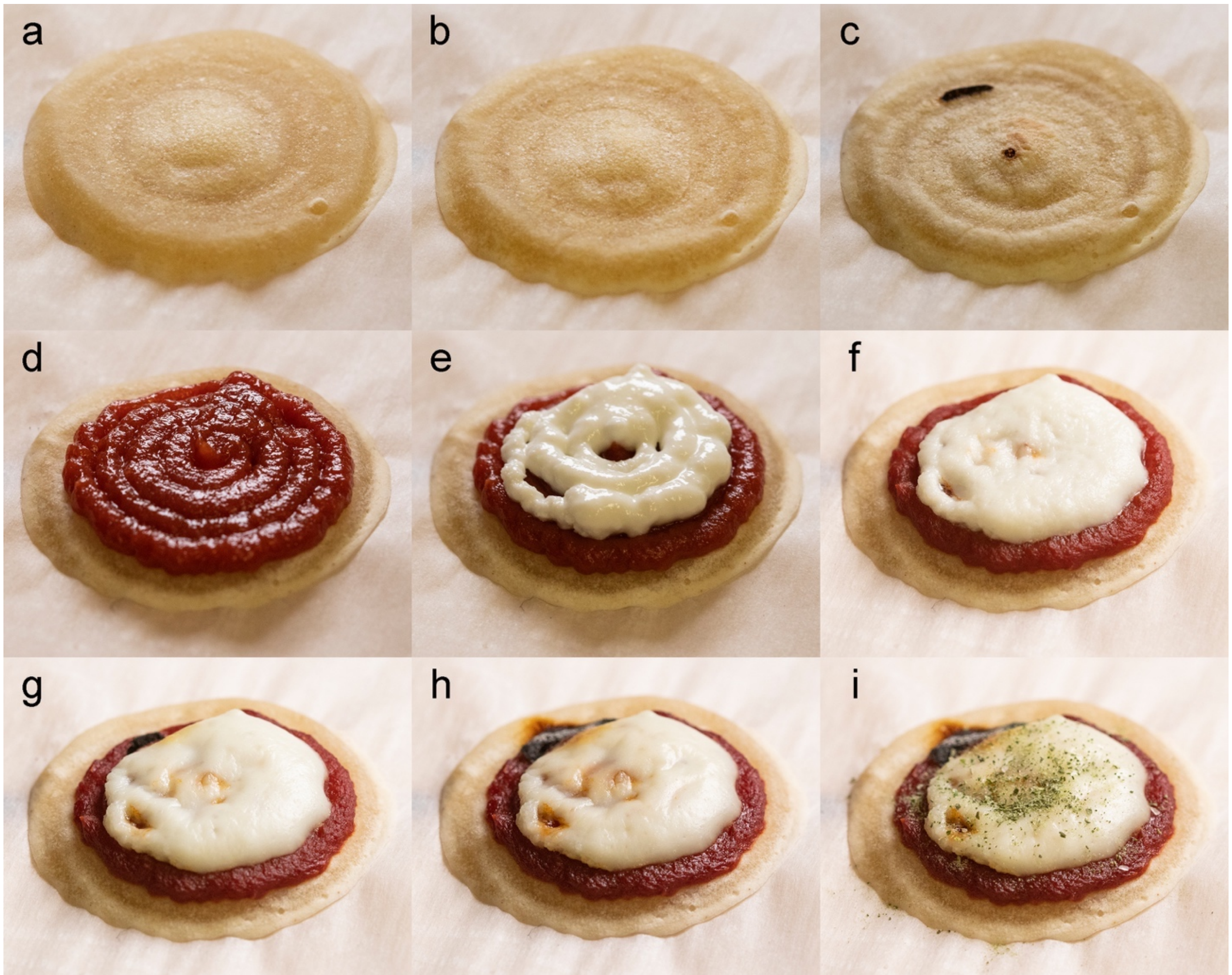

Figure 7 – Construction of a printed and laser-cooked pizza. Printed dough after (**a**) 2 heating cycles, (**b**) 4 heating cycles, and (**c**) 6 heating cycles. **d** Printed sauce onto cooked dough. **e** Printed cheese onto sauce. Printed cheese after (**f**) 1 heating cycle, (**g**) 2 heating cycles, and (**h**) 3 heating cycles. **i** Final-cooked pizza with a touch of basil salt.

Dessert: laser-crusted cheesecake

Initially, we intended to use the blue laser to cook the white filling and the crust of the cheesecake in an effort to achieve browning. Of the two ingredients, however, the crust showed more visual and textural changes from the blue light exposure (**Figure 8b**). Exposing the filling to blue light produced a more translucent color. Conversely, the crust became lighter in color and its texture became more brittle. When tasted, it had a texture more reminiscent of the crumbly texture of baked cookies. **Figure 8a** and **8b** show the same two-ingredient printed cheesecake before and after laser exposure with a 5 W blue laser, respectively. Cook time for the printed cheesecake shown in **Figure 8b** was approximately 4.5 minutes (three cycles of 1.5 minute passes). Other iterations of our cheesecake design can be seen in **Figure 8c**–**8e**.

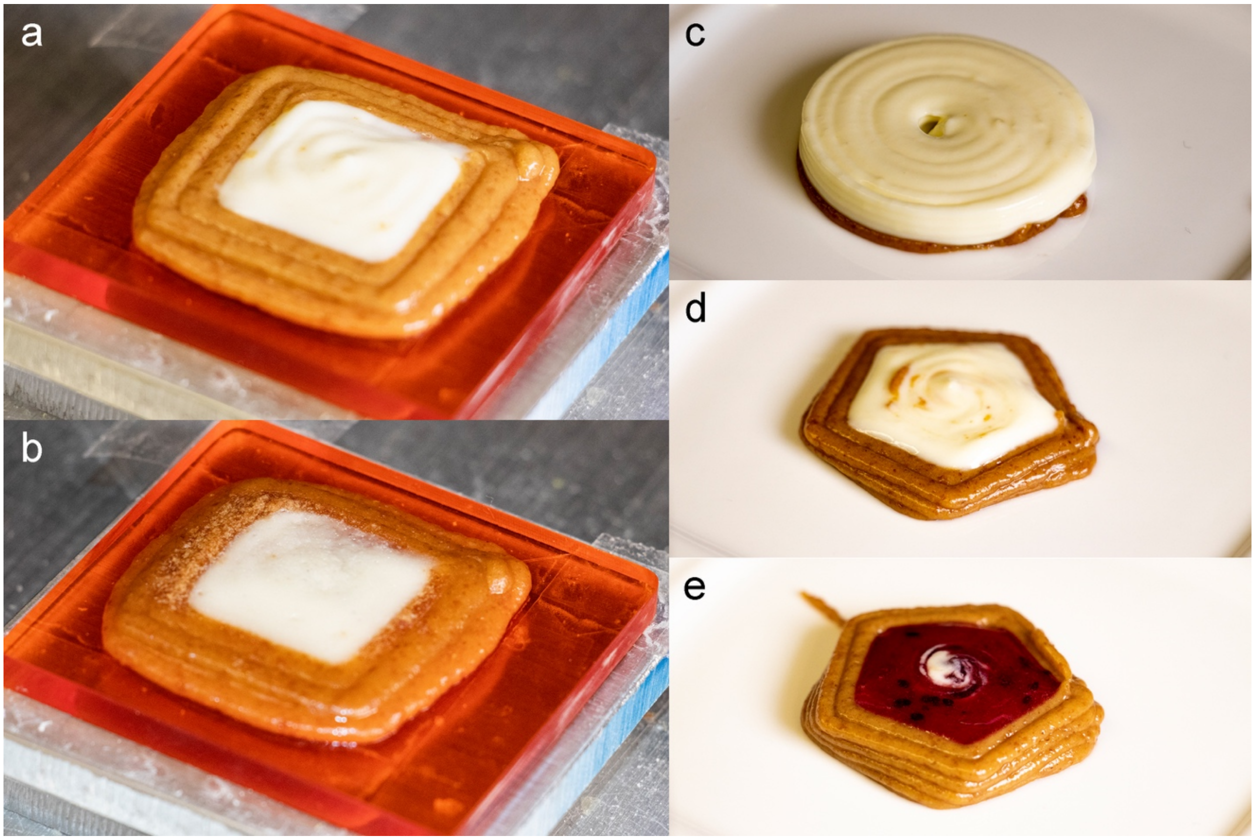

Figure 8 – A printed cheesecake (**a**) before and (**b**) after laser heating. Multiple other (**c**, **d**) two-ingredient and (**e**) three-ingredient cheesecake prints.

Seeing as the crust was more visibly affected by the blue laser light, we ran several more tests to observe to what extent we could spatially control heating to the crust. **Figure 9** shows the single-ingredient prints before and after laser heating. Cook time for square prints (**Figure 9e**) were approximately 5 minutes, while circular prints (**Figure 9f**–**9h**) took closer to 7.5 minutes to cook. The speed of the laser along the trochoidal path for these trials were slower than the full cheesecake cook times in the prior test, so we only had to run one cooking cycle to slightly cook and crust the confectionary ingredient.

To show the degree of spatial control we can achieve with laser cooking, we added a bull's-eye pattern into the crust to demonstrate the precision and customizability of the laser (**Figure 9h**). We assumed that the blue laser was symmetric and Gaussian during the cooking trials, when in actuality it's closer to an ellipsoid. As a result, it heats regions on certain parts of the path more so than others due to the speed and asymmetric spatial distribution of energy of the laser beam.

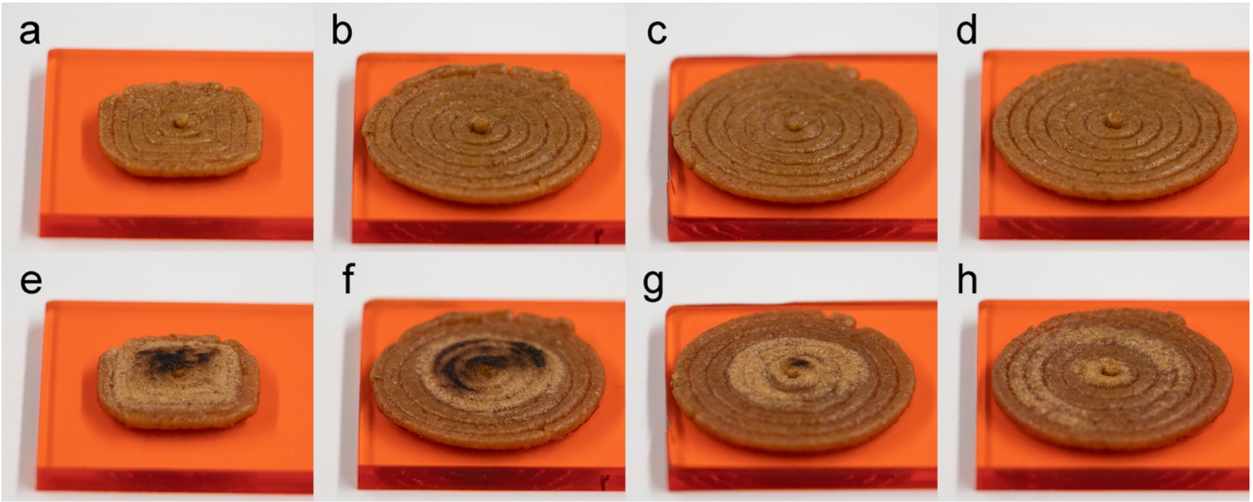

Figure 9 – Printed cheesecake crust (**a**–**d**) before and (**e**–**h**) after laser heating.

Future work
All of these meals were developed and constructed via software. As such, food products constructed in this manner can be tailored and adjusted for nutritional content for a user's wants and needs. Future work would explore the extent to which we quantify the nutritional value of laser-cooked foods, since it's a processing technology that is in its infancy for food. This sort of exploration would also provide more credibility and allow people to accept software cooking as a technology that will provide people with more nutritious and customized foods. We also hope to explore the printing and cooking of vegetables, and to ultimately develop a machine that integrates the printing and cooking of foods into one contained system.

We also plan to explore the idea of closed-loop cooking, which we think will become an integrable part of software-controlled cooking. Closed-loop cooking is imperative on a food printer, especially given that edible materials have vastly different heat capacities, material properties, and temperatures—just to name a few—after printing. Lastly, the idea of medically tailoring meals through this software-based cooking method could have serious repercussion on health care costs and general well-being [34], [35].

Conclusion

Software cooking is a fairly uncharted space that we have explored with the digital creation of a three-course meal. Infusing software into the cooking process creates possibilities for new ingredient combinations, flavor profiles, textures, creative food products, and—most importantly—medically tailored meals. The food objects we produced in this paper were inspired by some of our favorite meals, and while they are only the tip of the iceberg, they aim to showcase a few of the possible combinations that can exist when two digital technologies are merged to construct novel food products. Each of the meals were constructed using actuated systems and cooked via selective laser broiling apparatuses. They were successfully assembled and cooked via software methods and consumed and enjoyed in the end.

References

[1] USDA, "USDA ERS - Americans Spend an Average of 37 Minutes a Day Preparing and Serving Food and Cleaning Up," 2016. [Online]. Available: https://www.ers.usda.gov/amber-waves/2016/november/americans-spend-an-average-of-37-minutes-a-day-preparing-and-serving-food-and-cleaning-up/. [Accessed: 18-Aug-2019].

[2] T. Barlow, "Americans Cook the Least, Eat the Fastest," *Forbes*, 2011. [Online]. Available: https://www.forbes.com/sites/tombarlow/2011/04/15/americans-cook-the-least-eat-the-fastest/#511b37f34162. [Accessed: 18-Aug-2019].

[3] A. Zoran, "Cooking With Computers: The Vision of Digital Gastronomy [Point of View]," *Proc. IEEE*, vol. 107, no. 8, pp. 1467–1473, Aug. 2019.

[4] D. Periard, N. Schaal, M. Schaal, E. Malone, and H. Lipson, "Printing Food," in *Proceedings of the 18th Solid Freeform Fabrication Symposium*, 2007, pp. 564–574.

[5] E.-J. Sol, D. Vd Linden, and K. V Bommel, "3D Food Printing: The Barilla collaboration," 2015.

[6] C. E. Ltd, "Complete 3D Chocolate Printing Guide [FAQ] Other."

[7] A. Shah, "BeeHex Aims to Bring 3D Printing to Print Food , One Pizza at a Time," *Xconomy*, 2017. [Online]. Available: https://www.xconomy.com/texas/2017/02/01/beehex-aims-to-bring-3d-printing-to-food-one-pizza-at-a-time/.

[8] "Natural Machines: The makers of Foodini - a 3D food printer making all types of fresh, nutritious foods." [Online]. Available: https://www.naturalmachines.com/. [Accessed: 30-Nov-2017].

[9] "3D Food Printer | Focus | byFlow." [Online]. Available: https://www.3dbyflow.com/. [Accessed: 23-Aug-2019].

[10] M. Willett, "3D Systems ChefJet Printers - Business Insider." [Online]. Available: http://www.businessinsider.com/3d-systems-chefjet-printers-2014-9. [Accessed: 30-Nov-2017].

[11] E. Hertafeld *et al.*, "Multi-material Three-Dimensional Food Printing with Simultaneous Infrared Cooking," *3D Print. Addit. Manuf.*, p. 3dp.2018.0042, Nov. 2018.

[12] R. N. Carmody and R. W. Wrangham, "The energetic significance of cooking," *J. Hum. Evol.*, vol. 57, no. 4, pp. 379–391, Oct. 2009.

[13] W. S. Ratnayake and D. S. Jackson, "Starch gelatinization.," *Adv. Food Nutr. Res.*, vol. 55, pp. 221–68, Jan. 2009.

[14] D. R. Lineback and E. Wongsrikasem, "Gelatinization of starch in baked products," *J. Food Sci.*, vol. 45, no. 1, pp. 71–74, Jan. 1980.

[15] B. Zanoni, A. Schiraldi, and R. Simonetta, "A naive model of starch gelatinization kinetics," *J. Food Eng.*, vol. 24, no. 1, pp. 25–33, Jan. 1995.

[16] E. Tornberg, "Effects of heat on meat proteins – Implications on structure and quality of meat products," *Meat Sci.*, vol. 70, no. 3, pp. 493–508, Jul. 2005.

[17] C. Bircan and S. A. Barringer, "Determination of Protein Denaturation of Muscle Foods Using the Dielectric Properties," *J. Food Sci.*, vol. 67, no. 1, pp. 202–205, Jan. 2002.

[18] J. P. Danehy, "Maillard Reactions: Nonenzymatic Browning in Food Systems with

Special Reference to the Development of Flavor," *Adv. Food Res.*, vol. 30, pp. 77–138, Jan. 1986.
[19] E. Purlis, "Browning development in bakery products – A review," *J. Food Eng.*, vol. 99, no. 3, pp. 239–249, 2010.
[20] A. K. Datta and V. Rakesh, "Principles of Microwave Combination Heating," *Compr. Rev. Food Sci. Food Saf.*, vol. 12, no. 1, pp. 24–39, Jan. 2013.
[21] J. D. Blutinger, Y. Meijers, P. Y. Chen, C. Zheng, E. Grinspun, and H. Lipson, "Characterization of CO2 laser browning of dough," *Innov. Food Sci. Emerg. Technol.*, vol. 52, pp. 145–157, Mar. 2019.
[22] J. D. Blutinger, Y. Meijers, and H. Lipson, "Selective laser broiling of Atlantic salmon," *Food Res. Int.*, vol. 120, pp. 196–208, Feb. 2019.
[23] J. D. Blutinger, Y. Meijers, P. Y. Chen, C. Zheng, E. Grinspun, and H. Lipson, "Characterization of dough baked via blue laser," *J. Food Eng.*, vol. 232, pp. 56–64, Sep. 2018.
[24] P. Y. Chen, J. D. Blutinger, Y. Meijers, C. Zheng, E. Grinspun, and H. Lipson, "Visual modeling of laser-induced dough browning," *J. Food Eng.*, vol. 243, pp. 9–21, Feb. 2019.
[25] K. Fukuchi, K. Jo, A. Tomiyama, and S. Takao, "Laser cooking," in *Proceedings of the ACM multimedia 2012 workshop on Multimedia for cooking and eating activities - CEA '12*, 2012, p. 55.
[26] A. Gracia and E. Sepulveda, "Apparatus and method for heating and cooking food using laser beams and electromagnetic radiation WO 2016053681 A1," WO 2016053681 A1, 2015.
[27] I. Singh, "Method and apparatus for plasma assisted laser cooking of food products US 2013/0344208 A1," US 2013/0344208 A1, 2013.
[28] J. Blutinger, H. Lipson, and Y. Meijers, "Method and systems for laser-based cooking," 18-Apr-2019.
[29] "Repetier Software," 2019. [Online]. Available: https://www.repetier.com/. [Accessed: 28-Aug-2019].
[30] C. Sandu, "Infrared Radiative Drying in Food Engineering: A Process Analysis," *Biotechnol. Prog.*, vol. 2, no. 3, pp. 109–119, Sep. 1986.
[31] K. Eichner and M. Karel, "Influence of water content and water activity on the sugar-amino browning reaction in model systems under various conditions," *J. Agric. Food Chem.*, vol. 20, no. 2, pp. 218–223, Mar. 1972.
[32] E. Pustinger, "Can we 3D print our food?" [Online]. Available: https://www.bbc.com/reel/video/p07l59b1/can-we-3d-print-our-food-. [Accessed: 23-Aug-2019].
[33] E. Purlis and V. O. Salvadori, "Modelling the browning of bread during baking," *Food Res. Int.*, vol. 42, no. 7, pp. 865–870, 2009.
[34] D. Mozaffarian and D. Glickman, "Our food is killing too many of us," *The New York Times*, 27-Aug-2019. [Online]. Available: https://www.nytimes.com/2019/08/26/opinion/food-nutrition-health-care.html?auth=login-email&login=email. [Accessed: 31-Aug-2019].
[35] D. Mozaffarian, J. Mande, and R. Micha, "Food Is Medicine—The Promise and Challenges of Integrating Food and Nutrition Into Health Care," *JAMA Intern. Med.*, vol. 179, no. 6, p. 793, Jun. 2019.