Digital cooking could increase the availability of nutritious meals

Jonathan Blutinger (jdb2202@columbia.edu)
Columbia University https://orcid.org/0000-0002-5075-5757
Shravan Karthik
Columbia University
Alissa Tsai
Columbia University https://orcid.org/0000-0003-1493-0279
Yorán Meijers
Wageningen University & Research
Hod Lipson
Columbia University

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Abstract

Health, convenience, and cost – herein lies the predicament that we all face when deciding on a meal, which two do you pick? With price usually being the biggest influencer, we tend to sacrifice health or convenience. Multi-ingredient food printing combined with laser cooking could offer a way out of this conundrum: A viable method for convenient, nutritious, low-cost meals, yet has never been demonstrated. Here we showcase the advantages of marrying software with food through the creation of digitally-crafted meals.

Main

Revolutions in food science over the past few centuries have enabled mass food preparation techniques to produce food at a large scale and with a longer shelf life, making it easier to transport and disseminate food commercially[1]. Urbanization and industrialization catalyzed this food revolution, and now we find ourselves on the cusp of the next revolution—the injection of software and robotics into individualized meal production. With food trending towards mass production, we lose our ability to customize, but software bridges this gap. Robotics is already beginning to change the way we think about production in three-dimensional (3D) printing, an additive manufacturing technique, and it's growing rapidly[2].

Robotized methods for producing foods have also burgeoned ranging from assistive articulated arms[3,4] to automated meal preparation machines[5–8]. The use of additive manufacturing (AM) in food began in 2007[9] and has since been explored by academics and by commercial companies[6–8,10–14]. Food printing involves a roboticized system that deposits food pastes, powders, and liquids in a precise spatial arrangement, according to a digital blueprint.

But while current food printers can provide a chef with more autonomy and automation in the kitchen, they are somewhat limited to preparatory functions for few ingredients and don't have any cooking abilities. The real potential is for systems that can (1) print with multiple ingredients, (2) cook inline, and (3) give individuals personalized meal design options. Meeting all of these consumer demands while remaining cheap, convenient, and healthy[15–18] is the ultimate task at hand for this emerging class of personal food production appliances.

As a demonstration of this approach, we challenged ourselves to create a system that can combine many ingredients and cook them in-line. We printed and laser-cooked a range of software-generated meals (see Supplementary Table S1 for recipes) and successfully automated the creation of a seven-ingredient cheesecake (Fig. 1a), which—to our knowledge—is a record setting number of ingredients in a single printed food product. We used a blue laser (operating at 445 nm) and a near-infrared laser (operating at 980 nm) as precision heating appliances since they have emerged as a versatile cooking technology for thin-layered ingredients[19–22].

The expectations versus reality gap of foods that have been physically realized from a digital medium gets wider as the food comprises more complex geometries and more ingredients. Our cheesecake print (Fig. 1), for example, required six design iterations before reaching a stacked ingredient form that was structurally stable to print (Supplementary Video 1). Mechanical factors such as compression and sagging of ingredients, slight perturbations in temperature, and non-uniformity of deposited ingredients can introduce flaws which compound errors depending on when they occur over the course of a 30 minute print (Supplementary Fig. S1).

We found that food materials need to be classified as a “structural” or “filler” ingredient based on viscoelastic properties, such that they can be more accurately placed within a design model to eliminate likelihood of failure. For example, our printed cheesecake needed to be at least 70% graham cracker paste —thickest of the printed ingredients—by volume to achieve a structurally stable product. Initial prints used a more distributed composition of ingredients. With each successive design iteration, the use of more graham cracker throughout the structure contributed to the success of these prints (see Supplementary Table S2).

Most print failures can be attributed to lack of structural rigidity of the softer ingredients. The two main methods of layering ingredients in a multi-material food product are by pooling ingredients (Fig. 2a, 2b, 2c, 2d), layering ingredients (Fig. 2e, 2f), or using some combination of both (Fig. 2g, 2h). Structural material properties greatly inform the design of all foods; dough is the foundation of pizza and crust is the foundation of most pies. This is what incentivized us to use a shelled approach to form pools to hold less structurally stable foods[23], which proved to be most effective.

As important as appearance, taste, and smell can be on accepting a food for consumption[24], texture is something that most people reference when describing the palatability of a meal[25]. Ingredients that are ideal for printing tend to exhibit shear-thinning behavior, a non-Newtonian behavior of fluids where viscosity decreases under higher shear strain (i.e. they act like a fluid during deposition and a solid once deposited onto a plate) and are, therefore, much softer. Most foods we eat, however, are palatable since they have a variable texture throughout the food product.

To achieve high-fidelity texturization we utilize heat from visible and infrared diode lasers to cook printed food products. Lasers are ideal in this setting since they can be precisely controlled in software, they have various cooking modalities (e.g. baking, browning, broiling, grilling, etc.), and they are compact (Supplementary Fig. S3, S4). In our experiments, laser cooking has a resolution of about 2mm.

Cooking via laser has different results based on the food. Radiative heating with a blue laser induces a lighter color change on graham cracker paste (Supplementary Fig. S5), a lighter color change on the tofu-curry bite (Fig. 2a), a darker color on the tofu-tomato square (Supplementary Fig. S2b), and a range of both on the pizza dough (Fig. 2e). Slight textural changes were also observed in the graham cracker paste as well as the printed pizza, which both stiffened slightly after laser-heating.

While some printers have the hardware capacity to print with more than three ingredients, design software and slicer engines—software that converts designs into coordinated commands for a 3D printer—that support multi-material food printing and cooking do not exist. We have demonstrated the robustness of our slicer engine (*Juli3nne*), by assembling and cooking the most complex seven-ingredient print to date; but this is just the tip of the iceberg. Machines under development that can accommodate dozens of ingredients, will face a problem of recipe and ingredient availability. There currently exists no public repository of printable food ingredients or digital recipes for printing. This is akin to having an iPod with no mp3 music files to play. Supportive ecosystems need to be developed to foster the growth of this technology: a repository of printable ingredients, a repository of digital recipes, a design software to model printable meals, and a supply chain for the manufacturing and dissemination of food capsules.

This work sheds light on some of the challenges involved in realizing the potential of multi-material food printing, which stems from rheological variance in printed ingredients. It took the engineering community three decades to master the art of printing in a few plastics and metals[26]; it might take a while to master the more complex scope of food materials. We need to account for food's viscoelastic sensitivity by either controlling the printing environment (e.g. a consumer's kitchen) or by creating a closed feedback loop to adjust the printing process *in situ*. We can take a software approach to address material variances in a multi-ingredient print but further modeling is required for the commercial success of this technology.

This is the beginning of a new era, not just defined by the technology or by the business ecosystem, but by the quantitative understanding of the nutritional ecosystem, and the creation of easy, cheap, and healthy foods driven by quantitative personalize nutrition. Digital cooking allows for new flavor profiles, variable textures, and medically-tailored meals to be designed for and by the end consumer. The obesity epidemic and malnutrition is a systemic problem that stems, in part, from the lack of convenience of low-cost nutritious foods[27]. Many give up health only because they have a harder time giving up cost and convenience. While there are many policy approaches to addressing nutritional health, technology can also help resolve the "pick any two" food tradeoff.

Methods

Ingredient preparation and printing

To minimize processing and preparation time, we largely chose ingredients that were premade or off-the-shelf. For the ingredients that required processing prior to printing, we used an FP-8GMFR Food Processor (Cuisinart, Stamford, USA) and a Spinzall food centrifuge (Booker and Dax, New York, USA). More details on sample preparation can be found in Supplementary Section S1, S2, and S3. More details on the printing mechanism can be found in Supplementary Section S4.

Designing multi-ingredient foods for printing

Food products were modeled in SolidWorks (Dassault Systémes, Vélizy-Villacoublay, France), a commonly used computer-aided design (CAD) software. Each ingredient was designed in a separate part file, and the multi-ingredient food product was constructed as an assembly. Figure 1 shows a design rendering of a modeled cheesecake fully assembled (Fig. 1a) and as an exploded cross-section (Fig. 1b). We wanted to replicate an aesthetic that is similar to a slice of cake. We chose this design for three reasons: 1) a 'slice' of cake is a familiar shape representing a smaller part of a larger whole, 2) cakes have a number of ingredients that are layered in succession, and 3) there's a celebratory association with eating it.

Slicer engine

Once a food product has been designed in CAD, it's exported as a stereolithography (STL) file which represents the surface geometry of the object. To enable printing, the STL representation needs to be converted into layers (slices) and a path to fill these slices must be specified. An open-source library (*Slic3r*) is used to slice the STL file into code that is printable. G-code is the de-facto standard to instruct mechanized tools to make objects. We modify the *Slic3r* library to ensure that our ingredients can be printed, customize the software to enable multi-ingredient products, and enable printing and cooking in succession. Details of this customized *Slic3r* library for printing (called *Juli3nne*) are described in Supplementary Section S5.

Declarations

Data availability

Software and G-code used in the printing of the Cheesecake are provided as electronic supplemental materials.

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Author information

Affiliations

Department of Mechanical Engineering, Columbia University in the City of New York, 500 West 120th St., Mudd 220, New York, NY, 10027, USA

Jonathan David Blutinger, Shravan Karthik, Alissa Tsai, Yorán Meijers, Hod Lipson

Department of Food Technology, Wageningen University, 6708 PB, Wageningen, Netherlands

Yorán Meijers

Contributions

H.L. supervised the research. J.B. and H.L. developed the concept. J.B., S.K., and A.T. executed all of the experiments and analyzed the data. S.K. developed the slicer software used in the experiments. J.B., S.K., A.T., Y.M., and H.L. composed and edited the manuscript.

Competing interests

The authors declare no competing financial or non-financial interests.

Corresponding author

Correspondence to Jonathan Blutinger.

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Figures

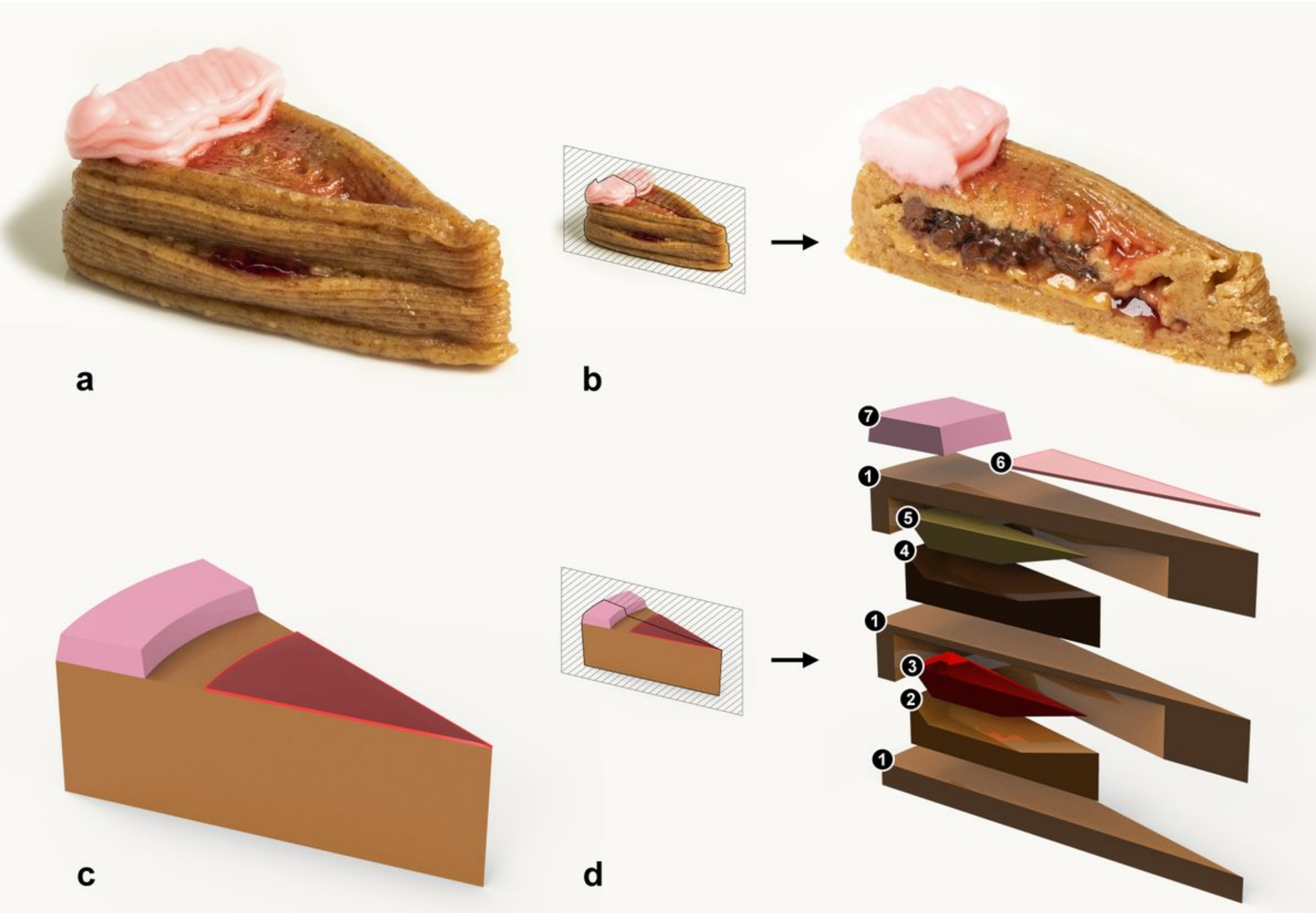

Figure 1

Seven-ingredient printed cheesecake. a, Final printed food product with laser-crusted top surface (total cook time was approximately 4 minutes, 80 seconds for three cooking cycle at a laser power of 5 – 6 W). b, Cross-sectional view of final-cooked print. c, Graphical rendering of final design iteration of cheesecake. d, Cross-sectional exploded view rendering of cheesecake showing (1) graham cracker, (2) peanut butter, (3) jelly, (4) Nutella, (5) banana, (6) cherry juice, and (7) frosting.

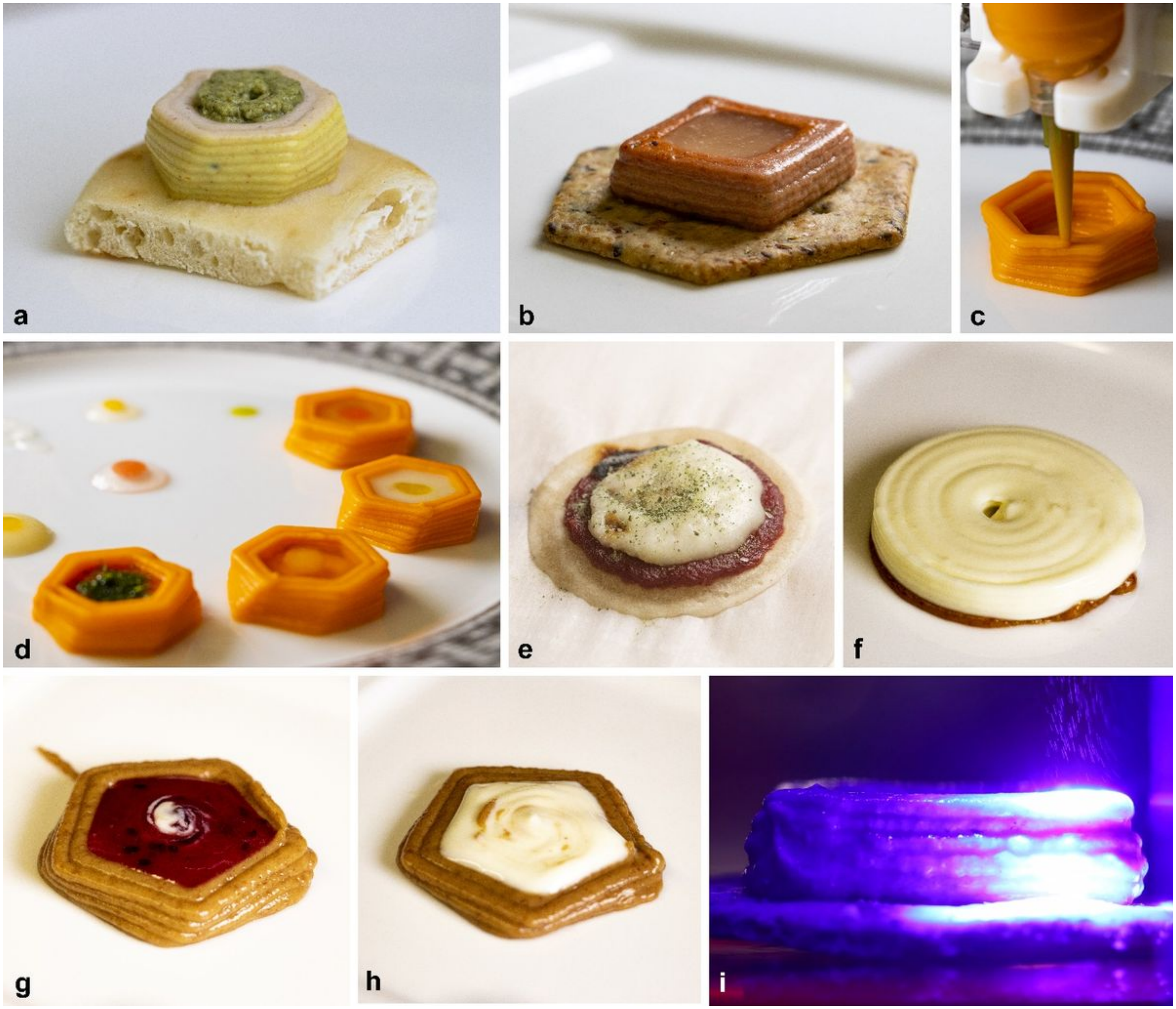

Figure 2

Digitally-crafted meals. a, Tofu-curry spiral with a pesto infill printed on a slice of naan. b, Tofu-tomato square with a miso glaze infill printed on a cracker (Supplementary Fig. S2). c and d, Printed carrot puree structures with various liquid infills. e, A three-ingredient printed and laser-cooked pizza. f, g, and h, Three different variations of a printed cheesecake. i, Side view of the tofu-tomato square (b) being broiled by a blue laser.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterials.docx

- SupplementaryVideo1lowres.mp4
- finalcheesecake.txt