Future Foods 9 (2024) 100375

Contents lists available at ScienceDirect

Future Foods

journal homepage: www.elsevier.com/locate/fufo

Dynamic simulation of 3D-printed foods

Shir Goldfinger [a,c,*], Hod Lipson [b], Jonathan Blutinger [b,d]

[a] California Institute of Technology, 1200 E California Blvd., Pasadena, CA, 91125, USA
[b] Department of Mechanical Engineering, Columbia University in the City of New York, 500 West 120th St., Mudd 220, New York, NY, 10027, USA
[c] Department of Radiology, University of Pennsylvania, 3400 Spruce Street, Philadelphia, PA 19104, USA
[d] U.S. Army DEVCOM Soldier Center, General Greene Ave, Natick, MA, 01760, USA

ARTICLE INFO

Keywords:
Dynamic simulator
3D food printing
Rheology
Additive manufacturing
Fluid modeling
Autodesk Maya

ABSTRACT

Simulation environments for 3D-printed structures are crucial to assess failure modes prior to printing. Multi-ingredient additive manufacturing (AM) of food is particularly susceptible to failure due to differences in ingredient viscoelasticity. Current simulation software handles objects in their final fabricated form. Here, we present a simulation framework that digitally replicates the deposition process of disparate material pastes using a physics-based simulator. Our simulator takes a digital recipe file (G-code) as input and uses Bifrost—a plug-in for Autodesk Maya—to generate a digital replica of the 3D printing process. We ground truth our print simulator by successfully reproducing a custom designed seven-ingredient dessert. Designs that are dynamically simulated prior to being printed develops user intuition for stable structures, mitigates material waste, and enables faster proofing of printable designs to achieve structural and aesthetic creations.

1. Introduction

Unlike conventional fused-deposition modeling (FDM), the substrates for a food printer are edible and can range vastly in terms of rheology (Zhu et al., 2019). The preferred medium for these printed ingredients are uniform and consistent pastes that exhibit shear-thinning behavior (e.g. peanut butter or chilled cream cheese) (Hertafeld et al., 2019; Periard et al., 2007). Contrary to more conventional filament-based FDM that utilize man-made materials—like plastic—for printing, food rheology properties are very sensitive to shifts in temperature (Cancela and Maceiras, 2006). Printers that have sensors for closed-loop control have the ability to minimize errors during printing (Baumann and Roller, 2016; Ma et al., 2023), but commercial models and those developed in academic research, more often than not, are open-loop and are thus more prone to failure (Hertafeld et al., 2019; Blutinger et al., 2023).

While plenty of research exists on the modeling of processed foods and shape deformations for accurate digital replication (Stomakhin et al., 2014; Ram et al., 2015,10; Chen et al., 2019), no simulation environments exist for testing 3D-printed part models for error prevention. Objects crafted via additive manufacturing (AM)—especially food “inks”—can have multiple failure points. Issues during printing can be threefold: (1) hardware, where a nozzle clogs or a motor stops moving; (2) software, where the slicer-engine incorrectly interprets a design file into a digital recipe file; or (3) design, where the material rheology cannot accommodate the intended structural design (Wolfs and Suiker, 2019; Blutinger et al., 2023).

Here, we generate a physics-based modeling framework to simulate digital recipe files in a virtual environment to address the third failure point. Bifrost, a plug-in for Autodesk Maya, is used as a simulation engine to test print files based on the rheological properties of the ingredients used. Designs are ground-truthed by physically printing them to qualitatively validate findings. This research will stand as a benchmark for future food AM software, to mitigate print failures, and to improve our design intuition for multi-ingredient 3D structures.

2. Simulation

Because of the complexity of the properties of the food ingredients, it is important to be able to simulate single- and multi-ingredient food designs prior to printing as a means of validation. Programs such as Repeteir-Host allow for the visualization of G-code (digital recipe file format) (Sukindar et al., 2017), which consists of data such as the 3D printing coordinates, ingredient feed rate, and printer instructions for switching between ingredients. Such programs fail to incorporate the viscoelastic properties of the ingredients used; one would need a more

* Corresponding author.
E-mail addresses: shirg@sas.upenn.edu, sgoldfin@caltech.edu (S. Goldfinger).

https://doi.org/10.1016/j.fufo.2024.100375
Received 10 March 2024; Received in revised form 3 May 2024; Accepted 14 May 2024
Available online 17 May 2024

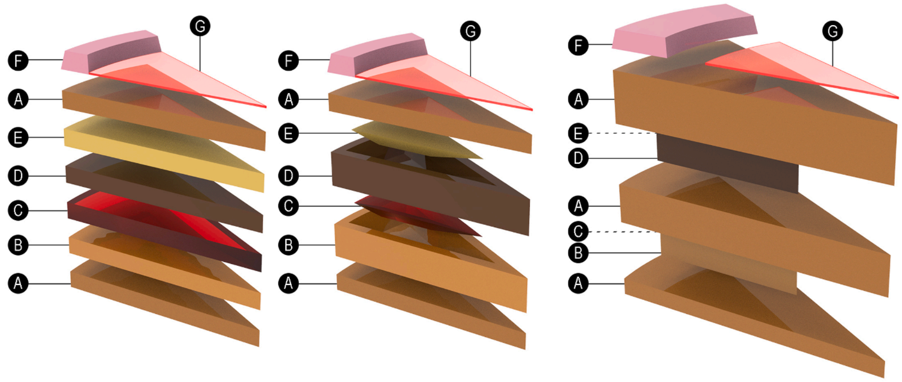

Fig. 1. Visualization of three different printed food structures. Ingredients are listed as follows: (A) graham cracker paste, (B) peanut butter, (C) jelly, (D) Nutella, (E) banana puree, (F) frosting, and (g) cherry juice. (Left) Version 1 of the cheesecake has each ingredient with an equal thickness. (Middle) Version 2 of the cheesecake uses peanut butter and Nutella as collection pools for thinner ingredients. (Right)Version 3 of the cheesecake uses the most graham cracker paste for structural support. The dotted lines indicate that ingredients are hidden from the view but nested within the structure. This visualization does not take the viscoelastic characteristics of the ingredients into account.

advanced method of visualization to get an accurate food print model. We showcase a dynamic simulator capable of modeling the viscoelastic properties of food ingredients during the 3D printing process.

Autodesk Maya (Autodesk, San Francisco, California, USA) was used to create advanced simulations of the AM process. Initially, Maya's nParticle Liquid Simulations were considered to model final print designs due to their ability to simulate fluids contained within a particular shape/mesh. While these simulations would allow us to directly evaluate a mesh of the final print, they would be unable to capture failures in design integrity that occur during the printing process itself.

Instead, Maya's animation feature, which allows the user to set object location and property keyframes to create smooth animations (Terra and Metoyer, 2004), could be used along with Bifrost to create simulations of the entire printing process. Bifrost is a physics-based simulator that models fluids as system of point particles given properties such as surface tension, density, and viscosity. To model different ingredients in our simulator, each Bifrost Emitter (i.e. simulated food "inkwell") was given a user-defined dynamic viscosity and mesh color to simulate each ingredient (15). While other properties such as density or the heterogeneity of the ingredient itself could influence the printing process, dynamic viscosity defines a particular ingredient's resistance to deformation, making it integral to the prediction of ingredient rigidity and thus to the structural integrity of a print design.

Using coordinates and feed rates specified in the G-code (i.e. recipe file), animation keyframes for an ovoid mesh were set to mimic the food extrusion process. In doing so, the simulation modeled the flow of the different ingredients as they were being printed according to the recipe file. The file that was used for physical printing and for simulation generation were identical. Each Bifrost Liquid was deposited along the same toolpath and thus represents a digital surrogate of each printed ingredient.

In reality, as a new ingredient is being deposited onto an already printed one, some degree of deformation or buckling will occur due to the increased downward force from extrusion. Due to computational limitations, however, each Bifrost Fluid being deposited in simulation was set as a "collider" and ingredients that had already been deposited became part of a static mesh; in other words, different ingredients printed in simulation cannot interact with one another. Fig. 1 shows

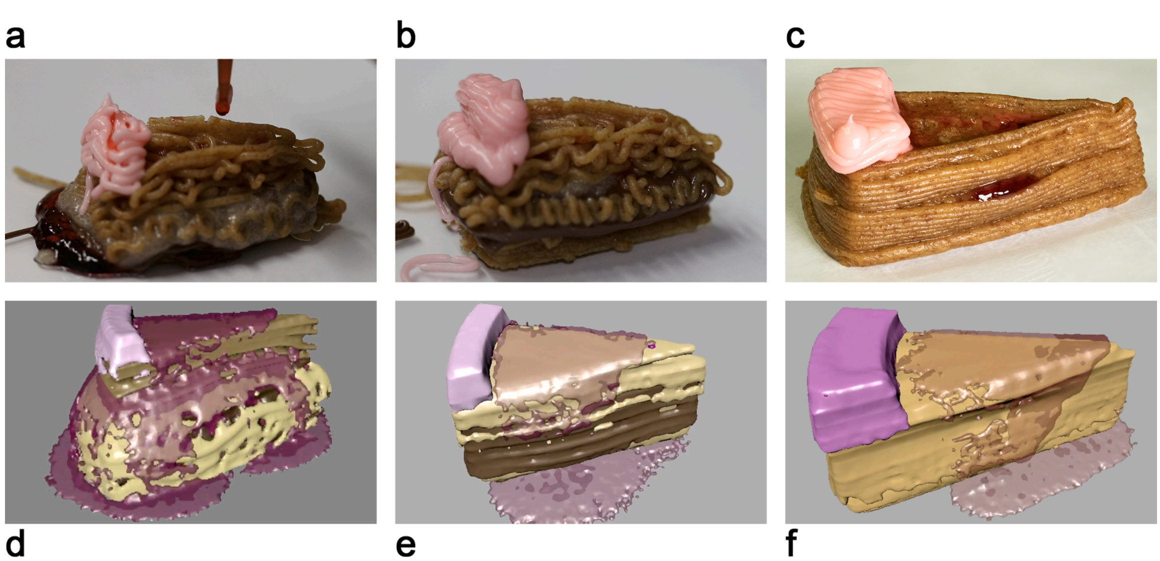

Fig. 2. Comparison of three different cheesecake structure real print iterations (top) with their corresponding simulations(bottom, a) the first iteration collapsed due to the low-viscosity ingredients at its base, as was seen in both the simulation and the real print, (b) the second iteration used its higher-viscosity base ingredients (peanut butter and Nutella) in higher quantities, and this resulted in a sturdier structure, as was seen in both the simulation and the real print (c) the last iterationutilized the high-viscosity graham cracker crust throughout the entirety of the print to support the low-viscosity ingredients, resulting in the sturdiest structure of the three prints, as was seen in both the simulation and the real print.

exploded views of three different printed cake structures that were simulated with our software engine and Supplementary Table 1 details the ingredients' dynamic viscosities used to define the individual Bifrost Emitters.

3. Results and discussion

In summary, we demonstrate a dynamic simulator that can accurately replicate the multi-material printing process for food "inks" with different viscoelastic properties (Supplementary Video 1). The successes and failures of each ground-truthed cake structure were successfully predicted by our simulation (Fig. 2). Designs that layered soft ingredients in succession tended to crumble under stress (Fig. 2, a and d) but structures that layered thinner ingredients within more viscous walls (Fig. 2, c and f) tended to hold their shape with less deformation.

The main difference between the simulated and the real-life printed structures was the interaction between ingredients. A limitation of Bifrost Fluids is that they don't have the ability to interact completely, as their particles cannot mix and bounce off one another. To overcome this, we have allowed the interaction of the Solid Bifrost Meshes instead. While this allowed us to layer ingredients to some accuracy, it is not nearly as accurate as having full Bifrost particle interactions. Further iterations of this engine could also be adapted to accommodate thermally processed foods. This would involve a more complex simulation with Bifrost Meshes having variable viscosities that are time-dependent. Moreover, laser cooking is a versatile cooking method that is particularly well-suited for food AM (Hertafeld et al., 2019; Blutinger et al., 2023; Blutinger et al., 2021) and would also allow more complex designs to be realized due to the increased stiffness that results from thermal processing.

Due to the novelty of creating a dynamic print simulator, this paper considered a more qualitative approach to developing and testing the simulator. In the future, a quantitative analysis of the differences between the print simulations and the real print structures can be done. In this analysis, features (i.e. height, width, weight) of both the real print and simulation print could be measured throughout the printing process and compared to obtain percent error values. The viscoelastic properties of the ingredients in simulation could then be iteratively adjusted to minimize the error.

Software is a major enabling technology for food fabrication. The primary limitation to commercializing food printing for consumer use is a lack of digital infrastructure. Standardized design software, recipe repositories, and food "ink" cartridges don't exist—at present—for food printing technology. The dynamic simulator presented in this paper is necessary for the development of future food design software and other hybrid 3D printing applications. It will serve as a validation engine and can also be integrated into generative design software to create optimized food structures based on user-specified ingredients.

CRediT authorship contribution statement

Shir Goldfinger: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation. **Hod Lipson:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jonathan Blutinger:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Code availability

All code used to generate supporting visuals can be found in the Supplementary Information.

Acknowledgements

S.G. was supported in part by the Kiyo and Eiko Tomiyasu Scholarship. H.L. and J.B. were supported in part by the US National Science Foundation (NSF) AI Institute for Dynamical Systems (dynamicsai.org), grant 2112085, and by a grant from the Redefine Meat Ltd. (redefinemeat.com).

Ethical statement

This work did not involve the use of human or animal subjects.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2024.100375.

References

Baumann, F., Roller, D., 2016. Vision based error detection for 3d printing processes. In: MATEC web of conferences, 59. EDP Sciences, p. 06003.

Blutinger, J.D., Cooper, C.C., Karthik, S., Tsai, A., Samarelli, N., Storvick, E., Seymour, G., Liu, E., Meijers, Y., Lipson, H., 2023. The future of software-controlled cooking. npj Sci. Food 7 (1), 6.

Blutinger, J.D., Tsai, A., Storvick, E., Seymour, G., Liu, E., Samarelli, N., Karthik, S., Meijers, Y., Lipson, H., 2021. Precision cooking for printed foods via multiwavelength lasers. npj Sci. Food 5 (1), 24.

Chen, P.Y., Blutinger, J.D., Meijers, Y., Zheng, C., Grinspun, E., Lipson, H., 2019. Visual modeling of laser-induced dough browning. J. Food Eng. 243, 9–21.

łvarez, E.A, Cancela, M., Maceiras, R., 2006. Effect of temperature on rheological properties of different jams. Int. J. Food Propert. 9 (1), 135–146.

Hertafeld, E., Zhang, C., Jin, Z., Jakub, A., Russell, K., Lakehal, Y., Andreyeva, K., Bangalore, S.N., Mezquita, J., Blutinger, J., et al., 2019. Multi-material three-dimensional food printing with simultaneous infrared cooking. 3D Print. Addit. Manufact. 6 (1), 13–19.

Ma, Y., Potappel, J., Chauhan, A., Schutyser, M.A., Boom, R.M., Zhang, L., 2023. Improving 3d food printing performance using computer vision and feedforward nozzle motion control. J. Food Eng. 339, 111277.

Periard, D., Schaal, N., Schaal, M., Malone, E., Lipson, H., 2007. Printing food. In: 2007 International Solid Freeform Fabrication Symposium.

Ram, D., Gast, T., Jiang, C., Schroeder, C., Stomakhin, A., Teran, J., Kavehpour, P., 2015. A material point method for viscoelastic fluids, foams and sponges. In: Proceedings of the 14th ACM SIGGRAPH/Eurographics Symposium on Computer Animation, pp. 157–163.

H. Shao, L. Huang, D.L. Michels, A fast unsmoothed aggregation algebraic multigrid framework for the large-scale simulation of incompressible flow.

Stomakhin, A., Schroeder, C., Jiang, C., Chai, L., Teran, J., Selle, A., 2014. Augmented mpm for phase- change and varied materials. ACM Transactions on Graphics (TOG) 33 (4), 1–11.

Sukindar, N.A., k. a. Mohd ariffin, M., Baharudin, B.T., Ismail, M.I.S., Jaafar, C., 2017. Analysis on the impact process parameters on tensile strength using 3d printer repetier-host software. J. Eng. Appl. Sci. 12, 3341–3346.

Terra, S.C.L., Metoyer, R.A., 2004. Performance timing for keyframe animation. In: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation, pp. 253–258.

H. Watt, Simulate small-scale liquids in bifrost, 3D World (263).

Wolfs, R., Suiker, A., 2019. Structural failure during extrusion-based 3d printing processes. Int. J. Adv. Manufact. Technol. 104, 565–584.

Zhu, S., Stieger, M.A., van der Goot, A.J., Schutyser, M.A., 2019. Extrusion-based 3d printing of food pastes: correlating rheological properties with printing behaviour. Innov. Food Sci. Emerg. Technolog. 58, 102214.