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Digital gastronomy testcase: A complete pipeline of robotic induced dish variations

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ABSTRACT

Digital Gastronomy (DG) is a research territory exploring the integration of computational technologies in the kitchen, seeking a *human-centered practice* in DG, rather than replacing the chef with a machine. Our work highlights the *creative potential* of computers in the kitchen, presenting an in-depth investigation on the DG *Variations* principle (one recipe with infinite instantiations), demonstrated on a robotic induced noodle soup project. We contribute a new, complete DG cooking approach of an *end-to-end restaurant pipeline,* and evaluate the *technical* feasibility of the process, including: (1) a custom *multi-resolution paste 3D printer* that overcomes the slow printing time of prior paste printers; and (2) a novel *interactive graphic Dish Design application* to parametrically plan 3D printed noodles; all demonstrated using a new printable noodle paste and a special soup recipe. We discuss the technical outcomes and performance of our proposed DG pipeline using a comparison study on printing performance, and present chefs' reflection on the concept of design and control of segregation using GUI and a robotic paste printer, leading to general insights for the future of DG.

1. Introduction

Digital Gastronomy (DG) is a research territory investigating how, and why, we can use digital technologies in the kitchen, aiming to enhance traditional cooking with new computational capabilities (Mizrahi et al., 2016; Zoran and Cohen, 2018). DG continues a line of research in human-computer interaction that examines the application of digital manufacturing and fabrication (DMF) tools to various creative fields (Efrat et al., 2016; ETH, 2017; Gao and Cui, 2016; Ginosar et al., 2018; Lipson and Kurman, 2013; Magrisso et al., 2018; Zoran and Paradiso, 2013). Recently, DMF and other novel technologies have become increasingly prominent in the kitchen setting, and many projects have established their contribution to the culinary field. Among these technologies are 2D, 3D, and 4D food printing (ByFlow,; Kira, 2017; National Aeronautics and Space Administration, 2013; Wang et al., 2017); robotic chefs (Gibson, 2015; Nagoya Robot Ramen, 2009; NVIDIA, 2019; Samsung, 2019; The NYTimes, 2010); and theoretical research on the semantics and procedural relationships in culinary recipes (Huang et al., 2017; Kiddon et al., 2015) and other human-computer interaction (HCI) studies (Choi and Blevis, 2010; Vi et al., 2018). DMF technologies introduce a high level of control and precision and real-time complex computations that together enable great flexibility in manipulating food shapes and matter. Nevertheless, most of these projects still fall short when considering the practical barrier of restaurant setting, such as the ability to personalize and produce complex dishes fast enough in real-time.

Prior work already advocates for the integration of computers in the kitchen to enhance food optimization and minimize waste (Zoran, 2019). One way to reduce food waste (while easing production) is to rely on dried substances in the form of powders, which have a longer shelf life than fresh products and are easier to store and transport. Additionally, powdered ingredients are homogenous, which makes it easier to tune recipes and personalize the nutritional values of the end dish. For example, the Habit (2019) team draws on research in nutrigenomics to build personalized nutrition for their customers based on personal information, including DNA tests and awareness of specific illnesses.

As many general and food-specific 3D-printing technologies rely on powders (using various sintering and bonding techniques (Lipson and Kurman, 2013) or pastes that are made of powders (Kira, 2017; Lipton et al., 2015)), we believe that printing technologies will be increasingly relevant in the kitchen of the future. Applications could range from applying DMF technologies to cooking, to relying on optimization

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methods for better use of ingredients and tailoring personalized diets using data science (see Fig. 1).

In this work we demonstrate, end-to-end restaurant pipeline to evaluate the technical feasibility of DG, while pursuing a human-centered hybrid (traditional-digital) cooking practice where the art and culture of cooking are integrated with computational technological aspects. Hence, in addition to prior work, *this paper contributes all technological steps to complete DG pipeline* (hardware and software, see Fig. 2), including:

- A custom multi-resolution paste 3D printer *to overcome the slow speed of prior 3D printing technologies of noodles*, hence making noodle printing technology practical in restaurant setting.
- A novel interactive dish-design software (DDSW) that expends discretization to enable parametrically plan 3D printed noodles, including a graphic user interface.
- We present a new printable noodle paste recipe used for our special soup recipe, demonstrating how all these technical developments are integrated together. Hence, our research is mainly an evolution of the DG Variations principle, aiming at producing an infinite instantiation from a single recipe (Zoran, 2019).

Our work aims at minimizing the gap between DG technologies and practical aspects of restaurant pipeline. Hence, we do not evaluate the edible outcomes of the process as they are function of chef decisions and are not in the center of our contribution. Here we introduce a cooking approach allowing for new creative potential, while future work will focus on DG food portfolio and its study.

The paper is structured as follows: in the next section *Creative Motivation for Digital Gastronomy: From Vision to Practice* we present DG and its leading principles, highlighting our work on DG variations, leading to a *Computational Cooking: Related Work* section discussing both contemporary cooking trends and relevant DMF methods. Then in section 4 *3D Food Printing: Background and Setup* we focus and present a general background to 3D food printing and a novel multi-resolution printing head to optimize printing time using a robotic arm. Section 5 presents *A Case Study of a Segregated Soup* (revising a soup concept first published in (Mizrahi et al., 2016)). Alongside recipes for this case-study, we present a detailed description of the tools, technologies and algorithms we developed. Finally, in Section 6 *Design Software and Chef-Cook-Dinner Interaction*, we introduce custom design software and discuss our interaction scheme tool. Section 7 present the results of an expert evaluation we carried out among chefs, then in Section 8 we summarize and discuss future developments in the field.

2. Creative motivation for digital gastronomy: from VISION to practice

Our vision relies on a hybrid practice, integrating digital tools into the traditional kitchen and cooking methods. The concept of hybrids in both cooking (Mizrahi et al., 2016; Zoran and Cohen, 2018) and craft (Efrat et al., 2016; Magrisso et al., 2018; Zoran and Paradiso, 2013) has been discussed widely elsewhere and is taken for granted in our DG research. Here we explore the creative contribution DG brings to cooking in addition to the automation of cooking processes, from enabling a high degree of freedom in recipes to the discretization of food mediums.

2.1. Computational concepts and the DG principles

DG enhances cooking with new digital capabilities. The integration of computers with cooking allows cooks to individually address users' needs and desires, easily calculate the nutritional content of ingredients, or accurately affect cooking-related chemical reactions, and thus digitally fit dishes to personal preferences. In (Zoran, 2019) Zoran discuss a vision of how digital machines and interactive software can be integrated into kitchens to promote digital gastronomy, including a theoretical framework to allow chefs new capabilities such as controlling flavor patterns, looking in detail at the implications of DG to new cooking principles:

- **Variations** Extending traditional recipes into a wide opportunity space that presents numerous possible instantiations for the same meta-dish based on relationships and dependencies between cooking elements defined by the chef.
- **Progressions** Designing and manufacturing programmable flavor patterns and structures in dishes.
- **Morphing** Morphing one dish into another through flavor transitions by meticulously planned placement of (discrete) ingredients that provide a visual hint of the taste escalation taking place in the plate.

Together, these principles realize the deeper contribution of computers in rethinking dishes and recipes. Here, we look in depth at the first principle: Variations, which will be demonstrated in the following sections using our soup project.

2.2. Dish variations principle

The space of opportunities in recipes and cooking is huge, and even a single dish can have a vast number of recipes and interpretations, to meet both diners' and cooks' personal desires, requirements, and expectations. While many commercial (restaurant) dishes are fixed and

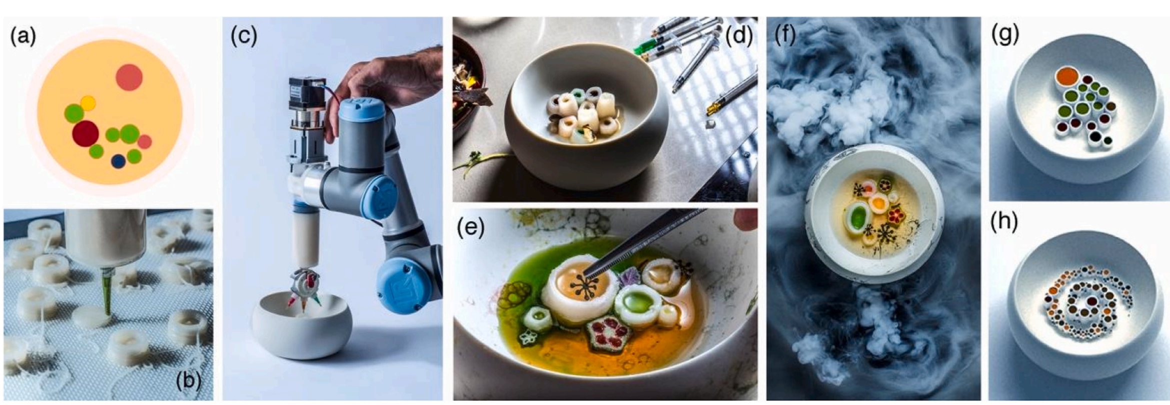

Fig. 1. Using a Dish Design application, the chef designs noodle pool structures to segregate the liquids in the soup and plans their distribution within the pools. The application renders the chef's design into a CAD model, and a Multiresolution 3D Printing Robotic Arm prints the noodle structure into a serving bowl. The chef prepares the rest of the ingredients and places them all together in the bowl. As the resolution of food printing improves, this process will enable digital design and manipulation of intricate flavor patterns.

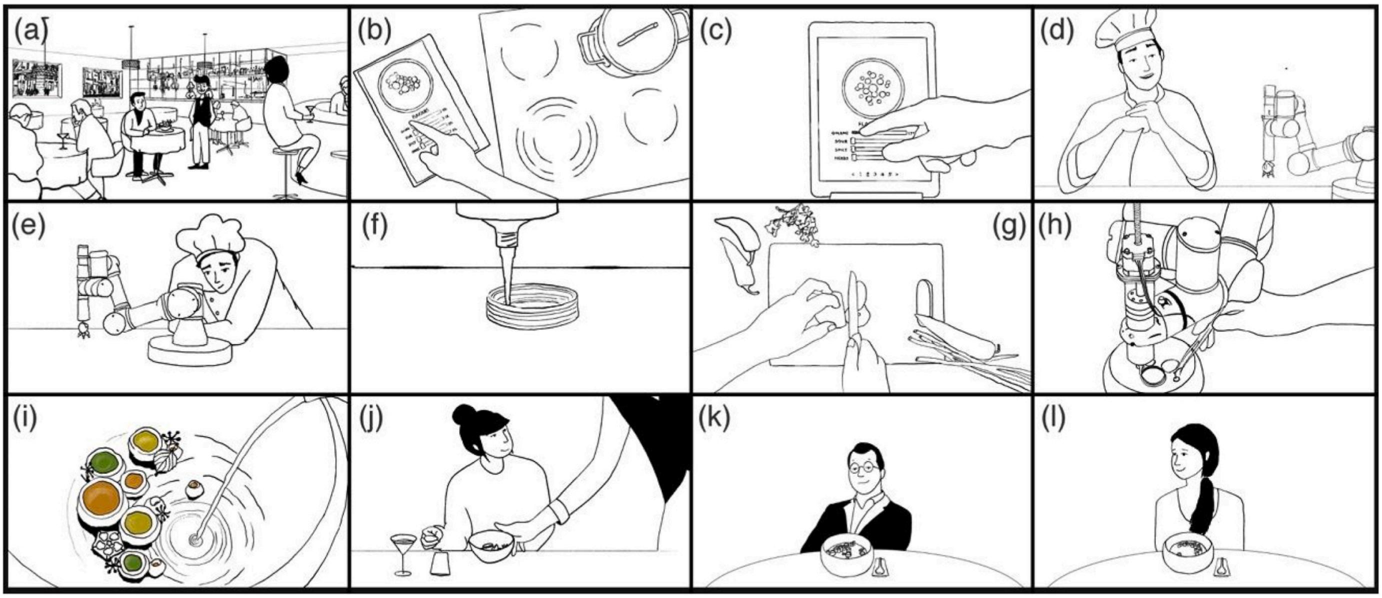

Fig. 2. In the DG vision-restaurant, digital tools enable the customization of a dish to the diner's flavor and nutritional preferences.

cannot be modified for each diner (beyond seasoning or salt), some of them are already subject to personal manipulations, as when ordering a pizza with individualized toppings or customizing a ramen soup.

Furthermore, as of April 6, 2021, a Google search for pho soup recipes returns 101 different recipes in the first 102 search results. Although one recipe might differ from another, essentially, they are all variations on pho soup. While these recipes capture complex relationships between ingredients, in many cases, one cannot easily interpolate two options, bounding the cook to a fixed set of options. However, computers can easily use this information as sampling points on a continuous ingredients space (in the Euclidian ingredients space of order n, n is the number of different ingredients in use), hence generating a continuous recipe space (meta-recipe) to allow fine-tuning of recipes per diners' preferences.

While data-science techniques can be useful in data-mining information from online recipes (see for example (Jaan Altosaar, 2017; Jacobson, 2014)), for many chefs, developing a new recipe is an intuitive process that involves an implicit study of such relationships while testing many recipe versions. For practical reasons, this process is often not well-documented, and results in recipes that offer roughly fixed quantities, limiting both the cook's and the diner's choices. We believe that chefs, cooks, and diners, when given an interactive recipe design tool, will benefit from a computational capability in creating meta-recipes that encompass relationship between ingredients, cooking modalities, and techniques, and are based on personal cooking knowledge and experience and datamining of existing recipes. We suggest a broad perspective, where chefs design recipes with higher degrees of freedom in the form of defining constraints and relationships between ingredients. From this perspective, the hybrid recipe is now a set of possible allocations of ingredients within a continuous recipe space, defined by capturing these relationships.

An example by (Mizrahi et al., 2016) is a ramen recipe where the volume of ramen soup broth, with varying quantities of dashi, chicken stock and soy sauce, can be represented as a sum of liquid volumes:

$V_{ramen} = V_{dashi} + V_{chicken} + V_{soy}$ for which a chef can define simple constraints such as $V_{dashi} \in [0, v/2]$, $V_{soy} \in [v/30, v/15]$. According to these constraints and personal preferences from consumers (how much do they like dashi and soy?), a simple procedural process finds the correct amounts of chicken stock, soy sauce, and dashi stock in order to satisfy volume constraints and consumer preferences. Nevertheless, while the stocks are made manually, and toppings can be added to the soup, the ramen still relies on a traditional recipe, side by side with computational procedures.

This ramen example suggests one way to implement a dish with high degrees of freedom (i.e., many variations for the same dish based on a meta-recipe). Yet, DG centers on enabling a high degree of cooking freedom as well as the potential to use this freedom to render complex edible structures and patterns, while controlling flavor (and aesthetics) locally and precisely. While 3D food printing is one way to achieve such control, there are other techniques that can be used, such as programmable molds or laser-induced heating.

The DMF tools that enable the ramen dish discussed earlier open the door to digital manipulation of dish structure and composition. The representation of a final dish, or the arrangement of ingredients in a given space, resembles 3D graphic models, with several differences. In addition to aesthetic (visual) qualities that can be described by a given color system, food elements contain flavor, which is composed of taste, mouthfeel, and aroma (Page and Dornenburg, 2008).

Parametric design becomes useful when the model becomes complicated, as in the case of flavor manipulation. Therefore, we translated the recipe designed by the chef into a parametric design process. The input parameters are given by the cook and the diners' preferences, and result in structures and ingredient quantities that meet the chef's constraints and form a variation of a dish—one of many (for process illustration see Fig. 2).

To summarize, extending the results of Mizrahi et al. work (Mizrahi et al., 2016) and as discussed by Zoran in (Zoran, 2019), we suggest two ways the DG vision contributes to the culinary realm to enhance chefs' creative capabilities in cooking: (1) dish variations relying on continuous meta-recipe space and (2) discretization, or the capacity to manipulate flavor voxels (an element in three-dimensional space representing a value on a regular grid, such that flavor_voxel = function (color, taste, mouth-feel, aroma), structures, and patterns locally. We believe that it is crucial to focus DG on creative benefits for chefs, cooks and diners, and to centralize future food movements around human engagements with food rather then turning to purely autonomous cooking agencies. As part of this work, we demonstrate these concepts in a case study of Asian soup focusing on the taste and structural properties of the dish. While this soup is merely serving as a design case, they create opportunities to study DG in depth for conclusions and future DG developments.

3. Computational cooking: related work

To allow computational manipulation of food elements using AM, we need to look at cooking methods that can support such an implementation. In the last 20 years, one scientifically based culinary revolution has already been led by chefs. Modernist Cuisine (MC or molecular gastronomy) exemplified how traditional kitchens can transform to embrace scientific research and cooking facilities, operating in a mode that makes them look like chemistry laboratories using advanced techniques to manipulate food (Myhrvold et al., 2011). MC is a cooking approach focusing on the physical and chemical transformations that occur during cooking to create new flavors and aesthetics, results arising from mostly powdered ingredients and progressive techniques.

Hervé This differentiated MC from more traditional food science, which deals primarily with the composition and structure of food, by clarifying that molecular gastronomy "deals with culinary transformations and the sensory phenomena associated with eating" (This and DeBevoise, 2008). The focus of MC is on gathering knowledge about the cooking process, demystifying some of its old techniques and, as a result, opening space for new avenues of exploration and creativity. Hence, MC techniques are useful in producing food using digital fabrication technologies, as they establish a diverse portfolio of creative ingredient manipulations. Moreover, digital information can allow us to calculate the nutritional content of ingredients (Johnson et al., 2019; Mizrahi et al., 2016) or accurately affect cooking-related chemical reactions, and thus digitally fit dishes to personal needs and preferences.

3.1. Applications of digital fabrication methods for digital gastronomy

A number of recent products using 2D fabrication techniques have enabled digital applications of patterns to food elements, such as digitally printing pancakes (PancakeBot, 2015) or digitally dyeing cappuccino foams (The Original, Patented Ripple Maker Printer, 2019), as well as sugar-paper edible-ink printing, which is already widespread commercially, thus paving the way for other digital instruments to move into the kitchen. The use of laser cutting machines with food has been explored, mostly in applying decorative heated patterns to food, but also in cutting nori seaweed for sushi into delicate patterns (Pinar, 2012). Fukuchi and Jo have used laser cutting to selectively heat bacon, applying different treatments to the meat and fat (Fukuchi et al., 2012), preceding our work on laser inductive heating for selective Maillard reaction (Losso, 2016).

While laser-induced selective heating can be used to heat food surfaces, only a few projects have explored the ability to selectively heat and penetrate volumetric food elements. One example is the work by Blutinger et al. (2018), who have used blue lasers coupled with an infrared laser to demonstrate heat penetration of dough products. An alternative method is to use selective heating of volumetric food elements by microwave (Kitchen et al., 2013). However, current industrial applications (such as the Miele Dialog Oven, which features some advanced microwave technologies (Dialog Oven by Miele,)) do not fully allow for such 3D capabilities.

3D food printing technologies hold promise for the future of digital food technologies, as suggested by the extensive investments researchers and engineers are making in this field. Five years ago, NASA announced it had started researching the implications of additive manufacturing to food in space, aiming to overcome the unique challenges of handling food for long-term space missions (National Aeronautics and Space Administration, 2013); this year, the 3D Food Printing Conference will hold its fifth annual meeting (The future of 3D Food Printing for professionals and consumers,). Lipton et al. (2015) have explored additive food manufacturing, motivated to allow customization, on-demand production, and geometric complexity. Foodini (Natural Machines, 2018) is a 3D domestic food printer using a paste extruder with fresh ingredients prepared before printing. 3D Systems has developed the ChefJet Pro 3D printer (3D Systems, n.d.), which is based on solidification of edible powders such as sugar. The company opened the 3DS Culinary Lab in Los Angeles (3DSystems, 2014) to explore the potential of food printing and presented several hybrid dishes made by top chefs with 3D printers, while Wang et al. (2017) 3D fabricate shape-changing noodles that transform from 2D sheets to 3D shapes when they interact with water during the cooking process. Another promising trend relates to printed meat supplements from non-living sources, as proposed by companies such as Jet-Eat (Jet-Eat,); these materials mimic animal tissue structures by 3D printing, relying on dry powdered ingredients to allow long shelf lives, and promising customer-tailored solutions with minimal impact on the environment.

While 3D food printers can "manufacture food products with customization in shape, color, flavor, texture and even nutrition," Sun et al. (2015) distinguish the world of additive manufacturing from robotics-based food manufacturing technologies that automate manual processes. A 2010 article in The New York Times reviews several cooking robots (The NYTimes, 2010), including a 2006 AIC-AI Cookingrobot that cooks pre-programmed Chinese food (Christensen, 2006), and a fully autonomous robot ramen restaurant in Nagoya, Japan (Nagoya Robot Ramen, 2009). Moley Robotics presented a machine featuring two robotic arms in a dedicated kitchen. Based on data retrieved from a human chef cooking a meal, this robot can imitate the movements of the chef and cook autonomously from scratch (Gibson, 2015).

In our research, we seek a hybrid cooking paradigm that preserves the chefs' control over the process while placing digital abilities into their hands as part of a creative cooking toolkit. This approach continues a line of research within the Human-Computer Interaction (HCI) and Computer Graphics (CG) fields that studies hybrid design territories, as presented in numerous projects merging craft practices with digital fabrication and design, in order to enrich the creative palate of both (old and new) mediums (Efrat et al., 2016; Jacobs and Zoran, 2015; Zoran, 2013; Zoran et al., 2014; Zoran and Buechley, 2012).

4. 3D food printing: background and setup

As noted, we have witnessed a growing interest in 3D Food Printing (3DFP) among the food and 3D printing industries, scientists from various fields, creative chefs, sustainability activists, and other enthusiasts. A similar movement and interest made AM with other materials, such as different types of plastic, accessible and affordable. Out of 7 a.m. process categories formalized by the American Society for Testing and Materials (ASTM) in 2010 (ASTM International, 2015), four processes were used for food printing: (1) material extrusion (ME); (2) binder jetting (BJ); (3) powder bed fusion (PBF) (through selective heating); and (4) material jetting (MJ).

4.1. Review of food printing techniques

ME is the process by which a cold or slightly heated material is extruded through a nozzle or an orifice to create a 3D structure. The Foodini 3D printer extrudes pastes made of fresh ingredients and can automatically switch between up to five different pastes in the same print (Natural Machines, 2018). Thick Paste Extruder by ZMorph is a syringe-based extruder that extrudes dense masses at high pressure through an exchangeable nozzle (ZMorph,). Researchers from the Netherlands Organization for Applied Scientific Research (TNO) have demonstrated the extrusion of traditional pastes alongside pastes containing nutrients from alternative ingredients such as algae and insects (TNO, 2015). In another work, a TNO and Barilla collaboration yielded a variety of 3D printed pasta structures for classical pasta recipes (Sol et al., 2015).

In **BJ** processes, a liquid bonding agent is selectively deposited to join layers of powder materials. 3D Systems have developed the ChefJet Pro, which applies colorful edible liquid binders to sugar and other powders, resulting in complex structures decorated with high-resolution colorful patterns (3D Systems, n.d.). In 2015, researchers from TNO patented a binder jetting method where a powder composition, comprised of a water-soluble protein, a hydrocolloid and a plasticizer, is selectively sprayed with edible liquid, aiming to produce edible objects.

PBF processes use powder forms of materials and fuse layer to layer by selective heating. The application of PBF to edible powders is rare and has not yet produced any comprehensive study of materials and printing parameters, although there are specific applications that can be instructive, making use of sugar, sugar-rich powders, and spices. For example, TNO applied selective laser sintering (SLS) to edible powders and fabricated a TNO logo, cups, chain links, and stirring sticks out of sugar and Nesquik chocolate powder (a sugar-and-fat-rich powder), as well as Curry Cubes, Paprika Pyramids, Cinnamon Cylinders, and Pepernoot Pentagons (Gray, 2010; Sol et al., 2015). The CandyFab Project produced a series of DIY sugar 3D printers that printed complex mathematical structures (CandyFab, 2017; Irwin, 2007) using selective hot air sintering and melting (SHASAM).

MJ is a process in which droplets of build material (usually low-viscosity materials such as chocolate sauce) are selectively deposited; this process is mainly used for 2D decoration and cavity filling on food surfaces. FoodJet is an inkjet printer that dispenses edible droplets on food surfaces, such as tomato sauce on pizza dough; decorates cookies and cakes with chocolate figures; and fills cavities in waffles with crèmes. Ripples offers inkjet printers with edible inks to decorate foam-based drinks such as cappuccino, beer, cocktails and milkshakes.

4.2. 3D food printing challenges

The majority of the projects mentioned in the previous section focus solely on intricate structures and complex aesthetics, while the processes are slow, require new skills from the operator (chef or cook), and rely on properties that limit the feasibility of post-processing (Godoi et al., 2016) (e.g., boiling and frying). This cost-effectiveness analysis suggests that before it can be incorporated into kitchens and food industry, 3DFP must overcome these challenges to achieve more of its potential and improve its productivity.

A higher degree of control over the nutritional values and flavor of 3D-printed foods depends greatly on the variety of printable ingredients. As few chemical and physical studies have researched material printability (Godoi et al., 2016; Kim et al., 2018), the choice of ingredients in use and the development of new printable materials is far from trivial. In the course of our study, we have developed new recipes for printable pastes and a novel printing head to overcome the challenges we encountered in past and current work.

4.3. Paste development

Out of the 3DFP processes listed in 4.1, ME is relatively easier and more affordable to implement, and thus, boasts wider adoption. Drawing upon prior work (Mizrahi et al., 2016), we have experimented with the deposition of two edible pastes by ME and faced the challenge of developing recipes for printable pastes. Paste printability is essentially determined by the material's ability to (1) flow through a nozzle; (2) maintain the structure of a printed object; and (3) withstand a cooking process.

A number of recipes we experimented with during the development process did not meet these requirements. For example, the rheological properties of traditional pasta dough did not allow it to flow through our extruder, and choux pastry did not maintain the printed structure.

Harnessing a technique from MC, we added edible pastes with methylcellulose and starch, altering their rheological and mechanical properties to meet the above qualities. Due to the properties of methylcellulose (MTC), when cooked in 80 °C liquid, the printed food changes its viscosity, hardens, and resembles traditional noodles in its mechanical performance.

4.4. Setup and development: 3D printers and robotics

To enable the DMF of food, we equipped our lab with digital tools, adjusted them, and developed new ones. In (Mizrahi et al., 2016), Mizrahi et al. have installed a paste extruder on a Printrbot Simple Metal 3D printer and printed a tofu coral structure, resulting in a very slow printing time.

Here, we contribute a design (Fig. 3) using a UR3 Robotic Arm (by Universal Robots) as a CNC agent to carry an original extruder and printhead that we developed, and 3D printed mung-bean noodles. As the paste extruder is a non-heated extruder, a cold extrusion must be enabled. The paste consistency and texture in combination with the nozzle diameter require several adjustments: (1) relatively slow head traveling and faster extrusion; (2) bigger/higher layer height; (3) faster and longer retraction.

4.4.1. Robotic arm

We developed a multi-resolution paste 3D printer (see Fig. 3) by designing and building a dedicated extrusion system (see Extruder and Multiresolution Printhead) to function as a UR3 (Universal Robots) Robotic Arm end-effector. Implementing a communication protocol between the Arduino-based extrusion system and the UR3 system, we enabled the control of the extruder and choice of printing resolution by the UR3 Control System. Using the RoboDK IDE we plan and simulate (offline) a single program that controls the entire print course and system.

4.4.2. Extruder and Multiresolution Printhead

The paste and food-extruder kit used for the Simple Metal 3D printer (above) is bulky and, as an end-effector for the UR3, reduces movement on several axes and increases the chance for self-collision. Therefore, we decided to build a dedicated paste extruder based on a Nema17 through-type stepper motor, which controlled the piston of a 140 ml luer lock syringe (see Fig. 3). The paste extruder is controlled by an Arduino Mega 2560 with a DRV8825 driver-based shield that runs firmware we designed.

Although AM is a method for rapid prototyping, this family of processes is very slow on a kitchen time scale: as discussed, printing duration is a major challenge for 3DFP. For example, the printing time of the tofu-methylcellulose structures for the Coral Reef Soup was 45–60 min. In this work, we developed a multiresolution printhead (MRP) that allows us to change the printing resolution within the same print and adjust it to the currently printed part. The MRP is a mechanism that aligns one of three nozzles with the extruder outlet and maneuvers between three different resolutions (Fig. 3). The MKS-DS65K servo motor-based rotating mechanism is controlled by the same firmware running on the Arduino that controls the paste extruder.

In order to demonstrate the potential of MRP in reducing print duration, we printed a tube and truncated square pyramid models on a silicone mat using the Mung-Bean-MTC recipe (see Table 1). Each of the models were printed by the MRP in three nozzle diameters/resolutions: 0.5 mm, 1 mm and 2 mm. The tube dimensions are 20 mm OD, 2 mm wall-thickness and 10 mm height; the truncated square pyramid dimensions are 20 mm base-edge, 4 mm top-edge and 10 mm height. Printing durations and graphic results are shown in Fig. 4.

Ultimaker presented a similar idea of reducing printing duration without sacrificing print quality in the adaptive layer (Jani, 2018) feature available with Ultimaker Cure Slicer. A single-resolution-printhead efficiency and speed depends greatly on the choice of nozzle diameter, which derives from the finest detail one wish to print. Extending the results from Fig. 4 to a composition of tubes of varying wall-thickness, we managed to reduce the expected printing time with a single resolution printhead by 83.43% (see Fig. 5).

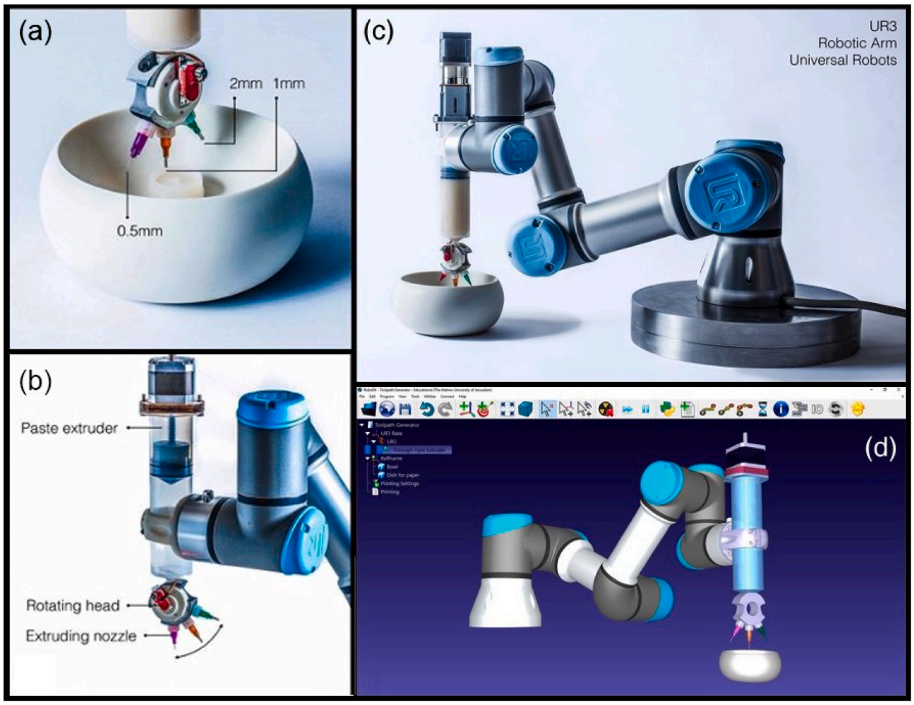

Fig. 3. Images of our UR3 (Universal Robots) robotic arm with the extrusion system as an end-effector (a) printing mung-bean paste (1 mm nozzle diameter) into a bowl; (b) the extruder and the MRP set on (d) toolpath planned in the RoboDK IDE.

5. A case study of a segregated SOUP

Soup creates an opportunity for programmable structures and composition, as previously argued by Mizrahi at el (Mizrahi et al., 2016). While it allows easy modification of flavor by mixing liquids, such as seasoning ramen soup with soy sauce, these liquids require containers to keep them apart prior to serving. Here we rely on a modified version of the soup idea, developed by the chef in our team, suggesting a segregated soup by keeping some of its ingredients apart.

Using a contemporary cooking technique, we created a tofu-methylcellulose paste that changes its viscosity as a function of temperature. At room temperature, the paste is very soft and can be easily printed using a paste dispenser, though it can still hold a 3D shape. When the tofu-methylcellulose structure meets 80 °C liquid (the soup), it changes its viscosity, hardens, and resembles regular noodles in its mechanical performance. The noodle is designed in such a way to allow for the segregation of these liquids in the soup, using a predesigned parametric style.

5.1. Alchemist Mortar Soup: robotic arm and a multiresolution printhead

The Alchemist Mortar Soup recipe is our digital-discrete interpretation of the traditional Vietnamese pho. Pho consists of broth, rice noodles and meat, and is typically served with plenty of greens, slices of lime, salty and spicy sauces, and pastes that introduce four distinct flavors:

- Freshness from green leaves.
- Acidity from lime.
- MSG and salt introduced from soy or fish sauces.
- Spiciness from chili peppers.

We segregated the broth to these basic flavors in their liquid form (using extractions of greens and chili peppers) and confined them in 3 d-printed, pool-like mung bean noodle (cellophane noodle) structures. Hence, the basic pho flavors were segregated and reconstructed to achieve many varying instantiations of the same meta-recipes.

In the thoughtful design process, the team chef developed the soup recipe and defined its structural aesthetic, leaving degrees of freedom in the form of flavors and composition. The chef's plan and constraints were then formalized by a computer scientist into a parametric procedure, resulting in a generative algorithm that produces a dish 3 d model. Computer scientists implemented the algorithm in Grasshopper and an interactive user interface that allows cooks to design dishes was advised by the entire team. The interface was designed and implemented by computer scientists and graphic designers as a web application which will be presented, discussed and evaluated in Design Software and Chef-Cook-Diner Interaction and Expert Evaluation and Technical Reflection.

Considering the chef's predefined constraints depicted in the recipe, the cook's inputs of structural design, and choice of liquid quantities and distribution, our algorithm generates a 3 d model of the noodle to be printed.

The algorithm works as follows (graphic implementation available in DESIGN SOFTWARE AND CHEF-COOK-DINNER INTERACTION): (a) Receive a contour drawing; (b) pack the contour with circles[1] (2 d pools); (c) repeat stages a and b as desired; (d) receive scaled quantities of the four flavors; (e) distribute liquids within the pools (see distribution methods below); (f) receive the choice of minimum and maximum pools, where the heights and depths of the pools satisfy the following constraints: (1) Pools containing seasoning should exceed the soup level; and (2) the sum of cavity volumes for each flavor should meet the assigned liquid quantities. Finally, (g) the algorithm generates a 3 d model that meets all the constraints and is ready to be printed. The printed mung-bean noodle structure is then assigned to the seasoning according to the cook's design.

Flavor distribution methods:

- Manual: Flavors are assigned to pools manually, one by one.

[1] Using a modified circle packing algorithm and radii predefined by the chef.

Table 1
Printable-paste recipes.

	Ingredients	Preparation
Tofu-MTC (TMTC)	340 g soft tofu 200 ml water at room temperature 12 g MTC Pinch of kosher salt Dash of sesame oil	Mix MTC with water in saucepan and bring it to a boil. After 1 min, move it to a food processor, add tofu, salt and oil, and process at high speed until it has a consistent uniform texture. Chill.
Mung Beans-MTC (MBMTC)	200 g mung bean noodles	MTC Paste: Boil 1000 ml of water, disperse MTC, simmer for 3 min and refrigerate for 6 h.
	1000 ml water at room temperature 20 g MTC	Bring water to a light simmer and add mung bean noodles. Add sliced shiitake Mushrooms, cloves and kosher salt.
	10 g of dehydrated shiitake-mushrooms	Stir occasionally until ready, remove from stove and pick out the mushrooms and save for garnishing later. Discard the cloves.
	3 cloves	Transfer noodles into a food processor with 200 ml of water left from cooking (to keep the starch) and add 130 g of MTC paste.
	Pinch of kosher salt	Pulverize the noodles on low speed until a uniform paste is achieved.
	Dash of Knorr Liquid Seasoning	After passing through a coarse sieve, refrigerate to incorporate the MTC paste.
Rice-MTC (RMTC)	200 g rice noodles	MTC Paste: Boil 1000 ml of water, disperse MTC, simmer for 3 min and refrigerate for 6 h.
	1000 ml water at room temperature 20 g MTC	Bring water to a light simmer and add rice noodles. Add sliced shiitake mushrooms, cloves and Kosher Salt.
	10 g of dehydrated shiitake-mushrooms	Stir occasionally until ready, remove from stove and pick out the mushrooms and save for garnishing later. Discard the cloves.
	3 cloves	Transfer noodles into a food processor with 200 ml of water left from cooking (to keep the starch) and add 130 g of MTC paste.
	Pinch of kosher salt	Pulverize the noodles on low speed until a uniform paste is achieved.
	Dash of Knorr Liquid Seasoning	After passing through a coarse sieve, refrigerate to incorporate the MTC paste.
Arabic Gum	340 g soft tofu 200 ml water at room temperature 12 g MTC Pinch of salt Dash of sesame oil	Mix MTC with water in saucepan and bring it to a boil. After 1 min, move it to a food processor, add tofu, salt and oil, and process at high speed until it has a consistent, uniform texture. Chill.

- Pattern: Each flavor is associated with a pattern (drawn by the cook) and assigned to the pools it intersects with.
- Random: The flavors are randomly assigned to pools.

Obviously, the concept soups we discussed here are only two illustrations of the potential for digitally determining dish aesthetics and distribution of ingredients. In Figs. 6 and 7 we show the potential of intricate and complex structures and soup instantiations of the meta-recipe presented in this work. A great deal of creative freedom to generate this structures and flavor composition was enabled by the Dish Design tool we developed and discuss in the following section.

6. DESIGN SOFTWARE and chef-cook-dinner INTERACTION

Prior work presenting advanced tools and algorithms to food structure design and manufacturing enabled by (Mizrahi et al., 2016) were essentially operated by skilled engineers and computer scientists, who are familiar with CAD/CAM, under the guidance of a chef. Yet here we developed dish-design software (DDSW) to allow chefs and cooks a direct design process in which they could rapidly explore different dish variations. The software was developed by a team that included a chef, graphic designers, and computer scientists.

The Alchemist Mortar Soup recipe was planned by a chef with several degrees of freedom in the form of noodle shape and seasoning. These degrees of freedom were translated into the algorithm presented in the previous section and implemented in Grasshopper. A web application was designed to communicate the cook's inputs to the algorithm running on a server, thus enabling an interactive design process.

Relying on the chronological manner of the recipe, captured by the algorithm, we have set up the application framework (stages) and flow. As part of the UI design process, several input methods were tested to achieve an intuitive interface that allows the degree of expressiveness required to take advantage of the tools DG enables in this recipe.

6.1. Application architecture and design

The application screen layout is maintained through the design process, updating according to the design stage and user choices, and structured as follows:

- **Top Instructions Ribbon** (TIR) shows the instructions for the current stage of the design process.
- **Information and Controllers** (IC) display the current stage input controllers and setting chose by the user.
- **Serving Bowl** (SB) display an interactive model of the designed soup in a serving bowl.
- **Tools Ribbon** (TR) presents the user with the input tools available in each stage of the design process.

Fig. 8 illustrates design process flow of the DDSW. The design process starts with the noodle structure design (a)–(c), therefore, the opening screen TIR displays an instruction for the user to draw the outline for the noodle. The IC interactively updates according to the noodle structure outlined by the user in the SB. The outline stage can be done repeatedly to add several structures and a random outline generator is available as well. The outlines are then packed with circles that will be used as pools for the soup seasoning.

In the next stage (d)–(f), the TIR instructs the user to set the relative quantities of seasoning (at a scale pre-determined by the chef when planning the recipe) and their distribution using the sliders displayed in the IC and the TR. We decided to allow the user to choose between manual or random seasoning distribution within the pools. We A/B tested two alternatives for the seasoning volumes input method: (1) sliders and (2) pie chart. While pie chart proportional display of the liquids in the bowl is an intuitive way to grasp the resulting flavors, it was hard to control and read due to the dramatic difference in volumes of different liquids (e.g., soup to soy sauce ratio). Another drawback of this method appeared when changing a single liquid volume changed the entire soup volume, resulting in an overall change of the pie chart slice proportions.

In the final stage (g), the user is instructed to choose minima and maxima pools and together with all the inputs entered along the process (noodle structure outline, seasoning quantities, and distribution and min/max points), the algorithm generates a 3D model of the pools (h)—each at the exact volume of seasoning chosen by the user and higher than the soup level to maintain liquid segregation.

7. Expert evaluation and technical reflection

With DG we aim toward a long-term creative and cultural contribution to the field of gastronomy. Hence, to evaluate the full potential of the DG vision, we need to produce a rich portfolio of methods and recipes and deploy them in real environments. Because we believe that intellectual discourse with culinary experts can assist and contribute to

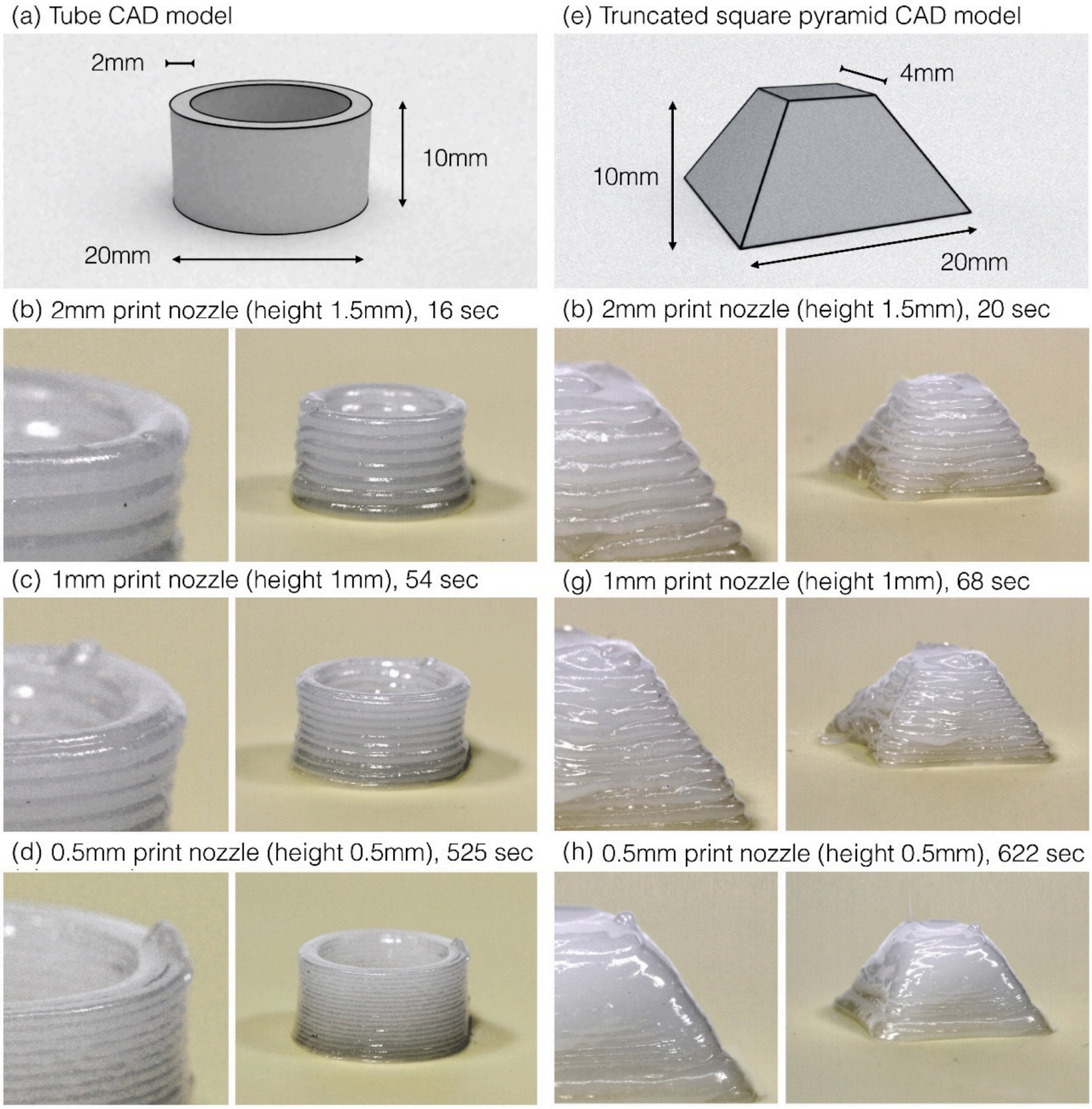

Fig. 4. (a–d) Images of the tube CAD model and the Mung-Bean-MTC printouts with the printing parameters and duration; (e–h) Images of the truncated square pyramid CAD model and the Mung-Bean-MTC printouts with the printing parameters and duration.

the evolution of DG in this early stage, we have invested significant effort into exposing as many people as possible to our work, collecting a wide range of inputs and comments.

In addition to the work presented in this paper, around 25 people (including students and experts from design, computer science, and culinary backgrounds) have taken part in our DG initiative. Four cooks and chefs contribute directly to our work, as well as several amateur cooks. We have learned that many others agree with our assessment that computers will play a larger role in tomorrow's culinary culture, and that there is a need to develop new methods and tools to pave the way for the DG revolution. In order to receive more practical feedback, we present the results and conclusions of an expert evaluation conducted with expert chefs to evaluate our work, focusing on soups created with our dish-design software.

In the evaluation meetings, we presented the chefs with the vision of DG, the concept of dish variations, and the case study recipe of Alchemist Mortar Soup, along with the dish-design software presented in the previous section. The experts then were asked to review the DG vision, design a dish using the software, elaborate about their experience, and suggest additions or changes to the software. As the meetings took place in the chefs' kitchens and restaurants, they did not allow for a complete survey, including printing and tasting the dishes.

We met with **E.H** (M, 35), an architect and a pastry chef at fine dining chef restaurant in Jerusalem. E. is a self-educated chef who creates his desserts in response to architectural aesthetics. Each dessert is a product of taste-matching research, a combination of culinary expertise, art and architecture, and is portrayed in a detailed architectural drawing prior to execution. E. would rather "start with a default dish (i.e., noodle structures and sauce volumes/quantities), alter it and have the option to reset the controlling parameters." While E. appreciates "working within a bounded structural space—that maintains similar noodle shapes (in different dishes)," he suggests "a greater degree of control over the cylinders' properties (e.g., location and diameter) via direct manipulation." E. questioned whether the "soup-to-noodle ratio should be taken as an input rather than displayed as an output" (constraint given by the chef vs. a consequence of his/her design). E. suggested using "absolute quantities on the sauces bar (ml, tablespoons, etc.)." He suggested that the ingredients distribution screen be shown earlier and asked to "see

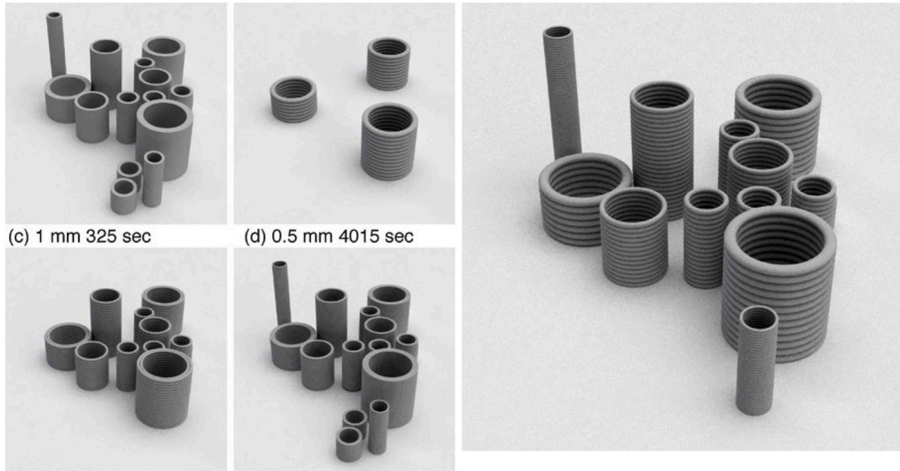

Fig. 5. (a) a CAD model of tubes of varying wall-thicknesses; images (b) through (d) show the printable tubes using a single-resolution-printhead of diameter 0.5 mm, 1 mm, and 2 mm (respectively) and their expected printing duration; (e) The printable tubes using a MRP and their expected printing duration.

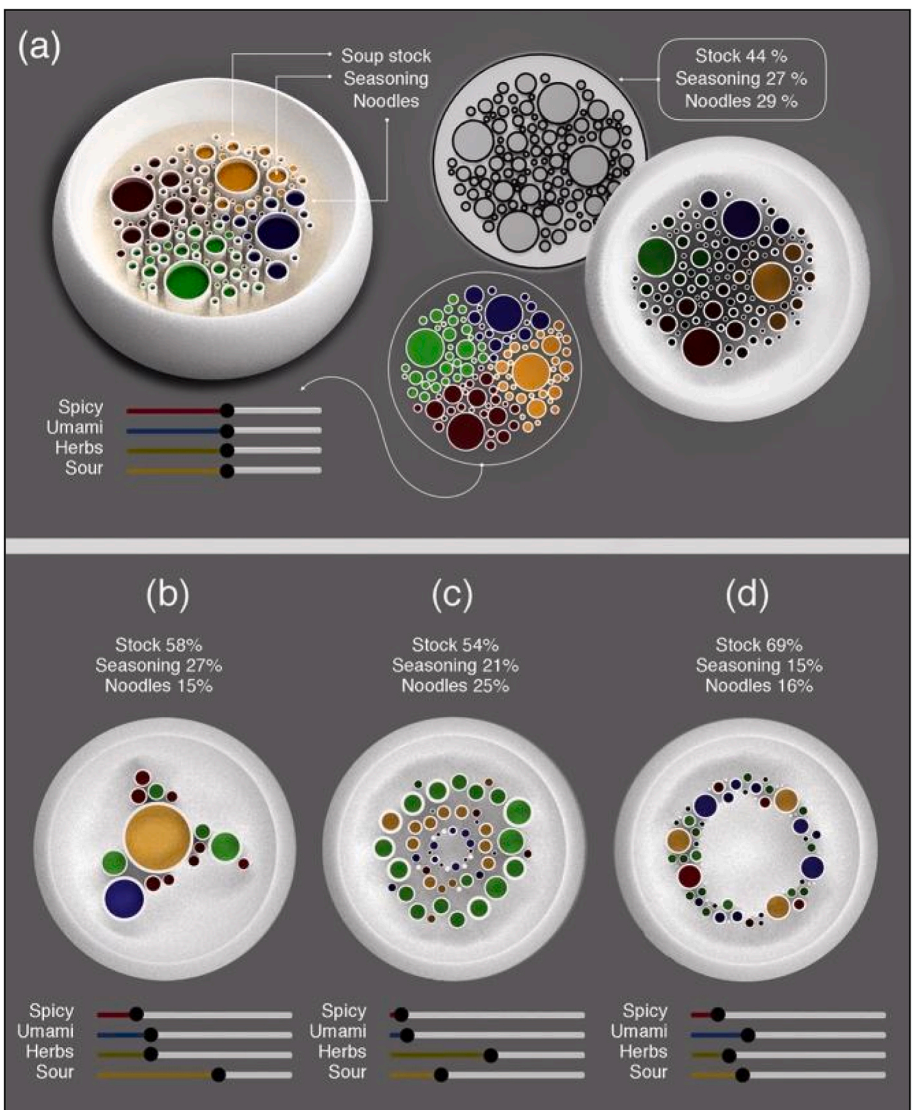

Fig. 6. Dish Variations of the Alchemist Mortar Soup (a)–(d) designed by cooks using the DDSW.

Fig. 7. Several variations of the Alchemist Mortar soup exhibiting the DG variation principle.

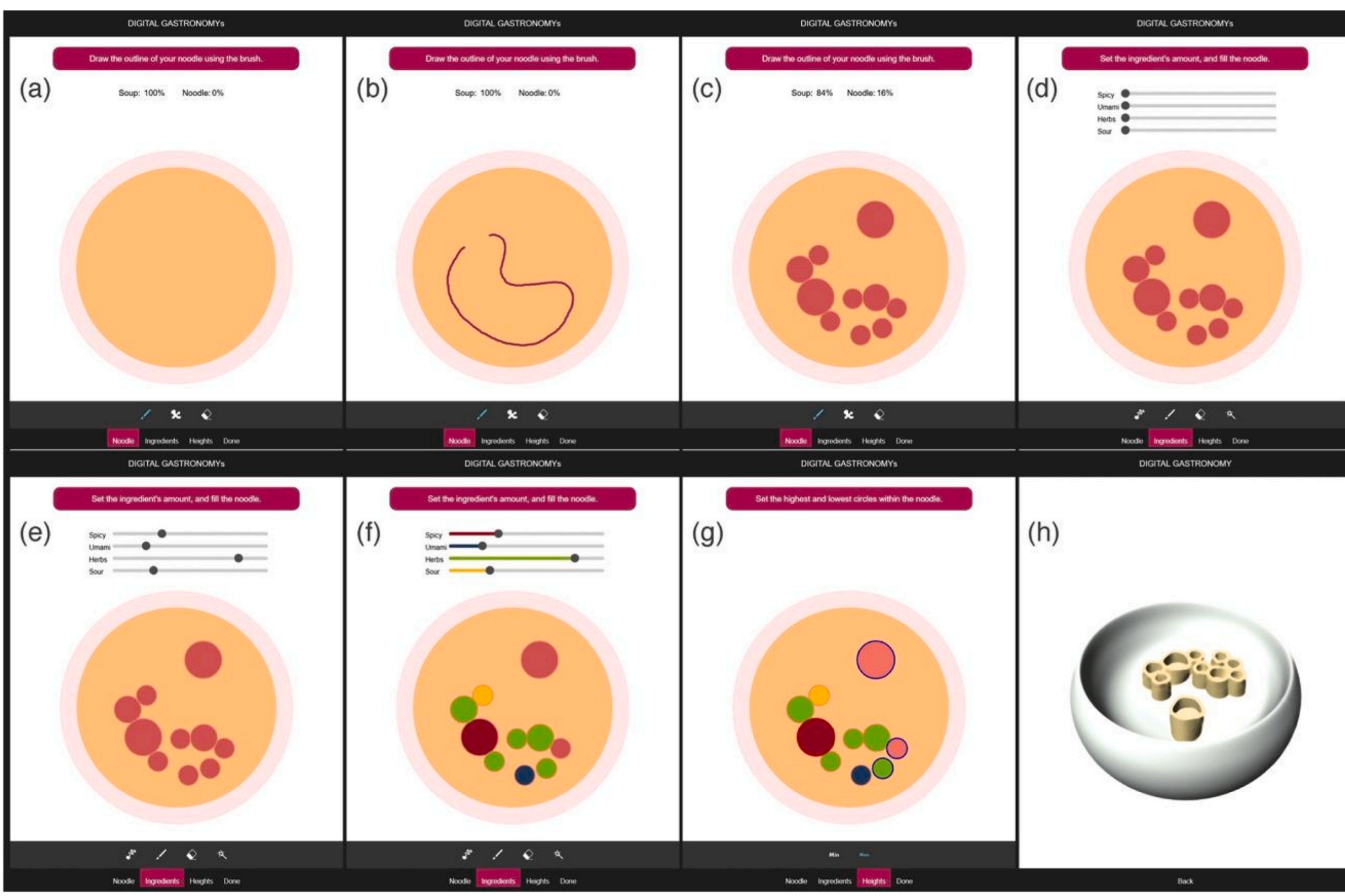

Fig. 8. Screenshots of a dish design process using the DDSW; (a) a top view of the empty bowl; (b) the cook draws the outline of the noodle structures; (c) the outlines are packed with circles; (e)–(f) the chef sets the relative quantities of seasoning (at a scale pre-determined when planning the recipe) and distributes them within the pools; (g) the cook chooses minima and maxima pools. (h) The final 3 d model to be printed.

the bowl volume in the first screen"; as the bowl volume is already known under the assumptions for this recipe, this might be a more relevant request for the recipe planning stage than for the dish design step.

A.P (F), the chef of an easygoing bar and restaurant in Tel Aviv, incorporates a creative twist on classic local cuisine, highlighting seasonal ingredients that are available at the neighboring market. A. remarked that "the top view of cylinders filled with sauces made their quantities easier to grasp," rather than the sliders used to adjust the quantities; like E., she would rather "work with a catalog of building blocks" for the structural design, which "would have been closer to the way she creates, and thus easier to express herself." A. says that usually, her "cooking process is intuitive and emotional, and the design software brings to the forefront her analytical side," which in her words "is a little addictive," and despite the "desire to evaluate a hard copy of the dish, seeing the instant digital result attracts me to keep on exploring and experiment with all the different options."

O.G. (M) and T.B. (M), work in a sushi restaurant in Tel Aviv. T. explains, "We are cooks, we repeat food, we don't create it"; the chef "needs to create the shape, and I (the cook) just need to print it … for me and for my customers, it's better that all dishes look the same. If I will serve a customer one dish, that is looking beautiful and I will serve his girlfriend same dish, same quantities but different shape—they will tell me something." In O.'s opinion, "Creating an extraordinary dish is possible, but recreating it satisfyingly many times—this is the real challenge." However, O. and T. agree that "working with the design software is relevant for home kitchen or cooking for a small group of diners—where the chef can afford to be more attentive to each and every dish."

M.D. (M), director of a culinary school in Tel Aviv, was educated at Le Cordon Bleu, and cooked in several Michelin-starred restaurants. "Today one has to work with conventional shapes and structures and the fact that this [software] allows the creation of shapes one dreams of, it's its only virtue."

H.L. (M), director of the Cooking Department at the same culinary school in Tel Aviv, said, "Personally, I like low-tech, I want to chop, stir, taste and control the fire—[but] the software transfers this part to the computer. If you have this [software], you don't need the chef." He continued, "It would work in restaurants that offer the diner [a chance] to take an interactive role in the making of the dish, such as trending Japanese restaurants."

To summarize, most study participants preferred to share their feedback regarding the overall concept of DG, rather than commenting on the SW. All the participants, though to different extents, showed concern that computational tools will take the place of the chef in the kitchen. It seems that the novelty of the vision and the concerns about the chef's role in tomorrow's kitchens distressed most of the participants, although we emphasized that we aim for hybrid vision, incorporating DG side-by-side traditional practices, focusing on the expansion of the chef's creative capabilities rather than automation. The main points of their evaluation were:

- **Generative design vs. Catalog**: Several chefs mentioned that in designing the noodle structures, they would prefer to work with a catalog of basic shapes and adapt them, rather than using the Pen tool to draw their designs from scratch.
- **Control**: All the participants showed an interest in a higher degree of control over the properties of the cylinders (location and radius), specifically via direct manipulation.
- **Chef vs. Cook**: As a result of the interviews, we came to understand that a more accurate description of the SW user is required, as we had not previously understood the chef-cook relationship.
- **Interaction**: Most of the participants mentioned that some of their notes were a result of working with a recipe they had not created.

8. Discussion and future work

Considering the full potential of DG, we turn to summarizing the primary open points for research investigation as extracted from the work presented in this paper. As the main technical comments on our current work were discussed in the previous section, we focus our discussion here on additional topics.

Through the experience of designing hybrid recipes, adapting DMF tools for cooking, developing dish-design tools, and consulting experts, we outlined the topics we see as the main milestones for additional study.

- Investigation into a universal model to characterize continuous recipe space and dish representation.
- Forming a chef-computer interaction scheme and developing a meta-recipe design tool.
- Forming a cook-computer interaction scheme and developing a particular dish design tool.
- Designing hybrid (traditional-digital) cooking tools and methods.
- Studying the diner-cook interaction and paving the way for DG in domestic cuisines.

We wish to further analyze and formalize the concept of continuous recipe space as discussed by Zoran in (Zoran, 2019). A recipe is a set of instructions for preparing a particular dish, including a list of the ingredients required (Oxford Living Dictionaries,). Usually, this list of ingredients is a fixed set of materials and quantities. However, dishes hold the potential to express many variations on the final flavors and aesthetics, and to satisfy different requirements from different chefs, cooks and diners. From a culinary perspective, one can define dependency functions between ingredients to allow degrees of freedom in recipes. One can easily imagine a recipe being described as a function of ingredients with degrees of freedom (DOF) rather then set quantities, spanning a wide space of interpretations for the same dish. While static recipes cannot represent such a complexity, a computer program can easily do so, envisioning a reality where a chef (probably together with a computer scientist) builds recipes based on kitchen experiments and constructs a high DOF function. To explore the full potential of computational cooking in the construction of dishes and recipes, there is a need to formally (digitally) represent both cooking procedures (recipes) and final results (dishes). A unified model for digital representation will allow a coherent research paradigm to organize research in the field, and an easy interface for collaboration between engineers and chefs.

The development process and expert evaluation of the DDSW raised the need for an interaction waterfall framework, in which a recipe designed by the chef derives an interface for the cook to devise a specific dish variation that results in (a) instructions for the digital tools involved in the cooking process and (b) the setting for the diner interaction.

Thus far, our work has demonstrated the construction of edible structures and flavor patterns by discrete manipulation of flavor, structure, and aesthetics. We aim to achieve designs of greater complexity by exploring the potential of discretization methods synergy. To attain this, we plan on employing generalized executing agents, mainly robotic arms (see illustration in Fig. 9), in printing, heating, scanning and precisely positioning and assembling a dish from ready-made elements. To support this plan, we intend to develop multiple no-collision robots' tool-path design tools and integrate ready-made with custom-made end-effectors for the robots.

In order to continue evaluating DG concepts and tools, we intend to deploy them into professional cooking environments. Like other appliances and techniques introduced to a professional kitchen, DG tools require setting adjustments and team training; at the current level of development, they also demand the addition of a technician to the team. For example, the integration of the robotic arm presented in this work would require (1) space allocation for the control system described in

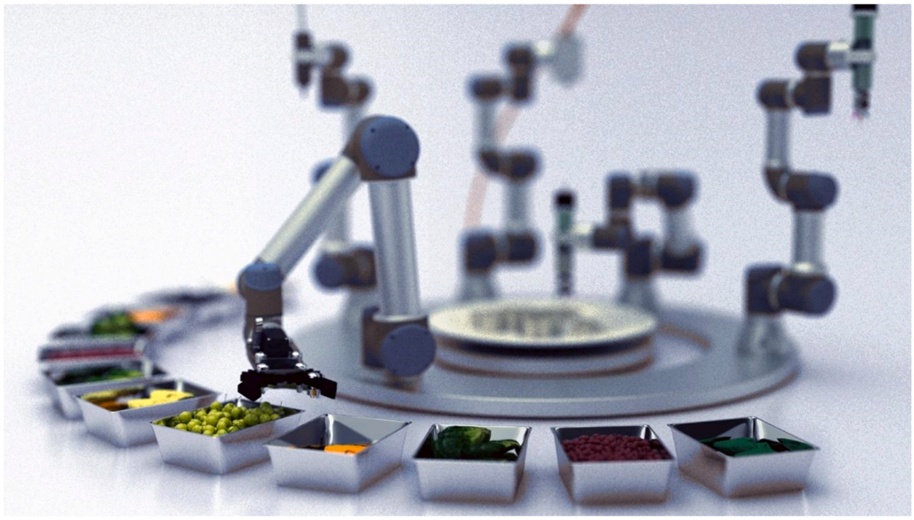

Fig. 9. Illustration of robotic arms working in synergy—printing, heating, scanning and precisely positioning and assembling a dish from ready-made elements.

Robotic Arm; (2) countertop working area for the robotic arm and the dish design tablet; (3) team training for (a) mise en place and (b) robotic-arm basic-use training. The mise en place process starts with paste preparation [see Table 1] that requires 6 h of refrigeration. Once hydrated, the paste is transferred into syringes, to later function as the printer feedstock. Loading the syringes should be done following the instructions in the recipe [Table 1] to avoid air bubbles and cavities, which shorten the paste's shelf life and are very likely to damage the printed objects. However, the size of the feedstock and its loading process were designed for an experimental small-scale kitchen and adapting to the workload of a professional kitchen will require altering the process. The standard operation procedure of the robotic arm requires the cooks to replace the extruder syringe (feedstock) and other basic tasks similar in nature to those performed when using traditional cooking tools. Lastly, a designated technician should carry out abnormal and troubleshooting procedures such as calibration, which in the current stage of development might be required frequently.

9. Conclusions

We discussed an in-depth investigation on the DG Variations principle, demonstrated on our original noodle soup project, contributing a complete, end-to-end restaurant pipeline to evaluate the technical feasibility of the DG steps, including: (1) a custom multi-resolution paste 3D printer to overcome the slow printing time of prior paste printers; (2) a new printable noodle paste; (3) a novel interactive Dish Design graphic application to parametrically plan 3D printed noodles; and a soup recipe.

Based on our experience in this project, we suggest building recipes with certain degrees of freedom, such as variations in the amount of some ingredients. In a realm where a recipe is being extended to a wide opportunity space, a dish-domain presents numerous possible instantiations for the same meta-dish. When a chef can define the relationship and dependencies between cooking elements, each diner can have a personalized product based on personal preferences and needs.

Most of this paper documents novel developments in printing technologies (using a robot arm and MRP), materials and dish design, technical printing evaluation, dish-design software, and expert evaluation of the tools and the results. However, to present a comprehensive study we also discuss and present prior art (Mizrahi et al., 2016) that contributes to complete documentation.

In addition to our technical contribution, this work also presents an in-depth case study on a fundamental DG concept: the ability to render many variations on the same dish. Based on the concept of a segregated-liquids soup, we suggest an approach to generate many variations for the same dish, by segregating soup liquids into 3D-printed noodle pools. A future improvement in printing resolution of the noodles will achieve a true digital food-medium using a high number of flavor voxels. Yet, for now this dish is used as an exemplifying opportunity to evaluate several aspects of DG, serving as a platform for future development of digital cooking methods and human-computer interaction challenges around DG.

We mark several recommendations for future development of DG. First, we believe there is a need to investigate the interaction challenge in depth: how a chef constructs a meta-(interactive)-recipe, how a cook would use this interactive recipe, and how a diner will interact with the cook. Moreover, if we move DG from the professional setting of chefs' restaurants, what HCI issues will arise when DG facilities are integrated into domestic kitchens? Next, and perhaps obviously, to realize DG, digital cooking capabilities must be improved significantly. While 3D printing is a promising technology, there is a need to continue exploring other methods to bring the vision of digital control over flavor voxels and patterns to reality. Lastly, more recipes and dishes need to be explored, using methods from data science to bring machine learning tools to DG without alienating human cooks from the cooking experience and its expressive character.

To summarize, DG is a new research territory exploring the integration of computational technologies in the kitchen, both as a recipe planning system and as a digital cooking agent. We envision that DG will gain a central role in tomorrow's cooking, helping to minimize waste and personalize dishes by using ingredients with well-known nutritional values; relying on the long shelf life of dried ingredients; and giving chefs novel creative cooking tools to justify computational cooking from a culinary perspective.

10. Implications for gastronomy

Digital Gastronomy (DG) is a research territory exploring the integration of computational technologies in the kitchen, seeking a *human-centered practice* in DG, rather than replacing the chef with a machine. Our work highlights the *creative potential* of computers in the kitchen, presenting an in-depth investigation on the DG *Variations* principle (one recipe with infinite instantiations), demonstrated on a robotic induced noodle soup project. We contribute a complete, *end-to-end restaurant pipeline* to evaluate the technical feasibility of DG, including: (1) a custom *multi-resolution paste 3D printer* that overcomes the slow printing time of prior paste printers; and (2) a novel *interactive graphic Dish Design application* to parametrically plan 3D printed noodles; all demonstrated using a new printable noodle paste and a special soup recipe. We discuss the technical outcomes and performance of our proposed DG pipeline using a comparison study on printing performance, and present chefs' reflection on the concept of design and control of segregation using GUI and a robotic paste printer, leading to general insights for the future of DG.

Author statement

Ariel Bezaleli Mizrahi: Conceptualization, Methodology, Hardware, Software, Validation, Writing, **Alexander "Zoonder" Lachnish:** Conceptualization, Methodology, **Amit Zoran:** Supervision, Conceptualization, Writing, Visualization.

Data availability

No data was used for the research described in the article.

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