Hydrocolloid Printing: A Novel Platform for Customized Food Production

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ABSTRACT

Solid Freeform Fabrication (SFF) of food has the potential to drastically impact both culinary professionals and laypeople; the technology will fundamentally change the ways we produce and experience food. Several imposing barriers to food-SFF have been overcome by recent open-source printing projects. Now, materials issues present the greatest challenge. While the culinary field of molecular gastronomy can solve many of these challenges, careful attention must be given to contain materials-set bloat. Using a novel combination of hydrocolloids (xanthium gum and gelatin) and flavor agents, texture and flavor can be independently tuned to produce printing materials that simulate a broad range of foods, with only a minimal number of materials. In addition to extensively exploring future applications of food-SFF, we also present a rigorous proof-of-concept investigation of hydrocolloids for food-SFF. A two-dimensional mouthfeel rating system was created (stiffness vs. granularity) and various hydrocolloid mixtures were characterized via an expert panel of taste testers.

INTRODUCTION

Few things are as natively intertwined with humanity as food, which is essential to biological and social life (Counihan, 1999). Not only does food support life and underpin social relations, but it also accounts for a substantial part of our economy. As of 2008, Americans spent $1.02 trillion annually on food, i.e., 9.6% of the nation's combined disposable personal incomes (USDA Economic Research Service, 2009). Solid Freeform Fabrication (SFF) has the potential to leverage its core strengths (e.g., geometric complexity, automated fabrication) and make its mark on the culinary realm by transforming the way we produce and experience food. We foresee SFF extending new capabilities both to culinary professionals and to laymen, as well as having global social implications by directly extending Web 2.0 phenomena to food.

Technological innovations are necessary, however, before these visions can be realized. In addition to lowering barriers to SFF, such as cost of the machine, materials must be developed to feasibly enable a wide range of foods to be produced on SFF platforms. While many raw foods are natively printable, other foods can only be printed if novel materials are developed. Advancements in the field of molecular gastronomy will likely influence the development of these novel food-SFF materials, especially with respect to the use of hydrocolloids. Food-SFF material platforms must be developed in such a way, however, that enables the printing of a very wide range of foods without bloating the size of the required materials-set. A potential solution to the issue of materials-set bloat is the use of novel combinations of hydrocolloids and flavor additives; this platform delivers many degrees of freedom in texture and flavor, while comprising a minimal number of required materials.

In this paper, we conceptually explore the broader future implications of food-SFF, as well as present rigorous scientific experiments that tackle materials issues that are central to its feasibility.

BACKGROUND: PRIOR WORK AND LOWERING OF KEY BARRIERS

There are several barriers that have been standing in the way of food-SFF. One of the most imposing barriers is that most SFF machines have very limited material-sets. For example, machines typically only support a handful of materials and nearly none incorporate food-safe printing materials into their repertoire. Moreover, most machines exclusively use proprietary materials and tools, and therefore leave no room for experimentation with food-related printing materials. Thus, it remains that a materials-flexible, open-source printing platform is critical for enabling the growth of the food-SFF paradigm.

There are indeed several open-source printing projects that lend the necessary freedom for innovators to experiment with novel, non-proprietary printing materials. One such project is RepRap; however, this open-source printing platform does not offer the deposition tools required to print edible food (Biever, 2005). CandyFab, is another open-source printing project. This platform uses a bed of sugar and a sintering tool to build 3D prototypes (Irwin, 2007). Even so, the primary use is not for producing edible food. Rather than being used for its potentially edible nature, sugar is mainly used because it is a cheap, available and safe printing material. Only one open-source printing platform offers a flexible enough materials-set to enable printing of a wide range of edible products, that is, the Fab@Home. The Fab@Home printing platform is not only open-source, but its syringe-based deposition tool allows for the printing of any material that can be loaded into a syringe (Malone & Lipson, 2007). This non-propriety, flexible-printing-material system overcomes some of the most imposing barriers to food-SFF.

Another barrier has traditionally been printing system cost. While large industrial enterprises may be able to afford $100,000+ SFF systems, many culinary community members and especially individual homeowners cannot get into the food-SFF game with such high equipment costs. In the last decade, we have seen SFF machine costs drop nearly an order of magnitude (with several open-source printers running under $1,500). It is only now, with the reduced SFF cost landscape, that food-SFF is feasible from a financial perspective.

To this point, the volume of work published on food printing has been rather limited. Daniel Periard *et al* investigated SFF of traditional food items that were printable in their raw form (e.g., chocolate, cake frosting). This food printing work was limited to those edible printing materials that were natively extrudable through a syringe and inherently held their shape under gravity (Periard, Schaal, Schaal, Malone, & Lipson, 2007). As a result of relying upon unmodified foods, this work did not fully explore the potential of food printing that could be realized with the development of novel material-sets.

Now that the proprietary restrictions, materials-set inflexibilities and cost barriers have been lifted, the stage is set to explore food-SFF's full potential by inventing new food-related printing applications and by developing the necessary novel materials.

POTENTIAL IMPACT OF FOOD-SFF

Impact on Culinary Professionals: Overview

Food-SFF would benefit the professional culinary domain primarily in two respects: by lending new artistic capabilities to the fine dining domain, and also by extending mass-customization capabilities to the industrial culinary sector.

Impact on Culinary Professionals: Fine Dining

Fine dining chefs are continually developing new, innovative techniques and seeking the enabling technologies that will help them push the boundaries of culinary art. In particular, chefs pioneering the cooking style known as "molecular gastronomy" (i.e., the scientific study of physical and chemical processes related to cooking) are at the forefront of this expanding frontier. They innovate by harnessing non-traditional ingredients, such as hydrocolloids, and by employing new tools pulled straight from the scientific community; the result is "culinary magic" including flavored gelatin spheres with liquid centers, sauce foams, hot liquid deserts with flash frozen shells, syringe-extrudable meats, and much more (Allen, 2008). One of the most notable molecular gastronomists is Chef Ferran Adrià, whose restaurant in Spain, *elBulli*, is considered to be among the finest in the world; the restaurant receives about 2 million applications for a chance at grabbing one of only 8,000 annual slots (Callaway, 2009). Other notable molecular gastronomists include David Arnold and Nils Noren, of the French Culinary Institute in New York City (Allen, 2008).

These pioneers are driving a new trend, in which a growing number of chefs are recognizing the important role that science and technology play in the culinary arts, a notion highlighted by Adrià's closing of *elBulli* for 6 months each year to purely focus on R&D (Callaway, 2009). During these closings, Adrià searches the world for the newest enabling technologies that will allow him to push the limits of the culinary arts even further.

SFF promises to be the next important enabling technology in the fine dining realm. SFF delivers new possibilities by lending this faction of culinary artists one of SFF's core capabilities: fabrication of multi-material objects with high geometric complexity. SFF's culinary potential has already been recognized by one of the most prominent molecular gastronomists; in a 2008 interview with *Popular Science*, Chef David Arnold mentioned that he "particularly dreams of getting a deal on a 3D rapid prototyping machine" (Allen, 2008). As the barriers fall (e.g., SFF machine prices have reduced nearly an order of magnitude in the last decade) and non-traditional ingredients gain credibility in the fine dining world (e.g., hydrocolloids), the question is not whether SFF will play an important role in the future of food, but rather, in what ways will it do so.

Examples of potential future applications include cakes with complex, embedded 3D letters, such that upon slicing the cake, a message is revealed. Or, even a prime rib with a hidden message. Perhaps an on-demand, customizable menu in which the dish is prepared in any 3D shape that the diner desires: the diner can co-create with the culinary artist in real-time.

Impact on Culinary Professionals: Industrial Production

The second way in which SFF could benefit the professional culinary community is by enabling mass-customization in the industrial culinary sector. Today, industrial food producers rely heavily on high-throughput processes such as molding, extrusion and die-cutting (Smith, 2004). These processes, however, are not amenable to mass-customization (i.e., the use of flexible manufacturing techniques to produce custom output in a low-unit-cost fashion). Molding, extrusion and die-cutting each require substantial custom-tooling, and consequently, producing custom output for low-quantity runs is simply unfeasible (Pine, 1993). This is precisely where SFF's inherent strengths can be leveraged: producing food with *custom*, complex geometries while maintaining cost-effectiveness. The cost-effectiveness is enabled by the fact that SFF does not require custom-tooling or extensive manual labor.

One potential future application is *custom* production of edible giveaways, for example, as marketing collateral for small corporate events. Currently, the cost of custom tooling prohibits low-quantity *custom* production runs, but with a flexible culinary production platform like SFF, such production runs would be feasible.

Impact on Non-Professionals: Overview

Culinary professionals are more primed to adopt SFF than are homeowners, however, the implications for laypeople are even more profound. The effect on laypeople is essentially twofold: increasing productivity and injecting knowledge.

Impact on Non-Professionals: Productivity

Since the late 19th century, a number of machines have been introduced to the home that perform routine tasks more efficiently and ultimately offload work from individuals. Several examples include washing machines, dryers, dishwashers and vacuum cleaners. Perhaps the most profound domestic technology was the sewing machine. Although sewing machines were developed for factory use in the 1850's, it was not until the late 1870's that the devices entered homes ubiquitously. Prior to the sewing machine, an average middle-class woman would spend several days per month making and mending her family's clothing (Museum of American Heritage, 2005). More specifically, it would take 14 hours to make a man's dress shirt and 10 hours to make a simple dress. With a sewing machine, dress shirts could be made in 1.25 hours and dresses in 1 hour. Women of the 1870's and 1880's used this saved time to branch out: taking in sewing work for extra money and becoming sales representatives for sewing machines. The reduction in housework ultimately transformed women's roles as household managers and contributed to women seeking employment outside of the home (Museum of American Heritage, 2005). Domestic technologies have had a tremendous effect on society over the last 150 years by offloading housework, and in turn, creating capacity for people to extend themselves beyond the home in new ways. SFF has the potential to join this portfolio of important domestic technologies by *end-to-end* offloading of food preparation.

Currently, the average American spends more than 30 minutes per day preparing food, according to USDA economists (Mancino & Newman, 2006). This amount changes drastically depending on a number of factors, including: marital status, working status, gender and income level. Single, working people spend 15 – 35 minutes per day cooking, while married, non-working women spend an average of 70 – 85 minutes per day (Mancino & Newman, 2006). Clearly there is potential to offload culinary housework for people of all genders, marital statuses, working statuses and income levels. If food-SFF were brought to the "set-and-forget" state, requiring minimal human labor, the average person could possibly realize time savings of 150+ hours per year (3.8 workweeks per year), with certain, large groups (e.g., married, non-working women) saving in excess of 500 hours per year (12.5 workweeks per year). Of course, operating the SFF system will still take some finite amount of time and, moreover, families will certainly choose to spend some of the mealtime either with a traditionally cooked meal or out-of-home dining. Regardless of how much time savings SFF could afford, and even whether it has potential adverse social effects, it is clear that food-SFF is something that warrants further contemplation and investigation.

Impact on Non-Professionals: Injecting Knowledge

The second way that food-SFF could impact laypeople is by abstracting culinary knowledge and injecting it directly into the home. The idea of abstracting knowledge is nothing new. When it comes to playing a popular song, amateur musicians do not have to learn how to play it from scratch. Rather, they obtain sheet music that prescribes the actions (e.g., valve, key or fret manipulations) necessary to reproduce the song. The composer's artistic skill and knowledge have been abstracted and captured in the sheet music, which somebody lacking the artistic skill and knowledge can use to reproduce the original work. Of course, the end-user (i.e., the musician) still needs a non-trivial skill set to properly interpret and execute the prescription (i.e., the sheet music).

Abstracting knowledge for the purpose of having less skilled practitioners reproduce the original work is also found in the realm of culinary arts. When chefs create new dishes and then write recipes, they are effectively abstracting their knowledge and distilling it into a prescription for others to reproduce their work. Nevertheless, just like the skills a musician needs to effectively play a song from sheet music, a recipe follower still needs non-trivial skills to execute a recipe.

It is not only in the abstraction of knowledge, but also in the execution of the prescription that SFF could have tremendous impact. Just as MIDI software can offload musical skill by taking in digital sheet music and directly creating sound, the SFF system could directly inject the skills necessary to follow a recipe end-to-end. Laypeople don't have to know the first thing about musical notation, valve/key/fret fingering, or tonal theory to be able to utilize a stereo system to deliver a distilled version of a live musical performance directly into their home. Likewise, a layperson would not necessarily need to possess even basic culinary skills to employ an SFF system to create geometrically complex, multi-material food items.

Culinary knowledge and artistic skill of world renowned chefs can be abstracted to a 3D fabrication file and then used by laypeople to reproduce famous chefs' work in the home. Also, expert knowledge of the world's leading nutritionists can be abstracted and encoded in 3D fabrication files to help laypeople eat more healthily, without necessarily having to learn healthy cooking techniques or even understand nutritional principles such as caloric intake and protein balance. SFF systems could even go one step further, and deliver customized solutions (SFF's core strength) to each user that incorporate the individualized nature of nutritional needs. For example, a layperson may soon be able to upload a report of their daily activity from a pedometer and digital food log, and the SFF system could use expert knowledge to print them a meal that fulfills their particular nutritional needs for the day. While experts can currently offer advice on how to balance a nutritional program, their influence falls short of delivering the end-to-end solution that only SFF system can provide: from personalized design through fabrication.

Food-SFF and Web 2.0

Whether professionals use SFF for cutting-edge capability or laypeople use it to borrow more basic skills, the abstraction and subsequent direct-execution of culinary knowledge has profound social effects. Once culinary knowledge can be abstracted, it can also be easily shared. It wasn't until music and photographs were represented in digital abstracts (i.e., MP3s and JPEGs) that sharing became easy enough for entire web communities to develop around them.

Some online Web 2.0 social networks have grown to more than 200,000,000 community members (Powell, 2009). In particular, networks established around sharing and communally experiencing photographs (e.g., Flickr) and music (e.g., Last.fm) boast tens of millions of users, each. Now that SFF will potentially enable the feasible sharing of food (via trading 3D fabrication files), we can start thinking of what the future could look like. After all, few things are more essential to social relationships than food. Through food, people share tastes, ideas, values and generosity (Counihan, 1999). Imagine amateurs and professionals alike, sharing their latest ideas and helping others solve culinary challenges. Not only would new types of social bonds form across the world, but people will harness principles of "wikinomics" and begin to "mass-collaborate" seamlessly from all corners of the globe (Tapscott & Williams, 2006). A *truly* global cuisine could emerge. Through mass-collaboration, people could even attempt to solve major challenges such as creating fundamentally new types of healthful foods.

Furthermore, we could see democratization of innovation and a major revision of the current business models of the culinary profession. No longer would only those with access to distribution channels be privileged with sharing their food with the world, but rather, any amateur or professional chef could see their work gain prominence as long as their ideas have merit. A more democratic business landscape will emerge, and the lines between amateur and professional will be blurred.

MATERIALS CHALLENGES

In order to unlock food-SFF's potential, we need to think about the specific technical challenges standing in the way. As mentioned earlier, SFF systems' materials inflexibility, prohibitive cost and proprietary restrictions were barriers that have largely been overcome by recent open-source printing efforts, such as Fab@Home. Now, the printing materials themselves are the bottleneck. Some foods, such as cake frosting, processed cheese, hummus and chocolate are natively printable; they are extrudable through a syringe tip and hold their shape under gravity (Periard, Schaal, Schaal, Malone, & Lipson, 2007). Other foods, such as fruits, vegetables and meats are not natively printable. In order to be able to print these important food-types, we would have to undertake substantial reformulation efforts. These types of challenges have already been tackled by molecular gastronomists. In this avant-garde culinary field, it is becoming typical to make solids (e.g., meats) extrudable by adding hydrocolloids (Allen, 2008). With the appropriate molecular gastronomic tricks, we can realize both printable solid foods and printable semi-solid liquids; the possibilities are nearly limitless.

However, as we attempt to target foods one-by-one in an effort to make them printable, the number of custom, one-off material combinations greatly expands. This leads to the challenge of containing the bloat of the materials-set. The question becomes: how do we enable the printing of a wide range of foods with only a limited, fundamental set of materials?

FLEXIBLE MATERIALS PLATFORM:
A MOLECULAR GASTRONOMIC APPROACH

Overview

One potential solution to containing materials-set bloat is to use a small group of ingredients to create a platform with many degrees of freedom in terms of texture and flavor. By fine tuning hydrocolloids' concentrations, and focusing on the ratios between combinations of different hydrocolloids, a very wide range of textures (i.e., mouthfeels) can be achieved. Furthermore, given the generally neutral flavors of hydrocolloids, the flavor can be independently tuned by using concentrated flavoring additives. By independently controlling these two parameters, texture and flavor, we suggest that a wide range of food experiences can be simulated.

Most Firm

Chocolate				Fried fish	Carrots	Biscotti
	Mushroom			Apple	Cooked chicken	Saltine
	Banana	Cooked spaghetti	Fresh mozzarella	Tomato		Hard-boiled egg yolk
Creamy peanut butter	Marshmallow fluff	Meringue				Ground beef
Jell-O						
Gravy	Mashed potato	Cake icing			Refried beans	
Self-supporting gel				White bread	Polenta	
Non-self-supporting gel	Pudding	Cake batter	Raspberry coulis	Apple sauce	Risotto	
Milk	Ice cream			Sorbet		Coffee grinds

Weakest

Smoothest — Most Granular

Table 1 Mouthfeel matrix with common foods placed as reference items

The two hydrocolloids focused on in this paper are xanthan gum and gelatin. Various combinations of the two were tested for mouthfeel. In order to rigorously describe the mouthfeel of each resultant material, we devised a rating system in which the material was rated along two orthogonal axes: 1) weak to firm, and 2) smooth to granular. This "mouthfeel matrix" was developed in cooperation with expert chefs from the Cornell University School of Hotel Administration (Table 1).

There are 7 discrete buckets on the smooth-to-granular axis and 9 buckets on the weak-to-firm axis. Common foods were placed within this framework for the taste testers' reference, and the testers were asked to place a particular hydrocolloid concoction within the matrix relative to these references.

Methods: Materials Preparation

Xanthan gum and gelatin were prepared in water at various concentrations, ranging from 0.5% gelatin in water (by weight) to 4% gelatin in water, and from 2% xanthan in water to 16% xanthan in water. After preparation, the hydrocolloid concoctions were loaded into 10 mL syringes.

Figure 1 Various hydrocolloid formulations loaded into 10 mL Luer-Lok syringes

To test the flexibility afforded by flavoring additives, various food grade flavor concentrates were infused with the hydrocolloids, including raspberry, strawberry, banana and chocolate.

Methods: Printing

After the materials were loaded into 10 mL Luer-Lok syringes, the syringes were loaded into the displacement deposition tool of the Fab@Home printer (Figure 2). Using the custom, open-source Fab@Home control software, 3 centimeter cubes were printed.

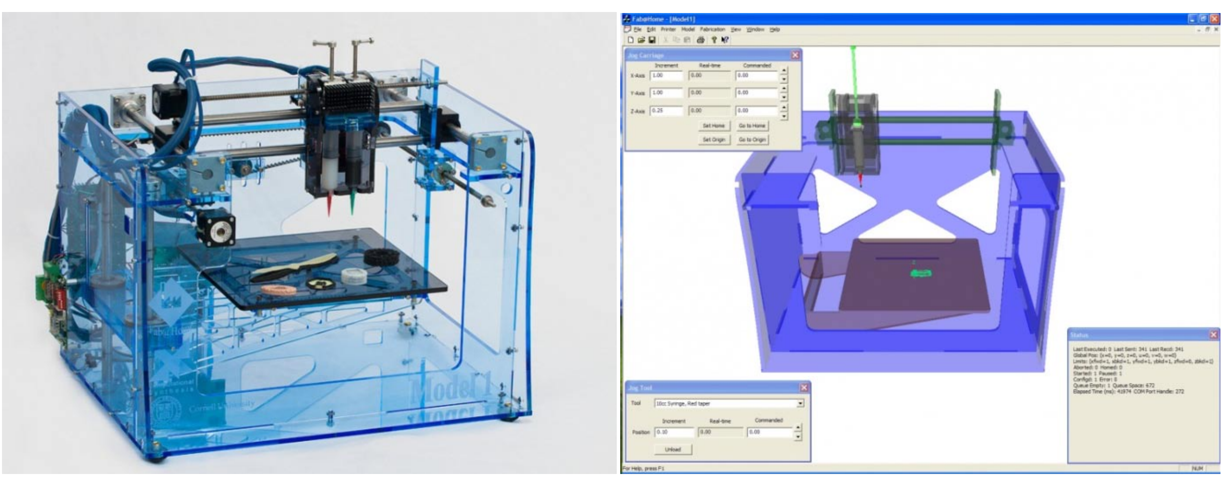

Figure 2 (left) Fab@Home printing platform, (right) Fab@Home control software

We printed each sample to properly account for any effect the extrusion process had on the texture. There is gel-ripping upon extrusion that creates a specific microstructure and texture.

Methods: Materials Evaluation

Various combinations of xanthan gum and gelatin were prepared and presented to a panel of seven taste testers, including two professional culinary instructors. Each rated the hydrocolloids within the “mouthfeel matrix” by comparing the texture to the matrix’s reference foods.

Results: Platform Flexibility Described Through Mouthfeel Matrix

The mouthfeels for xanthan gum and gelatin hydrocolloid concoctions were individually tested and pinned on the mouthfeel matrix.

Most Firm

4% gelatin ***CLOSE TO*** **CHOCOLATE/ MUSHROOM**						
		16% xanthan **COOKED SPAGHETTI**				
				1% gelatin 8% xanthan ***CLOSE TO*** **TOMATO**		
2% gelatin **JELL-O**		2% gelatin 8% xanthan ***CLOSE TO*** **CAKE ICING/ MERINGUE**	0.5% gelatin 8% xanthan ***CLOSE TO*** **CAKE ICING/ MERINGUE**			
	4% xanthan **MASHED POTATO**					
1% gelatin **SELF-SUPPORTING LOOSE GEL**						
2% xanthan **NON-SELF-SUPPORTING LOOSE GEL**				0.5% gelatin 4% xanthan **APPLE SAUCE**	1% gelatin 4% xanthan **RISOTTO**	
0.5% gelatin **MILK**						

Weakest

Smoothest — Most Granular

Table 2 Mouthfeel matrix of hydrocolloid mixture showing the formulations in the appropriate locations relative to common foods (see Table 1 for more detail) with the closest common foods are listed below the hydrocolloid concentrations in bold

Mouthfeels were achieved that simulated a broad range of common foods. These simulated mouthfeels ranged from milk to mushroom to tomato to risotto. The hydrocolloids spanned a range from liquids to solid vegetables. The mouthfeels followed a rather identifiable pattern. Pure xanthan and gelatin tracks directly up the weak to firm axis, but does not shift in granularity. However, as xanthan and gelatin are combined, the resultant hydrocolloids begin to possess some amount of granularity. Generally, the higher the concentration of xanthan and gelatin, the firmer and more granular the gels become.

The printability of the hydrocolloids reached a limit as the stiffness and granularity of the resultant materials prevented reliable extrusion of the materials through a 3 mm syringe orifice.

DISCUSSION AND CONCLUSIONS

Using only two ingredients, xanthan and gelatin, a very broad range of mouthfeels can be simulated. This type of approach addresses the issue of materials-set bloat that would be faced as end-users attempt to feasibly implement SFF for culinary applications with a small, practical materials-set.

While the work herein serves as a proof-of-concept, further materials development is required to progress food-SFF. Not only does the mouthfeel range need to be expanded, but the flavors also need to be refined by tuning the flavor additives. To truly demonstrate the capability of hydrocolloid-based printing, ideally a double-blind tasting should be performed and it would be seen whether the taster can distinguish between the natural food and the hydrocolloid version. It should be noted, however, that even if subtle differences are perceptible, it is not necessary in all cases to perfectly *reproduce* the original food; there is still great value in *simulating* the original food.

Regardless of whether a hydrocolloid approach is taken to food-SFF, or some other molecular gastronomic platform is employed, the potential future applications of food-SFF remain the same. From culinary professionals to laypeople, individuals from all walks of life will be drastically affected by food-SFF. Artistic boundaries will be pushed in fine dining and industrial producers will explore mass-customization. Laypeople will have housework time reduced and benefit from direct culinary skill injections. Web 2.0 will tackle the next great frontier as people from all over the world experience food in new ways, while forming social bonds and mass-collaborating.

Now that major barriers have been broken, such as high printer cost and proprietary restrictions, the stage is finally set for tremendous growth of food-SFF. Few things are more central to humanity than food, and therefore is should come as no surprise when food-SFF gains prominence as one of the 21st century's important domestic technologies.

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