Edible 3D Printing

Principle Author: Deborah Southerland, Second Authors : Peter Walters, David Huson. Faculty of Creative Arts, University of the West of England, Bristol, UK.

Abstract

The potential of 3D printing has been under technical and philosophical discussion for some time, but current rapid prototyping materials can be costly and are limited in terms of functional and visual qualities. Food-based materials could provide a novel and exciting alternative which may also be affordable and accessible as 3d printing extends from industrial applications towards educational and home use.

This paper will compare and contrast the findings of a research project that explores freeform fabrication of food-based materials using rapid prototyping techniques. The three techniques are:

Rapid tooling: Using conventional Z-Corp powder binder 3d printing to fabricate master models from which silicon moulds are made and food materials cast.

Powder / binder 3D printing using a combination of different sugars to produce edible forms.

Extrusion based rapid manufacture using materials that include potato, chocolate and cream cheese.

The investigation of food as a material used in conjunction with these technologies is a growing area of interest and investigation. This paper will review the work already being undertaken by others in the field, as well as articulating the findings of our research project, and pointing to opportunities for future developments in this field.

The Research

The potential of Solid Freeform Fabrication (SFF) to 'democratize innovation'[1] is huge, and through open source technology curious and inventive engineers, architects, designers, hobbyists, and now more recently even culinary experts, are collectively contributing to what has become a self-sustaining and self-perpetuating community of innovators.

The use of food as an SFF material is a rapidly growing area of interest and given the high cost and sometimes unsatisfactory aesthetics of traditional SFF materials is providing fertile creative and technical ground for experimentation. Since Noy Schaal began working with chocolate for her high school projects on the Fab@Home model 1 unit in 2007, [1] the idea of working with food has ignited imaginations globally, fuelled largely by the Fab@Home open source philosophy. Fab@Home is a syringe based deposition tool that allows for the printing of any material that can be loaded into a syringe. Perhaps the most significant of the current investigations is the work being undertaken between Cornell's Fab@Home research group and The French Culinary Institute in New York. David Arnold, director of culinary technology at the French Culinary Institute has been testing the technology since 2009 and has printed with icing, cookie dough and masa (corn dough) , even fabricating spaceships out of scallop and cheese puree [2]. Dr. Lipton, leading the Fab@home project, sees potential for this technology to transform the way in which we prepare and consume food through the future development of 'Fabapps' that allow you to tweak your foods taste, texture and nutritional content [3]. Instead of just using hand-made ingredients and purees, this system would utilize the use of hydrocolloid liquid ingredients allowing complete control over the food and its nutritional and behavioral properties. Digital molecular gastronomy for the culinary avant-garde.

The interest for Arnold however, lies in the capacity that 3D printing has to create a new material language for cuisine, to create new textures for consumption that were previously unimaginable [4]. This is made evident in his work with masa, using a stochastic printing technique to create edible 'squiggles' that are reminiscent of the texture of Velcro [5].

Another research group whose work has drawn on the Fab@Home model of extrusion based deposition and open source dissemination is the 'Fabaroni.' [6]. A student project from the MIT 'how to make almost anything' class in 2007, they tested working with foods such as cheese, chocolate, chocolate sauce, marshmallow, vanilla icing, marzipan, pasta dough and peanut butter. The most successful in their tests was pasta dough, for its good structure and speedy drying properties; it also offered good consistency, flowed well and hardened quickly [7].

ChocALM [8] is another extrusion based 3D printing project that utilizes food, but whereas our project set out to develop a comparative study of various food stuffs and fabrication techniques, the chocALM project, a collaborative research project between Exeter University's School of Engineering Computer Science & Mathematics, and Exeter Advanced Technologies, worked specifically with chocolate. Recently, findings from this project have been developed towards an online customization tool for the custom-design and manufacture of 3D printed chocolate products [9].

Candyfab is another freeform fabrication project initiated by the 'Evil Mad Scientist' laboratories. Instead of using a syringe based extrusion method it works by building up layers of 2D images and then selectively fusing them together, using a 'selective hot air sintering and melting method' (SHASAM). The print bed is then lowered slightly, a new layer of sugar is added, and the next 2D image is printed, fusing with the layer below. This process is repeated to build up the three-dimensional object [10]. Sugar is the ideal material for this project as it's inexpensive, nontoxic, and readily available, "and when you're cooking, it smells like cotton candy and crème brûlée" [11]. The type of objects built on the Candyfab have less gastronomic appeal than those developed using the syringe based methods, but it allows for the manufacture of complex edible shapes that cannot be manufactured using traditional subtractive or casting processes.

Of the three processes that we set out to explore in our project, probably the least successful in terms of aesthetic complexity has been the most conventional; the use of the Z-corp machine to fabricate master patterns from which silicone moulds were then taken. Having developed a series of miniature bombs in Rhino 3D CAD, using the H bomb, various different cluster bombs and nuclear missiles as visual models, I was interested in creating an uncomfortable juxtaposition between my casting material and the form, these were to be chocolate bombs - 'bomb bombs'.
Although this type of rapid tooling can generate an exceptional level of digitally generated precision, we had difficulty achieving this in chocolate – hence the aesthetic simplicity of the forms. Chocolate is a surprisingly capricious material to work with, and has relatively narrow temperature range for effective manipulation. The first moulds we made were approximately 50mm in length, and proved to be difficult to cast in chocolate with even the simplest details proving too structurally weak to survive being taken out of the silicone mould. This combined with the inherently grainy surface texture of the original Z-corps mould, meant that the cast objects were less than satisfactory.

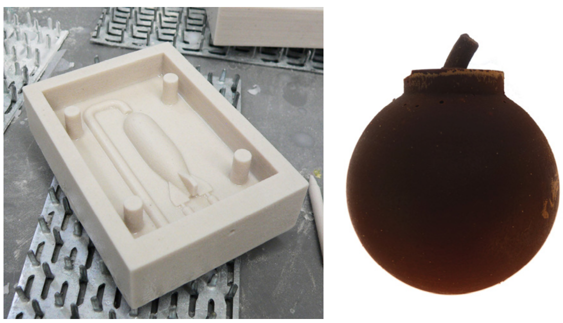

Figure 1 *Z-Corp printed master pattern and chocolate bomb*

Increasing the scale and finely sanding the printed mould before the silicone cast was taken afforded me opportunity to address both of those issues and the results can be seen in figure 1.
The second of the techniques the project aimed to explore was to investigate the potential of replacing the original Z-corp powder with sugars. Sugar being such a cheap and readily available material was the ideal substitute for the Z-corp powder in the context of the edible project.
Using a simple tooth shape ('sweet tooth') we began to experiment with a number of different sugar mixes in an attempt to find one that gave us the kind of print quality traditional Z-corp powder did. We started by investigating the particle size of the Z-corp powder and a range of sugars and sugar substitutes, with an aim of replicating the original Z-corp powder as closely as possible. We wanted a bimodal distribution of overall particle sizes between 149 and 37 microns, with at least 55% between 53 and 37 microns. Following a series of gradation tests we started with a 50/50 blend of icing sugar and caster sugar as this provided a similar range of particle sizes. The first test printed reasonably well and we were able to extract a form approximately 28mm in length within about an hour of the print finishing. The form was firmly bound and solid, although still too wet at this stage to brush effectively. The form had a depressed top surface, suggesting that there may be too much binder saturating the print, and as such it was notably bigger and less well defined than the original CAD model, indicating that binder had bled into the surrounding sugar particles during the print process.
We experimented using a number of different mixes and blends, adding and subtracting variant materials in 10 percentile quantities using the Z-corp particle sizes as a guide. We tested using combinations of caster, icing and silk sugars as well as blends with maltodextrin.

Figure 2 *Sugar teeth, 50/50% icing / caster sugar, 35% saturation.*

The most successful of these (see figure 2) occurred early on in our tests, and is a 50/50 blend of icing sugar and caster sugar with a 35% saturation. The surface is still coarse by comparison to an original z-corp print and the forms are more brittle, but after testing other sugar blends that either saturated too easily or were too brittle to extract from the machine, these were the most successful.

Figure 3 *Chocolate star print extruded at 'Bits from Bytes'*

The third part of the research project, using the RapMan 3.1 3D printer to extrude edible materials, (See figure 3) has been by far the most exciting and still has the most potential for creative and culinary exploration. We soon discovered this technique relies less heavily on the minutiae of particle sizes and recipes, and more so on creative intent, and taste!
The Rapman normally extrudes a filament of plastic through a heated nozzle, but we adapted the machine to extrude cold pastes. 'Bits from Bytes' [12] and Dries Verbruggen [13] recommended that we try using an auger valve, an off the shelf component part normally used in adhesive dispensing. It requires constant pressure; we used approximately 10-20 psi for these tests which we achieved using a bicycle pump connected to a pressure reservoir.
The auger allowed us more control over the extrusion process as it allowed us to experiment with both the level of pressure and the speed at which the material was extruded. The most precise control was reached by working with a slower speed over a longer period

of time, but increasing the pressure helped to clear small blockages or air bubbles. (See figure 4). We used a variety of plastic tapered tips on the auger, ranging in size from 18 – 22 gage. Tapered tips produce less back pressure than straight walled tips, but are less resistant to paste drool, which at this point in the project wasn't a problem, but may need addressing as we refine the product.

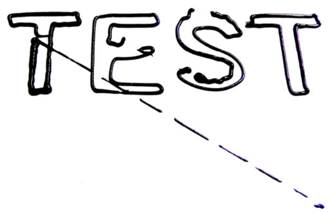

Figure 4 *Chocolate flavoured icing test print, evidencing the effects of uneven paste flow and air bubbles in the paste.*

Early experiments working with chocolate revealed its sensitivity as a material and instead of loading up the syringe barrel with previously melted chocolate we wanted to try working with the principle of heating the chocolate whilst it was in the syringe, and then keeping it at optimum temperature during the extrusion process. We initially tried to do this using a small thermostatically controlled and made-to-measure heating jacket wrapped around the syringe, but it proved unsuccessful as we couldn't wrap the jacket around the inlet fitting and auger valve. This meant that although the chocolate in the syringe was kept at the right temperature of between 44 and 45°C, it cooled and hardened in the valve before it could be extruded.

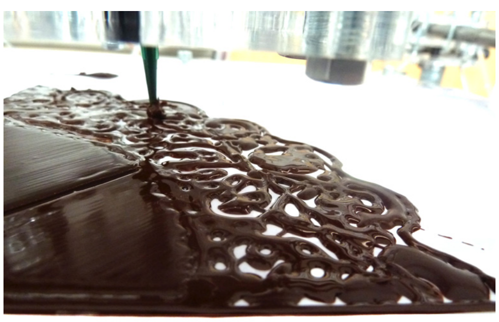

Figure 5 *Extruding melted chocolate; the extruded chocolate loses definition due to its liquid nature.*

We then went on to try several different chocolate and chocolate based products. Figure 5 shows another melted chocolate sample being extruded through a 0.84mm tip (18 gage), this time with the auger valve. This rendered poorly and was unworkable in terms of 'build' as the melted chocolate spread and expanded at the point of extrusion. Figure 6 shows a truffle mix experiment that clogged and separated during the process due to the shearing action of the auger valve. Figure 7 shows a lace doily, extruded in 'Betty Crocker ready mix chocolate fudge icing' using a 0.41mm tip (22 gage), This gave an even extrusion rate and generated an aesthetically strong and consistently smooth and detailed build.

Figure 6 *Truffle mix trials. Butter, cream and chocolate.*

Figure 7 *Lace doily made using Betty Crocker icing.*

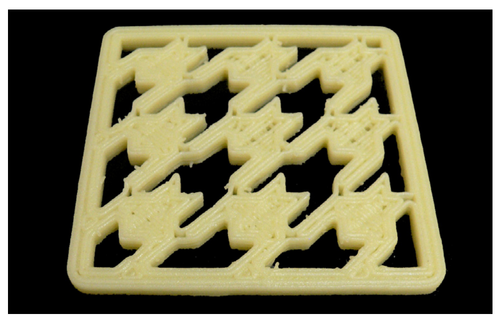

Figure 8 *Mr. Mash dogtooth checks potato waffle.*

Figure 9 *Real mashed potato waffle print.*

Figure 10 *Cream cheese lace doily.*

Further material enquiry on the Rapman involved the use of both real mashed potato and 'Mr. Mash' instant mashed potato, with the aim of producing dogtooth check waffles. Unfortunately, as far as taste is concerned, Mr.Mash provided a more consistently smooth paste that extruded evenly once we found the right settings. See figure 8.
Figure 9 by comparison, is real mashed potato that 'puffed' once it had been extruded due to the high level of pressure in the auger valve. We also experimented with extruding cream cheese, (see figure 10). This provided an almost ideal consistency of paste when we used 0.84mm tip (18 gage), but when we tried with a smaller size tip 0.41mm (22 gage) the shearing action of the auger caused the cheese to shear and separate.

Summary
We tested 3 forming methods using a range of foodstuffs and edible products. The tables below indicate the overall findings of the project to date. Future research will include further experimentation with the Rapman and different ingredient types, as well as preliminary work in molecular gastronomy, with hydrocolloids and gelling agents such as gellan, sodium alginate and calcium lactate.

Tables of findings

Z-corp printed mould	Findings
Range of materials	Chocolate, jelly, materials that are castable.
Resolution	High.
Types of geometry	Limited to forms that can be removed from moulds.
Aesthetic qualities	Good, provided the forms are not too complex.
Structural strength	Solid.
Z-corp printed powder	Findings
Range of materials	Powders such as sugars, starch, cornflour etc.
Resolution	High quality, but coarse by comparison to the original Z-corp powder material, definition lost due to excess saturation.
Types of geometry	Complex shapes are possible .
Aesthetic qualities	Good.
Structural strength	Brittle by comparison to original Z-corp prints, but robust enough to be handled / consumed.
Extrusion method	Findings
Range of materials	Materials that can be finely pureed into a paste or puree.
Resolution	Variable, depending on diameter of tip and material behavior under pressure.
Types of geometry	Potentially complex at low relief level, objects with height necessitate structural integrity of material not always achievable in paste form. Material dependent, 3D shapes need to be self supporting.
Aesthetic qualities	Extruded line always visible, this becomes less obvious with materials that do not harden, e.g. potato and cream cheese.
Structural strength	Dependent on materials. If materials harden – e.g. chocolate, the objects are handlable, whereas cheese / potato remain fragile.

References

[1] Malone, E, Lipson, H, *'Fab@Home: The personal desktop fabricator kit*, Rapid prototyping Journal, VOL 13, NO 4, 2007
[2] http://creativemachines.cornell.edu/node/194 (accessed 04.07.11)
[3] http://www.bbc.co.uk/news/technology-12069495 (accessed 04.07.11)
[4] http://money.cnn.com/2011/01/24/technology/3D_food_printer/index.htm (accessed 04.07.11)
[5] http://www.cookingissues.com/2011/01/24/fantastic-stochasic-masa-finally-a-good-3-d-food-printing-application/#more-5052 (accessed 04.07.11)
[6] http://fab.cba.mit.edu/classes/MIT/863.07/11.05/fabaroni/ (accessed 04.07.11)
[7] http://blog.sculpteo.com/2011/05/31/fabaroni-a-pasta-3d-printer-made-from-scratch/ (accessed 04.07.11)
[8] http://fabbaloo.com/blog/2010/2/3/chocolate-printing.html (accessed 04.07.11)
[9] http://www.alphagalileo.org/ViewItem.aspx?ItemId=107189&CultureCode=en (accessed 04.07.11)
[10] http://www.candyfab.org/ (accessed 04.07.11)
[11] http://www.wired.com/techbiz/startups/magazine/15-08/st_obsessed (accessed 04.07.11)
[12] http://www.bitsfrombytes.com/ (accessed 04.07.11)
[13] http://www.unfold.be/pages/projects (accessed 04.07.11)

Author Biography
Deborah Southerland, Senior Lecturer and Head of BA Hons D3 (Design) programme at UWE Bristol. As a recipient of UWE's Early Career Researcher Grant, she has been testing the use of 3D print and rapid manufacturing technologies using food and edible materials. Originally from a textile background, Deborah's teaching and research practice is driven by an exploration of the ways in which material languages can be used to create meaning, illicit emotion and gratify the senses.

Acknowledgements:This research was funded by an Early Career Researcher Grant from the University of The West of England. We are grateful to Bits from Bytes and Dries Verbruggen for advice on adapting the Rapman for use as a paste extruder.