The Development of a Colour 3D Food Printing System

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Abstract

Foods are becoming more customised and consumers want food that tastes great, looks great and is healthy. Food printing, a method of distributing food in a personalised manner, is one way to satisfy this demand. The overarching goal of this research is to develop the ability to print coloured images with food, but this thesis focuses on a subsection of that research. It aims to establish a broad base for future research in the area of food printing, present the design and development of mixing techniques applicable to food printing and finally use image processing to examine the distribution of colour in images likely to be printed.

By developing and testing various components and systems of the existing food printer and by performing a broad review of relevant literature, future researchers will be able to progress topics identified as essential in this field. Photographs of samples mixed using selected mixing techniques were analysed in order to produce qualitative and quantitative results. Six sample images were processed in such a way that colour distribution values were able to be used to estimate the average distances a food printing machine head would have to move between successive deposited volume elements while using discontinuous flow.

The results show each mixing technique tested has advantages and disadvantages, which make them more or less useful for different applications. Testing with static mixers and our oscillating mixer shows they are very capable of achieving complete mixing. However, the static mixing system used would be unable to achieve sufficient contrast between successive volume elements and the oscillating mixer needs development of operating mechanisms before it could be implemented. Mixing with our conical surface mixer showed it was unable to achieve complete mixing, but the novel technique has potential as a mixing technique if additions to the process are made. Results from processing the sample images showed the average distance was 3.26 pixels, which equates to 16.3mm with a 5x5x5mm volume element.

For research to continue, an appropriate mixing technique will need to be selected with regard to the goals and application of the food printing system. The distance between volume elements was deemed acceptable so the oscillating mixer or conical surface mixer would be most appropriate for discontinuous flow while static mixers should be used if a continuous flow is required.

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“Experience is a brutal teacher, but you learn. My God, do you learn.”
— C.S. Lewis

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1 Introduction

Usually, technologies developed for general manufacturing have subsequently been adapted for specific use in food manufacturing. This has been the case with steam power, mechanical mixing, electrical heating, computer control, machine vision and robotic manipulation. Each new technology has generated an irreversible change in food manufacturing internationally. This research aims to help push rapid prototyping as the technology that will cause the next revolution in food manufacturing.

1.1 Background

Food Trends

Food trends in countries all around the world have progressed through history in various ways. Many factors influence these trends and how they progress. One factor that has affected countries' food trends is the presence of indigenous peoples and their culture when immigrants of different nationalities settled in those places. The environment and natural habitat have also influenced how food trends have developed, and this influence continues today. In recent times technological advancements in food processing and transportation have hugely impacted eating habits of people all around the world [1]. Another major and important point in history that relates to food trends is the introduction and rapid growth of fast food outlets [2]. With this in mind, the general trends in food consumption have varied as the environment and people have changed. Some of these trends/stages include: wartime minimalist cooking, postwar luxurious and elegant cooking, easy and quick fast food, along with any number of health and wellbeing focussed trends. Some of the health and wellbeing trends, such as unprocessed, made-from-scratch, vegetarian, organic and fresh, simple, reduced-fat, low-fat and fat-free, are predicted to cause a counter-trend (R. Archer, personal communication, December 19, 2011). This counter-trend is predicted to comprise of a market that expects a food type that hasn't been seen before, due to technological and cultural barriers. The food type of this counter-trend is a processed food that delivers required nutrition, flavour and visual appeal in a customised fashion. The result is healthy, delicious and visually delightful food, coined Technofoods [3]. Some might say that this is overdoing it, but this is building on the already solid foundation of cake decorating (Figure 1-1). It's a commonplace activity, with businesses specialising in the art of cake decorating and some even having their own TV shows [4].

FIGURE 1-1 - GUITAR DECORATED CAKE – COURTESY OF OMAR DE ARMAS

Customised Foods and Mass Customisation

Consumers expect products to not only be reasonably priced and readily available, but also tailored to their needs, and they demand this from manufacturers [5]. For this reason, the market has increasingly produced food that is more and more personalised [6]. Supermarkets readily stock products labelled sugar-free, gluten-free, lactose-free, organic, halal and vegan. These are just a few of the subcategories or market segments. There is also an obvious trend towards availability and variety in fast food outlets. From the local fish and chip shop to Kentucky Fried Chicken offering a set range of options, to Subway and Dominoes offering custom toppings and fillings, consumers want and are getting food that is increasingly customised, and suiting their specific requirements. This trend towards customisation is coupled with the increased expectation of instant gratification, a powerful driver for efficient mass customisation [7].

One potential way of implementing efficient mass customisation is using forms of rapid prototyping (RP). RP avoids costly and time-expensive tooling and allows products made with the same equipment to be different from one another. Additive Manufacturing (AM) is the class of technology that allows solid 3D objects to be produced from a digital source by joining materials, usually layer-by-layer [8]. This differs from conventional machining or even other types of RP where material is removed from a stock in a subtractive manner. When applied to food, RP can take a number of forms, but most take two main types of AM

[9]. The first is Heat Fused Sintering, where selected particles (particularly sugars) are melted together with heat from a directed laser or lamp or a flow of hot air. Heat Fused Sintering has certain conditions required of the materials, which limits the types of food that can be used. Although it has been proposed that many different kinds of food could be a viable sintering material, only sugary materials have been used [10]. The second and most common method is extrusion. Research into food materials that can be used for extrusion has opened up many opportunities [11]. Although some current AM technologies allow multi-material models to be created, the materials are from distinct material sets rather than a combination of materials [11], [12].

Colour Rapid Prototyping

In 1991, Kinzie described a method and apparatus for printing 3D models made of sheets of material with colour on the surface [13]. A step closer to use with food was two patents presented by Nanotek in 2000, which described two methods of rapidly creating fully-coloured models [14], [15]. The idea of colour RP was then applied to foods [16], [17], but this method failed to explain how reasonable colour and spatial precision could be achieved. A big step towards making Colour RP technology (non-food) available in industry was Massachusetts Institute of Technology's binder and powder three-dimensional printing technique [18–20]. This technique was later licensed to Z Corporation, which led to the release of the ZPrinter range of 3D colour printers. With many of the barriers to food Solid Freeform Fabrication (SFF) being overcome, mainly aided by open source 3D printing projects, multiple colour/material printers have emerged [11], [12]. However, as of yet, only independently extruded multi-material systems have been developed.

There are two options for creating completely customised foods. A system could either use a material set that is large enough to satisfy all consumers' wants, or it could use a small material set, which could be combined in varying ratios. As the former has limited capabilities, especially on a small scale, the latter option has been explored. The result of exploration in this area by researchers at Massey University is a process called 'Food Printing' and a prototype machine still in development. Food printing is an additive manufacturing (AM) technique that uses computerised distribution of food material to manufacture food objects that are completely customised in shape, colour, flavour, texture and even nutritional value. The research presented in this paper only focuses on one section of the development of the food printer; the technology and engineering. The main research components were the pumping and mixing of the food materials. For completeness, most other aspects relating to the technology and engineering of the food printer have also been explored, albeit to a lesser extent.

Voxels

Food printing requires the ability to produce very small batches of mixture. In this paper, these very small batches of mixture are referred to as Voxels (Volume Elements). The voxels are created as the process progresses, with each voxel potentially being different from any other voxel being printed. This paper's use of the term 'voxel' falls in the middle of two divergent uses of the term: it is more than a virtual volume element used for modelling and data storage [21], but it is not a fixed and defined prefabricated object [22].

Research Team

The overarching project that this research is a part of is funded by the Riddet Institute. The Riddet Institute is a National Centre for Research Excellence, focussed on research in food applications. In 2006, a research proposal was made to the Riddet Institute to use food inks to print coloured images out of food. This research topic was accepted and a number of Chemistry PhD Students, Engineering Honours and Masters Students, and also external engineering contractors have contributed to this project, all supervised by senior Massey University staff.

This project has been noted to not only provide the end users with exciting foods, but to also be the next step to a future of fully customisable foods. Along with these end goals in mind, an attempt to maximise the research value of the project has directed the project team.

1.2 Existing Food Printer

The existing food printer consisted of three main blocks that interacted together. A personal computer allows the user to interact with the rest of the machine via purpose-written software. The software then interfaces with the motor control box, which in turn controls all the food printer motors. The way the hardware and software systems work together is demonstrated in the block diagram shown in Figure 1-2.

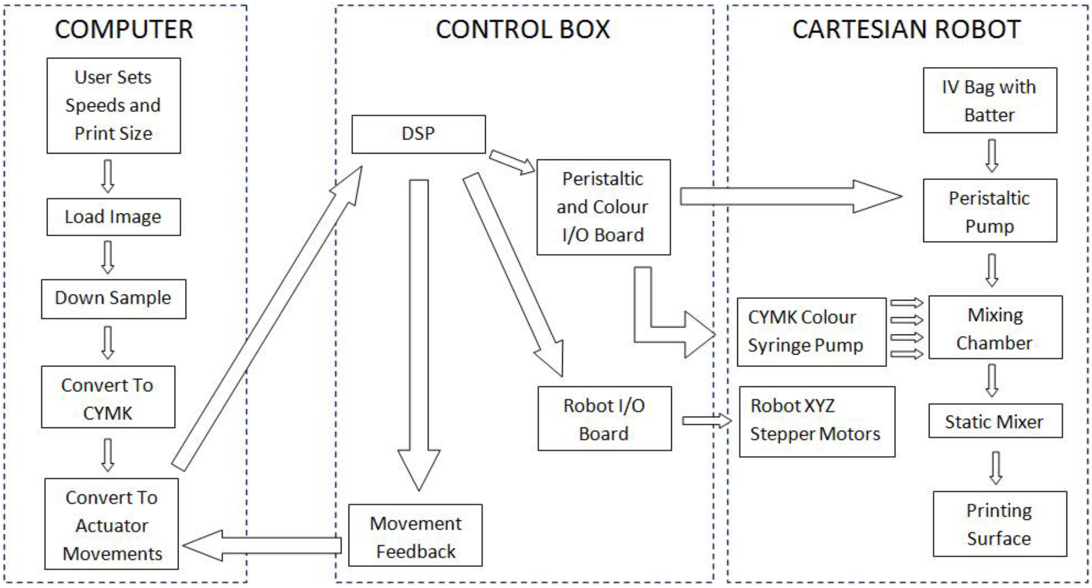


FIGURE 1-2 - BLOCK DIAGRAM OF THE SYSTEM [23] **(SEE APPENDIX)**

1.2.1 Hardware

The basis of the existing 3D food printer consisted of a three-axis Cartesian CNC machine driven by stepper motor linear actuators. The additional hardware that allowed food printing operations to be performed includes a peristaltic pump, a syringe pump and a motor control box. Figure 1-3 shows each of the components used.

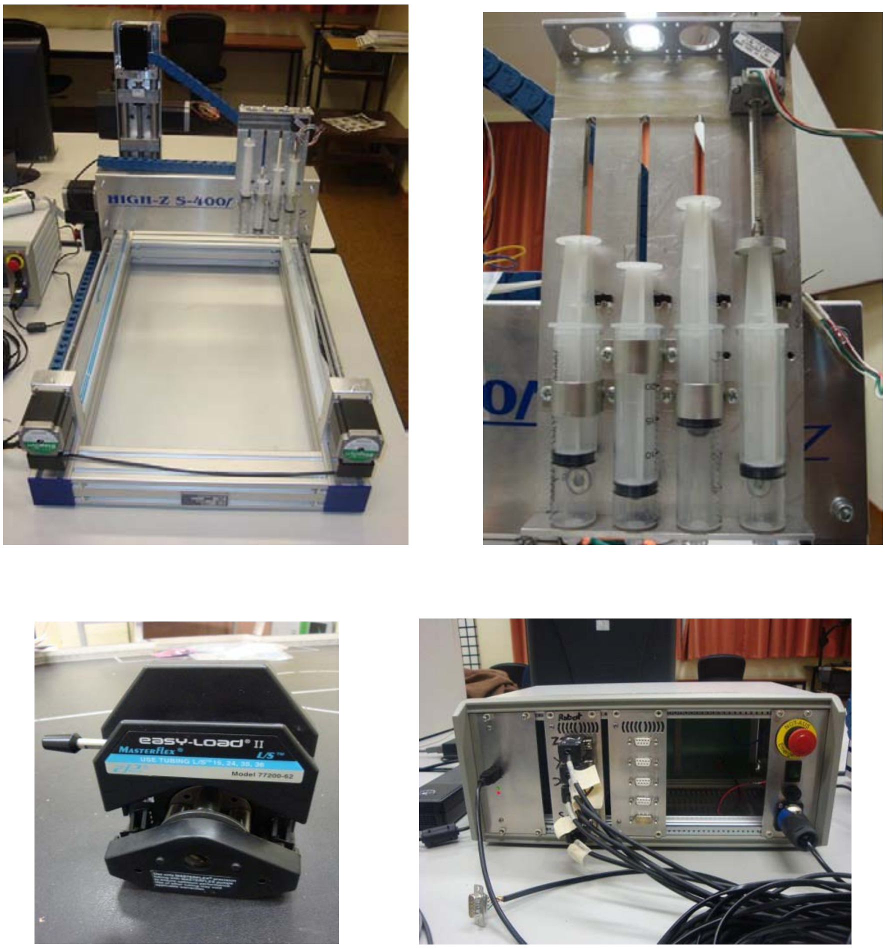


FIGURE 1-3 – 3D FOOD PRINTER COMPONENTS- CNC MACHINE, SYRINGE PUMP, PERISTALTIC PUMP, MOTOR CONTROL BOX

The peristaltic pump has been used to pump the food batter, while the syringe pump was intended for pumping food dye. A purpose-built controller box controlled all the stepper motors, including the peristaltic pump and the food dye linear actuator syringe pumps. More details of each of these components are given in Appendix.

1.2.2 Software

Image Down-Sampling and Colour Transformation

To allow images of any resolution to be printed, a down-sampling method was created to change the image resolution and colour to suit the printer's capability [24] (See Appendix). A simple averaging technique was used to reduce the number of pixels present in the image and a transformation from RGB colour values to CYMK colour values generates printable colour information. A sample of an image that has been down-sampled is shown in Figure 1-4.

FIGURE 1-4 - DOWN-SAMPLED IMAGE [24] (SEE APPENDIX)

DSP communication/Motor Control

To allow communication between a computer and the Motor Controller a custom communication protocol was created [23] (See Appendix). The protocol is bidirectional and the interpretation of the characters sent via serial communication depends on the sender and receiver. The computer can send commands such as reset command, various move commands with speed, acceleration and direction information, pump ON/OFF and connection check. These commands consist of up to 53 ASCII characters. The move commands use the full 53 characters with 17 characters per axis for the move commands, while other commands use fewer characters. The Motor Controller sends notifications to the computer, such as connection present, reached origin, move completed and individual axis moves complete. A program written in Visual Basic.net was run on a PC to allow communication with the controller box (Figure 1-5).

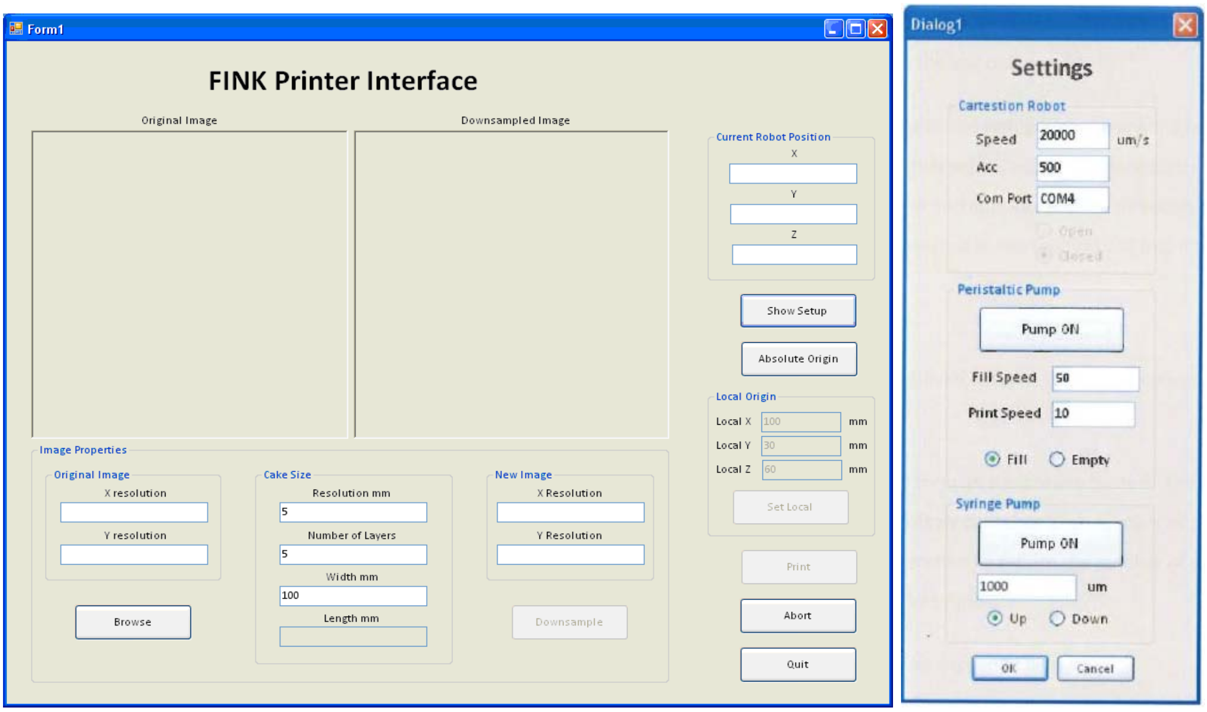


FIGURE 1-5 - GUI FOR PROCESSING IMAGES AND INTERFACING WITH THE FOOD PRINTER

The speed input parameter in the control software had units of μm/sec, which corresponded to actual movement speed of the axes (discussed further in Section 8.7). The acceleration input parameter had an arbitrary scale from 0 to 500.

Printing Routine

As the Motor Controller requires custom motor control commands, the printing routine was hard-coded rather than generated from a 3D digital model. A print routine was created to print a simple box of variable size. Two Visual Basic programs, separate from the main program, were written to generate variables to be used in the hard-coded printing routine. The variables generated would determine the size and shape of either the number ‘7’ or the letter ‘E’.

1.2.3 Food Printer Issues

There were a number of problems with this system, which meant that only basic shapes of one colour could be printed using the food batter.

The main issue with the extrusion of the food batter was oscillations in the flow due to the periodic nature of the peristaltic pump (Figure 1-6). This varying flow meant that the width of extruded food batter onto the printing surface varied continuously.

FIGURE 1-6 - OSCILLATING FLOW FROM PERISTALTIC PUMP WHILE PRINTING

There was one positive aspect of the oscillations in the flow of the food batter, which was that these oscillations were somewhat consistent and predictable. The peristaltic pump had four rollers that would produce repetitive oscillations every rotation of the pump head. This means that the flow is predictably oscillatory and able to be monitored using the position of the pump rollers, which are directly connected to the stepper motor. This made available the option to modify the flow by periodically changing the speed of the pump. However, the nature of the way the motor controller was programmed meant this solution was not feasible. Even if the motor controller was able to be programmed to dynamically change speed, the peristaltic pump flow rate was largely dependent on many other variables. This is discussed in more detail in 8.4.

The main issue with the mixing of colour into the system was the lack of control able to be obtained from the food dye syringe pumps with back pressure from the peristaltic pump. When pumping into atmospheric pressure, the syringe pumps would operate as desired. However, when the syringe pumps were trying to pump into the flow of food batter at the same time as the peristaltic pump pumped food batter through the static mixer onto the printing surface, the pressure of the fluid was too large. The pressure was increased due to the pressure drop across the static mixer (which could be as large as 110psi). With these pressures, the elasticity of the components and tubing and the static friction of the plunger in the syringe would result in inconsistent results. Section 5 presents the design of mixing techniques more applicable the food printing. The results from the testing a selection of these mixing techniques is presented in Section 8.

1.3 Specifications

The characteristics of the food batter and food dye that would be used as final products were as follows:

Characteristic	Food Batter	Food Dye
Viscosity μ (Pa.s)	1↔20	0.001↔20
Density ρ (g/mL)	0.9↔1.2	1↔1.2
Particulate size (μm)	400↔1000	0↔1200

TABLE 1 - FOOD BATTER AND FOOD DYE SPECIFICATIONS

To determine the speed at which these materials would be deposited, a number of assumptions were made to allow for two production situations. The two situations are next working day production and point-of-sale production. The first situation would be for when a customer orders a customized cake in a shop or online. From the outset of the overarching research project, it was specified that the printer should be able to print an A4 page in one minute. This would allow a ten layer cake to be produced within ten minutes, allowing a full sized cake to be produced at point-of-sale. With a voxel size of 5x5x5mm, this required a flow rate of 315ml/min. This flow rate was used as a target for non-agitated mixing, but it was deemed too fast for agitated mixing. To determine the flow rate for agitated mixing, the assumptions were that the cake would be approximately A3-sized and 100mm high, and it would be acceptable to be deliverable the next working day. Table 2 shows how these assumptions lead to the calculation of flow rate and time available per voxel printed.

A3 page	421 × 297mm
Voxel size	5x5x5mm
Voxel volume	0.125mL
Total Print Time (5pm-9am)	16 hours
print time/A4 layer	48mins
Volume of A4 layer	5x421x297 mm = 625185mm^3 = 625mL
Flow rate required	13.2mL/min (~2 voxels/sec)
Time per voxel	0.57ms

TABLE 2 - PRINT TIME SPECIFICATIONS

This information can then be used for the second situation, which would be for when a customer orders a customised piece of cake to be produced while the customer waits. This could happen in a café-type shop or online. The assumptions for this situation are that the cake would be produced in fifteen minutes, with the same rate as the first situation. This would mean a cake approximately 90x50mm and 60mm high would be achievable.

2 Review of Food Printing and Rapid Prototyping

2.1 Existing Food Printing Concepts, Designs and Prototypes

There are a number of current research projects and existing products that are related to food printing in various ways. Research projects in the area of rapid prototyping with food materials are at present in varied stages of progress. The existing research ranges from concept ideas (some of which could be achievable and some being futuristic ideas) right through to in-depth material and flow research for extrusion deposition.

2.1.1 Conceptual Ideas

There are a number of conceptual ideas in the literature that are relevant to food printing. Goals and standards can be taken from these concepts even though much of what is presented is unrealistic with current technology and the scope of this research.

Nanotek's Rapid prototyping and Fabrication Method for 3D Food Objects

Nanotek Instruments Inc. is a business involved in research, development, manufacture, sales and service [25]. The core technologies of Nanotek are nano-materials and processing, energy storage and conversion and rapid prototyping/tooling/manufacturing.

Nanotek has four patents relating to Personal Part Fabrication (PPF) and 3D colour food printing [14–17]. The patents of direct interest describe a method of rapid prototyping and fabricating 3D multi-coloured food objects. The method described utilises a machine with fixed extrusion head and a three axis CNC work table to print food material layer-by-layer in a line by line manner. Two extrusion head setups are described. The first is a simple positive displacement syringe/piston pump which forces fluid through a nozzle onto the printing surface. The second extrusion head consists of a positive displacement syringe/piston pump which pressurises the fluid, forcing it into the inlet of a metering gear pump. The outlet of this pump is split into two flows where each flow is combined with additional flows from additional positive displacement syringe/piston pumps before exiting through two separate nozzles. The patent suggests the food material would consist of a volatile ingredient. Figure 2-1 shows two figures included in the patent showing the preferred method and apparatus.

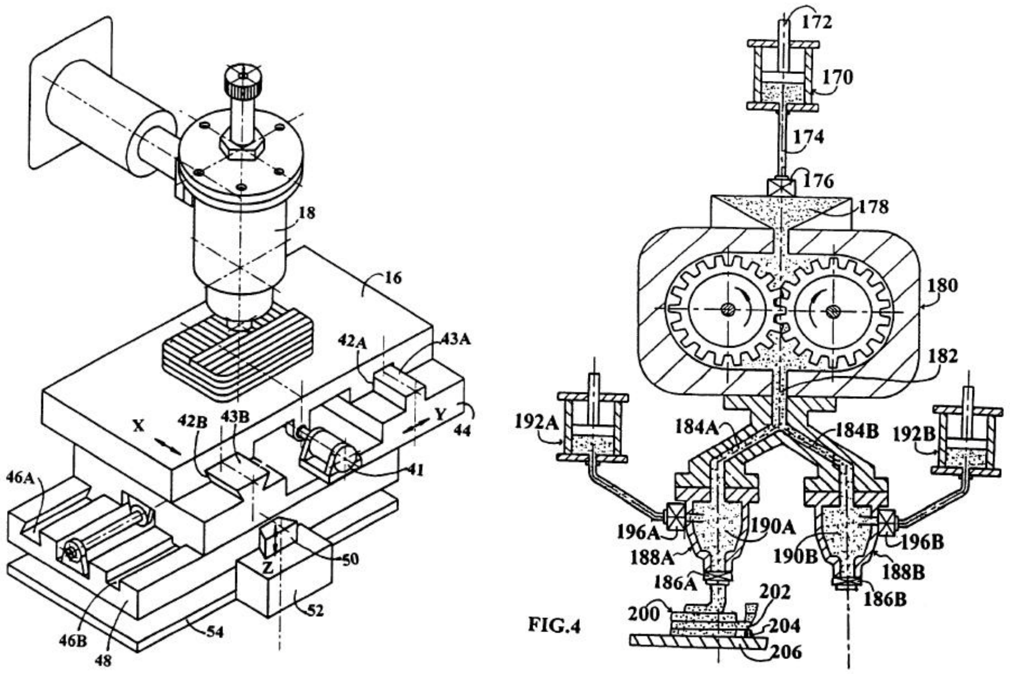


FIGURE 2-1 – NANOTEK'S METHOD OF PRODUCING 3D MULTI-COLOURED FOOD OBJECTS [16]

As this patent is describing a method rather than apparatus, no functioning machine has been produced. Since 2001 when the patent was granted, there is no evidence of further progress.

Electrolux Moléculaire

"Established in 2003, Electrolux Design Lab is an annual, global design competition open to undergraduate and graduate industrial design students who are invited to present innovative ideas for household appliances of the future." [26]. In 2009, Nico Kläber, a student of the Köln International School of Design in Germany was the winner of the competition.

The concept is a product that takes a range of ingredients consisting of small particles, which it then uses to build up 3D food products/meals [26]. The design incorporates molecular gastronomy to transform normal foods into many different forms. It utilises a small robotic arm, which distributes the food particles from a 'blister pack' in a precise way, allowing new and previously unseen types of foods to be created. The concept allows multiple materials to be printed within one food product/meal, all using the one robotic arm. Figure 2-2 shows a 3D CAD model rendition of the Moléculaire.

FIGURE 2-2 - ELECTROLUX MOLÉCULAIRE CONCEPT [27]

This concept shows what the distant future of food printing may entail. However, minimising the size of components so that they fit in the nice packaging presented seems a difficult task. Also, the 'blister pack' suggested doesn't deal with where any significant amount of food material would come from to create a fully customised meal.

Philips' Food Creation/Printer

"Philips Design Probes is a dedicated 'far-future' research initiative to track trends and developments that may ultimately evolve into mainstream issues that have a significant impact on business." [28].

One result of the 'Philips Design Probes' is the Food Creation program. The most interesting outcome of this project was the food printer. This concept is similar to the Moléculaire concept in that it also incorporates molecular gastronomy to form new and previously unseen types of food. The Food Printer allows users to place food into the cartridges at the top of the food, which seems like a more appropriate way to store the food than the 'blister packs' of the Moléculaire. An interactive graphical user interface allows the user to select ingredients, quantities, shapes, textures and other properties of the food. A printing head then uses the food materials from the cartridges to create the custom-designed food product in a layer-by-layer manner. Figure 2-3 shows a 3D CAD model rendition of the Food Printer.

FIGURE 2-3 – PHILIPS FOOD CREATION/PRINTER [29]

This is another distant future food printing concept with no detail about the methods that might be employed to implement it. The ideas presented about designing the foods may be applicable for any type of customised 3D food printing and seem feasible and useful. As with the Moléculaire, the size of the Food Printer seems vastly unrealistic for the kinds of products that it would fabricate.

Massachusetts Institute of Technology's Cornucopia

Cornucopia is Massachusetts Institute of Technology's "concept for futuristic kitchen machines with new digital cooking interfaces inspired by a novel digital gastronomy." [30]. Rather than molecular gastronomy as used by the Electrolux Moléculaire and the Philips Food Printer, Cornucopia takes the approach of simply digitising gastronomy. This means that rather than breaking the food materials down into molecular parts, the food materials are just combined in discreet (digital) volumes. Four concepts are presented, each focussing on different aspects of gastronomy.

Virtuoso Mixer Concept

The Virtuoso Mixer is a machine that processes raw food in an automated and customised way in order to produce customised food products. The three-layered machine has storage containers that monitor temperature, humidity and the weight of the product on the top layer. These feed the second layer, which is comprised of a number of processing chambers, with each chamber dedicated to a different process. These include mixing, whisking and crushing devices. Once the food has been processed in the second layer, it is fed into the third layer where food is extruded onto the surface, where it is either thermoelectrically heated or cooled to the desired temperature. Figure 2-4 shows a 3D CAD model rendition of the Virtuoso Mixer Concept.

FIGURE 2-4 – VIRTUOSO MIXER CONCEPT [31]

This concept seems to be the most realistic of all of the concepts, and does not use abstract ideas to form its products. Many problems would still have to be overcome to make this product feasible, such as distribution and metering systems between the layers, cleaning of the system and waste minimisation.

The Digital Fabricator

The Digital Fabricator is a multi-material 3D food printer concept [30]. Using temperature-controlled (refrigerated) canisters of food, the Digital Fabricator combines standard food ingredients in a customised manner. A three-axis mixing/printing head distributes the food onto the printing surface in the Digital Fabricator's chamber. By precisely metering, mixing, dispensing and cooking or cooling the food materials, standard meals as well as unusual meals can be prepared completely autonomously. The food materials can be cooled or heated in the connecting tubes as well as the chamber. Figure 2-5 shows a 3D CAD model rendition of the Digital Fabricator Concept.

FIGURE 2-5 - DIGITAL FABRICATOR CONCEPT [31]

While being more realistic than the Electrolux Moléculaire and the Philips Food Printer, the sub-millimetre precision expected by this machine is a high standard to set for being able to mix and dispense while still preventing material wastage. Cleaning of this system may also be relatively difficult with its many chambers and tubes that it comprises of. There is no mention as to how the different food materials arrive at the mixing head or how efficient the storage system may be. The idea of food canisters that can be refilled seems appropriate, although various sizes would make them far more practical.

The Robotic Chef

The Robotic Chef is just as its name suggests; a concept of a robot that can perform similar functions as any chef [30]. The concept utilises two five-degree of freedom robotic arms, a tool head and a heating bed to manipulate any kind of food object. The arms and tool head allow localised transformations such as drilling, cutting and dispensing via syringes. The tool head also includes a low-power laser diode, which can be used for cutting or cooking/sintering. Figure 2-6 shows a 3D CAD model rendition of the Robotic Chef Concept.

FIGURE 2-6 - ROBOTIC CHEF CONCEPT [31]

Although using robotic manipulators and incorporating a tool head as described is feasible, the size and apparent simplicity of the device would require a significant amount of development. The programming of such a device would be a very difficult task with each food object being a different shape and each operation requiring potentially complicated movements and manipulations.

The Digital Chocolatier

The Digital Chocolatier is a machine that dispenses chocolate and a small number of other ingredients in customised volumes into a container [31]. The Digital Chocolatier utilises compressed air (for liquid chocolate) or gravity (for solid ingredients such as nuts) to force the food materials out of the chambers when the solenoid-controlled valves are opened. The food material collects in a special container, which is then cooled using a thermoelectric device and the result is a customised chocolate candy. Figure 2-7 shows the 3D CAD model rendition of the Digital Chocolatier and the physical prototype that the researchers built.

FIGURE 2-7 - DIGITAL CHOCOLATIER - 3D CAD MODEL AND PROTOTYPE [32]

This is the only one of the Cornucopia machines to have actually been made. A functional prototype has allowed customised chocolate candies to be produced, but it has also identified a number of flaws [32]. The idea of not only controlling liquids, but adding customised amounts of solids such as nuts is appealing. However, either standardised sized ingredients or very robust metering and dispensing systems would have to be employed to allow a system like this operate reliably.

2.1.2 Research Projects with Prototypes

The following research projects all have some relevance to 3D Food printing. Even those that explore single material extrusion are valuable as there are many different methods of extrusion that have been applied. There are some that explore significantly different methods of building models, such as laser sintering and powder/binder 3D printing. The last project in this list is not related to food, however it is the only research that has explored the area of mixed multiple material extrusion. This list is not exhaustive as it would be impossible to keep track of all the 3D printing projects involving food, considering the number of tertiary institutes, private companies and open-source projects involved.

Cornell University's Fab@Home 3D Printer

The author of [33] says "The objective of the model 1 Fab@Home was to lower the cost of involvement in SFF, and encourage others to develop and invent new technologies.". The Fab@Home project team, based at the Computational Synthesis Laboratory at Cornell University has not aimed solely at this target. They have joined with a number of other groups to carry out focussed research [34].

The Fab@Home 3D printer is a three axis Cartesian CNC machine with either one or two syringe deposition tools on the tool head (Figure 2-8).

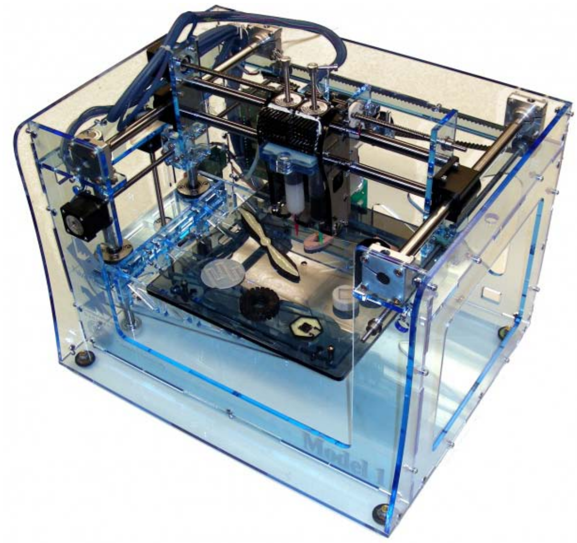


FIGURE 2-8 - FAB@HOME PRINTING PLATFORM [35]

One group in particular that has been involved with the Fab@Home is the French Culinary Institute, New York. Testing of a variety of food materials has been carried out, with many positive results [36]. These materials include: frosting, chocolate, processed cheese, muffin mix, hydrocolloid mixtures, caramel and cookie dough [11], [37]. Although this research has demonstrated multi-material printing, this has only been achieved using separate deposition heads that use a limited material set. The use of secondary material for supporting the main printing material has also been explored with considerable success [36].

CandyFab

"Evil Mad Science LLC is a small family-owned business based in Sunnyvale, California." [38]. The company produces DIY and open-source hardware designs, which originated with their project blog, Evil Mad Science Laboratories. One of the current members of the Evil Mad Science Laboratories is Windell Oskay [39]. In one of Oskay's posts in the blog, he describes the CandyFab 3D fabricator in detail [40].

"The CandyFab Project aims to reduce the costs associated with three-dimensional solid freeform fabrication, and to promote the use of fabrication technologies for culinary, educational, and artistic purposes" [41]. The CandyFab is an open-source 3D fabricator that builds up models layer-by-layer, by applying localised heat to a bed of sugar. The heat is applied using Selective Hot Air Sintering and Melting (SHASM) technology, which directs a narrow low-velocity stream of hot air towards the fabrication material. This is achieved with a modified hot air gun. Once the layer has been melted in the appropriate coordinates, a new layer of sugar is added by manually adding a scoop of sugar, which the machine then spreads evenly. Figure 2-9 shows the CandyFab 4000, one of the iterations in this project.

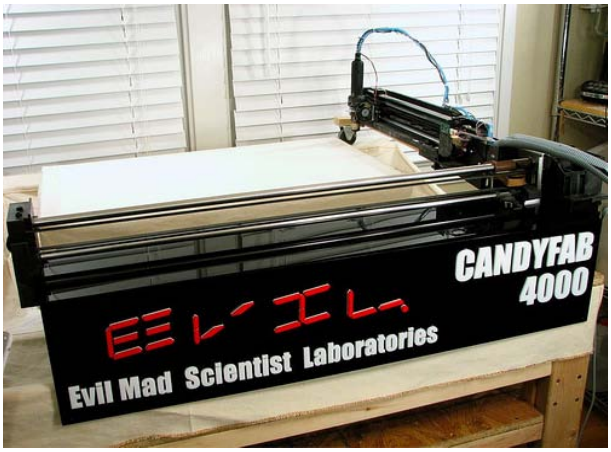


FIGURE 2-9 - CANDYFAB 4000 [40]

The main material used is sugar; however there are suggestions that other materials are possible. These would mostly consist of sugary or fatty materials that have relatively low melting points [10].

Exeter University's ChocALM

"The ChocALM system is developed through an interdisciplinary group student project in the University of Exeter. Since the proof of concept the project team has aimed to develop a robust system to manufacture dimensionally accurate, palatable 3D chocolate products from CAD models" [42]. The ChocALM is a three-axis Cartesian CNC machine with a chocolate extrusion head (Figure 2-10). The extrusion system consists of three main components. The first component is the tempering unit, which is a heat controlled chamber. The material from this chamber is then pumped with a lobe pump via a heated flexible hose to the last component, the extrusion head and nozzle. The extrusion head consists of an Archimedes screw that controls the flow of the chocolate. Currently only brown chocolate has been printed, but there are plans to be able to co-print white chocolate.

FIGURE 2-10 – CHOCALM [8]

Massachusetts Institute of Technology's Fabaroni

The Fabaroni is a three-axis Cartesian CNC machine capable of extruding pasta dough [43]. This system was part of a student project in the 'How to Make (Almost) Anything' class at Massachusetts Institute of Technology in 2007. Besides mentioning that it uses an extruder and testing materials by using syringes, no method of dispensing is explicitly stated. The only material used is pasta, which was selected after a range of food materials were judged on their viscosity, consistency and solidifying properties.

University of the West of England's Edible 3D Printing

The Edible 3D Printing research is a "project set out to develop a comparative study of various food stuffs and fabrication techniques" [44]. Bits from Bytes and the University's Centre for Fine Print Research are both involved with this research [45]. Bits from Bytes is a manufacturer of 3D printers based on the RepRap project [46], [47]. It focuses on three techniques: master pattern, mould creation and casting, direct powder/binder RP and extrusion RP. A Z Corporation powder/binder 3D printer was used to form master patterns, from which silicone moulds were created and used to cast food materials such as chocolate. The Z Corporation powder/binder 3D printer was again used, but using sugars and starch mixtures as the powder material rather than the standard Z Corporation powder.

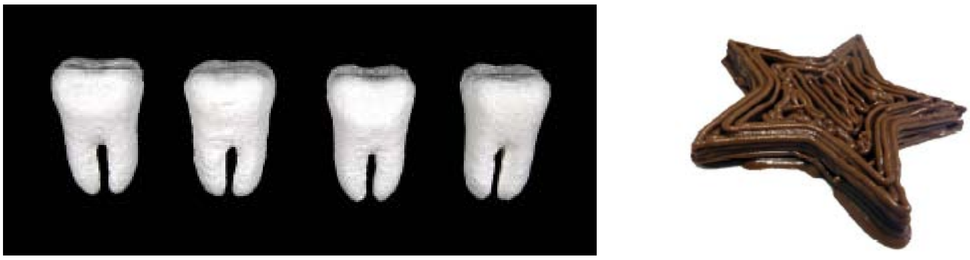


FIGURE 2-11 - Z CORPORATION 3D PRINTED TEETH AND RAPMAN EXTRUDED CHOCOLATE STAR [44]

Extrusion-based RP was carried out using a modified RapMan 3.1 3D printer. To extrude the food materials, an auger valve has been used to provide controlled feed rate. A number of food materials were tested including mashed potato, chocolate, truffle mix, icing and cream cheese (Figure 2-11).

TNO's Food Jetting Printer

"TNO is an independent research organisation whose expertise and research make an important contribution to the competitiveness of companies and organisations, to the economy and to the quality of society as a whole" [48]. Kjeld van Bommel suggests that a number of technologies that the company is researching could be combined to allow 3D printing of raw food materials such as algae protein, fat and starch [10]. The technologies that are of interest include 3D printing, jetting of high viscosity material (Figure 2-12), electrospinning and laser sintering.

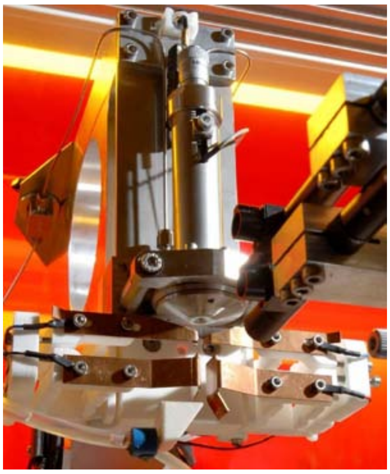


FIGURE 2-12 - TNO HIGH VISCOSITY INKJET TECHNOLOGY FOR RAPID MANUFACTURING [49]

Besides suggesting that 3D printing could be used to combine multiple materials, only single material extrusion models have been presented. Van Bommel has used laser sintering to create models with NesQuik powder and sugars, and also has worked with a jetting head for high viscosity fluids. The jetting head uses 'Stimulated Rayleigh breakup' to cause a fluid stream to break into droplets [49].

De Grood Innovations' FoodJet Printer

The FoodJet Printer is a commercial industrial nozzle-jet printer used for jetting non-mask patterns using food material (Figure 2-13). It uses pneumatic membrane nozzle-jets to deposit many drops of the selected material onto the printing surface. The printing surface can be almost anything, from pizza bases to biscuits and cupcakes. "The drops together form a digital image in the shape of a decoration or a surface fill."[50].

FIGURE 2-13 - FOODJET PRINTER [50]

Temperature controlled deposition and machine vision are two optional extras to increase its versatility. Some of the specifications of the system include: a print resolution of up to 30 DPI, material viscosity of up to 30,000 cps, silent (<40dB) operation and clean in place capable.

Missouri University of Science and Technology's Triple-Extruder Freeze-form Extrusion Fabrication System (Ceramic)

The Triple-Extruder Freeze-form Extrusion Fabrication (FEF) machine consists of a three-axis Cartesian CNC machine with an extruder head [51]. The extruder head has three linear actuators that drive the pistons of three plungers (Figure 2-14). The output of the three plungers is forced through a static mixer and finally through a nozzle onto the printing surface. The research was driven by the desire to develop an environmentally friendly free-form fabrication method to create ultra-high temperature ceramics with high solids loading ceramic paste. The original FEF machine only had one linearly actuated plunger and was designed to demonstrate the FEF method, but to implement Functionally Graded Materials (FGM), multiple plungers had to be used.

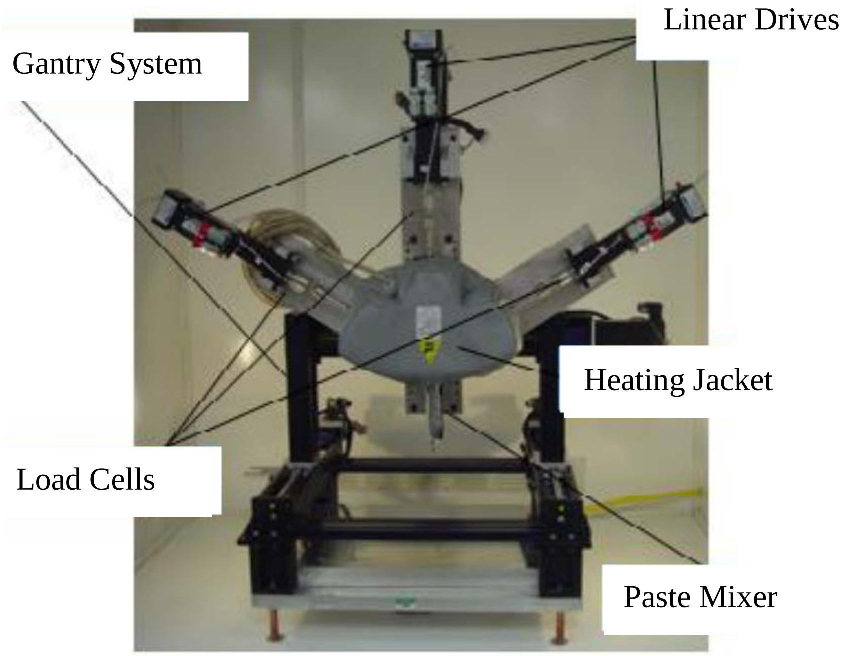


FIGURE 2-14 - FEF MACHINE WITH TRIPLE-EXTRUDER MECHANISM [51]

The materials used in this study include Alumina, Zirconia and Limestone. Water was used as the main medium, Polyethylene-glycol as the extrusion lubricant, and Aquazol 50 as the binder.

MakerBot Industries' MakerBot (Froststruder)

MakerBot Industries is the designer and manufacturer of the MakerBot open-source 3D printing project. The MakerBot project has many aspects to it, including its main CNC function, plastic filament extrusion, milling capabilities, 3D scanner, optional automated and/or heated build platform and time-pressure dispenser [52].

FIGURE 2-15 – FROSTRUDER TIME-PRESSURE EXTRUDER [53]

The Frostruder uses two solenoid valves to control the flow of material from the syringe (Figure 2-15). Using MakerBot RP machines and the Frostruder MK2, extruding frosting, creamy peanut butter, jelly/jam and Nutella has been achieved [53].

2.2 Food and Food Dye

Xanthan Mixture

The material that will be printed is a cake mixture consisting of xanthan, water, rice flour and any extra colours or flavours. The use of xanthan makes the fluid pseudoplastic [54]. The authors describe pseudoplastic fluid behaviour as being "characterized by an apparent viscosity, which decreases with increasing shear rate [55](p. 6). The mixture can also be likened to a viscoplastic fluid, which the authors say "is characterised by the existence of a yield stress (T0), which must be exceeded before the fluid will deform or flow" [55](p. 12). The range of viscosity of the mixtures being mixed for application to food printing is 1-10Pa.s, with the density ranging between 0.9-1.15g/mL. Corn syrup, a Newtonian fluid, has been used as a simulant fluid to simplify modelling, test preparation and cleaning. The corn syrup used was composed of 80% carbohydrates and 20% water with the author of [56](p. 153) stating the viscosity of corn syrup to be about 18Pa.s. This was then diluted with water to give the range of viscosities needed.

Basic Concepts of Colour Models

"Color is a material property. It is the visual effect resulting from the eye's ability to distinguish different wavelengths (ranges from 400 and 700 nm) of light. The apparent colors of an object depend on the wavelengths of light that it reflects. There are several formal systems, or photometric interpretations, to specify and represent colors. The most widely recognised system includes RGB (Red, Green and Blue primaries). This is an additive primary system and is popularly used in representing computer graphics. The CYM(K) (Cyan, Yellow, Magenta, (and black)) system is a subtractive primary system. This is used in ink-jet printers for mixing colors. HSB (Hue, Saturation and Brightness) is a model based on human perception of color. To incorporate color into RP, there should be an interface to store the color information generated during the CAD design of the model, which can be precisely related to the geometric description of the model." [57].

Once these basic concepts are understood, they can begin to be applied to the colouring of food for food printing as described in [58].

2.3 Rapid Prototyping Techniques

There are three main types of rapid prototyping (RP), which can be classified as liquid-based, powder-based and solid-based. Among these types of RP, there are many different technologies that work to recreate computer-aided design (CAD) models, through solidifying the working materials of the process. The authors of [59] say "the methods employed by each vendor can be generally classified into the following categories: photocuring; cutting and gluing or joining; melting and solidifying or fusing; and joining or binding".

The largest number of systems on the market as listed by [59] fall under the powder-based category with sixteen RP systems. Fifteen liquid-based RP systems are mentioned, and nine solid-based RP systems. This section summarises and evaluates the most relevant RP systems listed by [59]. The figures used in this section are courtesy of [59].

When these processes and the materials they use are examined with regard to food printing, two can be disregarded. The processes that can be disregarded are thermal fusion or sintering and photocuring due to the nature of the materials that are required. Even though these are two of the most prevalent RP processes, current food products are incapable of allowing these processes to be used for food printing. Melting has potential to be of use if combined with other processes, but if lasers or other heat sources were used as they are in RP fusion process, most food materials would simply burn. To create a photocurable food mixture that meets all the criteria for food printing is a long way from being a reality, if it is possible at all.

While these two printing techniques can be practically ignored, there are many aspects of other existing RP processes that can be useful in terms of food printing.

2.3.1 Solid-Based Rapid Prototyping

Stratasys's Fused Deposition Modelling [60]

Fused Deposition Modelling (FDM) uses a solid filament of material that is forced, using drive wheels, through a heated nozzle that melts the filament and distributes it onto the printing surface where it re-solidifies (Figure 2-16).

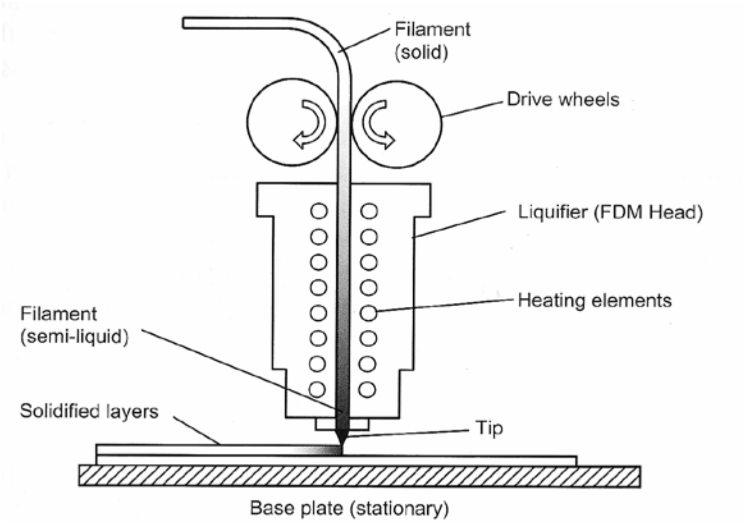


FIGURE 2-16 - FUSED DEPOSITION MODELLING PROCESS [59]

This process could be utilised with only a few materials such as butter or chocolate, and the material would have to be combined with other additives to create a complete food printing mixture. The phase change that this process requires is undesirable due to the complex nature of food rheology. However, the idea of being able to store the material as a solid at room temperature is potentially desirable.

Solidscape's Benchtop System [61]

The Benchtop system uses a similar principle to FDM, but rather than just being extruded out of the nozzle, the filament material is jetted out onto the printing surface. Along with the build material, a support material (soluble wax) is jetted out in a second nozzle. Once a layer has been printed, a precision milling head removes a thin portion off the top of the partially completed model (Figure 2-17).

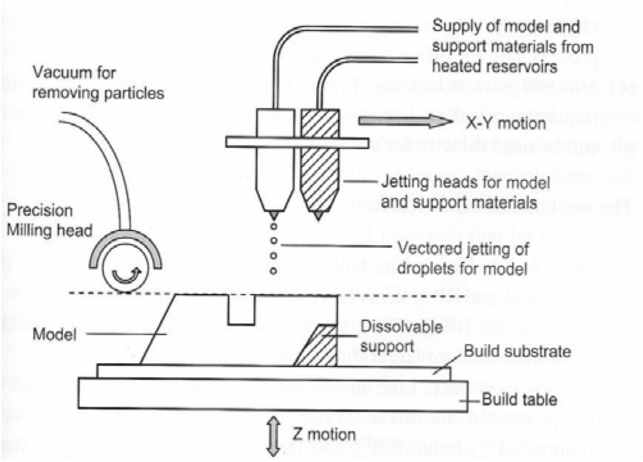


FIGURE 2-17 - BENCHTOP SYSTEM [59]

Again, this method would require additional material to be added to the melted material to create a complete food printing mixture. The materials used for food printing in our research are far too viscous to be jetted onto the printing surface, but the use of a second deposition head for a support material is a viable option. If an appropriate support material could be designed, this would allow more flexibility in the food batter mixture. An appropriate support material would melt, vaporise or create a non-joining boundary between itself and the food batter material. This would mean that the material would be easily removed during post-processing. The intra-layer milling would most likely be unnecessary for food printing, but something like a wiper could be used to improve surface finish. This may only be appropriate on the sides and top of a food model rather than in between every layer.

Solidimension's Plastic Sheet Lamination [62]

Layers of material are cut using a cutting knife and these layers are then bound together using adhesive. The result is a stack of material with cross-sectional outlines cut into each layer. Post processing is required to remove the waste material. To employ a process similar to Plastic Sheet Lamination using food materials for food printing, a pre-cooked, solid mixture would be required to allow carving. An effective interlayer binding material (such as cake icing) would be required to bind dry layers. It would be difficult to create layers thin enough to give reasonable resolution and positioning, and alignment mechanisms would have to be employed to place the layers. However using dry layers would open up the very appealing possibility of ink jetting food dyes onto each layer, which would mean no mixing would be required. If liquid material was to be used, something as excessive as a vacuum could be used to remove liquid from unwanted areas. This would possibly mean solidification between layers would be more important to prevent unwanted material removal.

3D System’s Multi-Jet Modelling [63]

This process is almost identical to SolidScapes Benchtop System, as it jets a build material as well as a support material. But rather than using a filament of thermoplastic material that solidifies once it cools, Multi-Jet Modelling uses Ultraviolet (UV) sensitive non-toxic wax materials, which solidify when exposed to UV light (Figure 2-18).

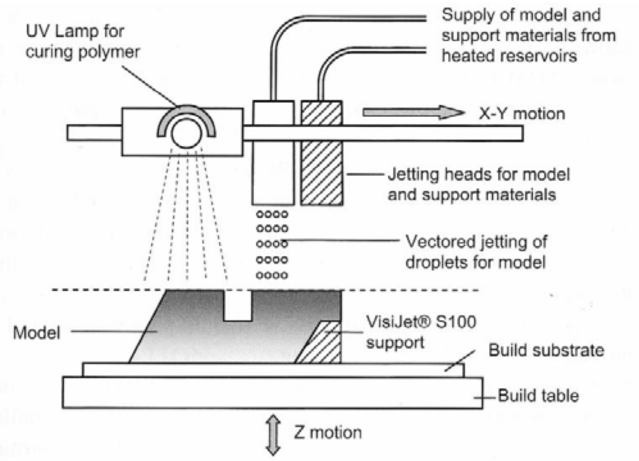


FIGURE 2-18 - MULTI JET MODELLING [59]

As mentioned before, photo-curable RP processes can practically be ignored, however, if the UV light source is substituted for a heat source, the food mixture could be cooked or solidified as the printing progressed. This method has a potential advantage and a potential disadvantage when considering its application to food printing. The disadvantage is that it is not a conventional way to cook food. The potential advantage is that it may give a more consistent and controllable cooking rate as thin layers are cooked in sequence with more even heat distribution possible.

Rapid CNC machining or Subtractive RP

Subtractive RP (SRP) take standard CNC machining to a level where is can be applied as a RP technique. This involves minimising user input by avoiding manual reorientation of parts and automating the process planning of the CNC machining [64]. By using a rotary axis and a number of layer-based (2½-D) tool paths, prototypes can be manufactured without continued user input. The standard technique to allow parts to be machined from multiple directions is to use an indexed rotary axis in order to rotate the part. This rotary axis generally consists of either one or two 3-jaw chucks to hold the stock material. Figure 2-19 shows a commercially available Roland Rapid CNC machine.

FIGURE 2-19 - SUBTRACTIVE CNC RAPID PROTOTYPING [65]

Once the machining of the model shape is complete, final support materials are removed to release the model. All tool paths and operations are generated automatically in software, allowing unskilled machinists to operate SRP machines. This would most likely be an unachievable process with food materials due to the rigidity required.

2.3.2 Powder-Based Rapid Prototyping

Massachusetts Institute of Technology's Three-Dimensional Printing [18]

Three dimensional printing (3DP also referred to as TDP) uses powder and binder to build models layer-by-layer. The machine spreads a layer of powder and then uses ink-jet printer heads to distribute binder materials (which can be coloured) that, by capillary action, infuse into the layer of powder. The binder dries and holds the regions of interest together while the remaining powder is vacuumed away (Figure 2-20). Z Corporation's ZPrinters [66], The Ex One Company's ProMetal technology [67] and Therics Inc's TheriForm [68] technology also use Massachusetts Institute of Technology's 3DP technology. TheriForm technology focuses on application of 3DP to the biopharmaceutical industry. ProMetal uses post-processing to sinter the powdered material, burn off the binder and finally infiltrate the part with bronze.

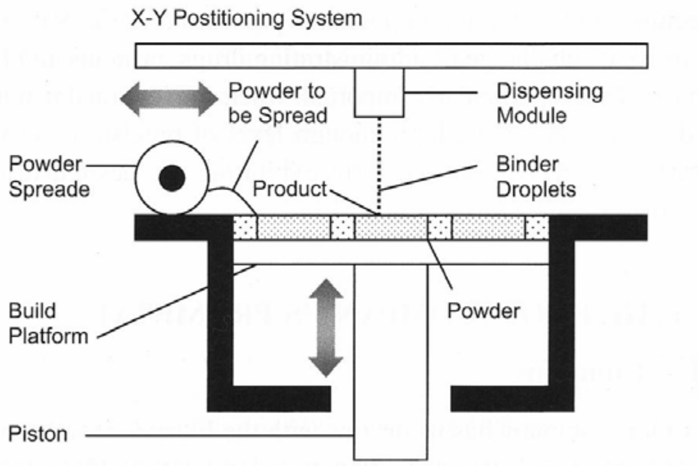


FIGURE 2-20 - THERIFORM SYSTEM SCHEMATIC [59]

This whole process has great potential if appropriate materials were to be available. The dry components of the food printing mixture would replace the standard printing powders and the wet components of the mixture could be jetted in place of standard binders. This would provide a way to avoid actually mixing colour into the mixture by causing the colour and other wet components to infuse into the dry materials. By using a homogeneous dry component powder mixture, only wet components could be placed in a customised way. There is a potential to not only spatially control the distribution of the wet components, but to also spatially control the distribution of the dry components.

In terms of the possibilities of infiltration with food materials, a completely specialised food material would have to be designed. This post-processing doesn't offer any immediate advantages over the simple 3DP printing process, but could be considered if the food mixture required some extra body after printing.

The disadvantage of this technique with regard to food printing is the complex nature of the food material and the requirements for producing a homogeneous material. Research into a premixed wet and dry mixture has already shown that even with standard controllable procedures it is difficult to produce a high functioning mixture.

Fraunhofer's Multiphase Jet Solidification [69]

Metal alloy materials for use in Multiphase Jet Solidification are supplied in powder, pellet or bar form. These are then heated in a chamber where the material melts. A piston forces the molten material out of the chamber through a nozzle (referred to by Fraunhofer as a Jet) where the material solidifies. This is similar to FDM, except the materials are metal alloys rather than thermoplastic filaments, and the feed system uses a piston rather than drive wheels. This technology is one way of distributing a complete mixture starting from a solid form, as it incorporates powder as well as a binder (wax). A very simple example of how this could be applied in food printing would be to use a mixture of flour and butter. The flour would be in place of the metal powder and the butter would be in place of the wax binder. Again, this method would require refining of the food batter mixture, but allows flexibility in terms of its properties (solid rather than liquid).

2.3.3 Liquid-Based Rapid Prototyping

EnvisionTec's Bioplotter [70]

The Bioplotter uses controlled air pressure to dispense plotting material into a reservoir filled with plotting medium [71]. The plotting medium is used to support the plotting material between the time it is dispensed and the time it hardens. Figure 2-21 shows a schematic diagram of the Bioplotter system.

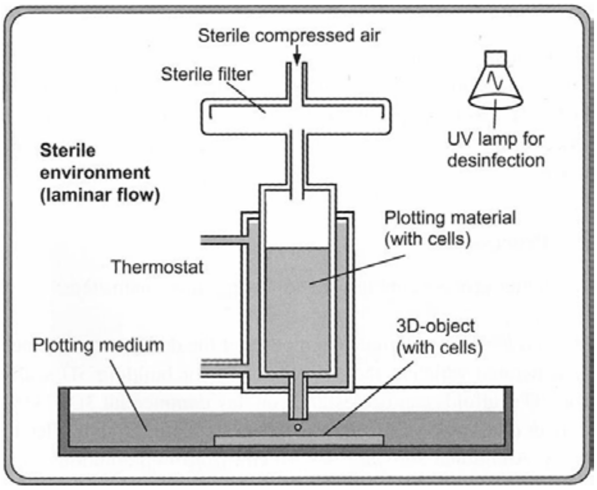


FIGURE 2-21 - BIOPLOTTER SCHEMATIC DIAGRAM [59]

Not only can the air pressure dispensing technique be used rather than a physical mechanical pump, but the concept of using a plotting medium could be useful for food printing. A food safe plotting medium would have to be selected or designed. Also a technique would be needed to utilise the supporting ability of the material, while also being able to remove it once the printing cycle is complete. If the densities of the fluids were matched, support structures are unnecessary. Figure 2-22 shows how a plotting medium can be useful while 3D printing.

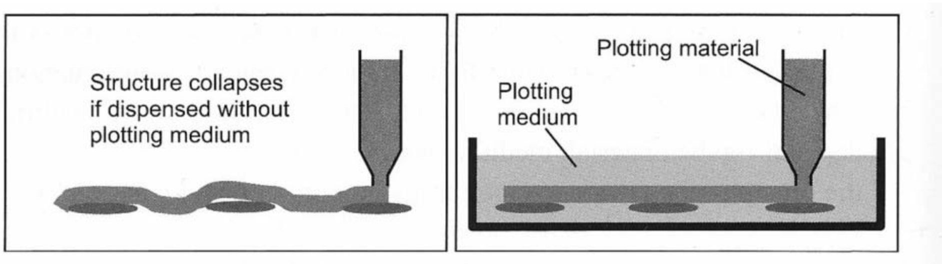


FIGURE 2-22 - BUOYANCY FORCE EFFECT WHILE PLOTTING [59]

A solution could be as simple as printing into a reservoir of refrigerated water and once printing is complete the water could be drained and the mixture cooked. The cool water would cause the food batter to cool quickly (especially if the mixture was pre-heated), resulting in an increase in viscosity. It would also provide buoyancy forces to help support the mixture and prevent flow or drooping while the rest of the model is printed on top. Once the printing was complete, the water could be drained away, and because of the high viscosity of the food batter, the model should not be dissolved or deformed. Internal cavities may pose problems as the water would have no way (unless it's designed in the CAD model) of being removed.

University of Missouri-Rolla's Rapid Freeze Prototyping [72]

Rapid Freeze Prototyping (RFP) is just as its name suggests; it's a method to dispense and rapidly freeze a material (particularly water) in order to build up a model of frozen solid material. In order to improve its build speed, it deposits water droplets around the perimeter of regions to be solidified and then fills these regions with a faster flowing water stream (Figure 2-23).

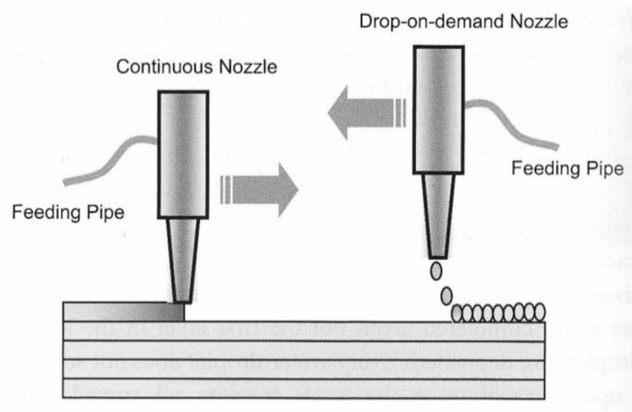


FIGURE 2-23 - TWO METHODS OF WATER DISTRIBUTION USED IN RAPID FREEZE PROTOTYPING [59]

RFP could work with some food materials, but it would add complexity to the system. The food material would have to be frozen then thawed again to allow it to then be cooked. These extra processes mean expansion, contraction, phase changes and extra energy requirements.

3 Review of Mixing and Pumping Techniques

3.1 Mixing

To be able to create completely customised foods, there are two options. Using a material set that is large enough to satisfy all consumers' wants, or using a small material set that can be combined in varying ratios. As the former has limited capabilities, especially on a small scale, the latter option has been explored.

3.1.1 Challenges

To design a mixing system that is capable of producing good colour resolution as well as allow it to be incorporated into a food printing system has required a number of challenges to be identified. These challenges are interrelated and it is the combination of all of them that makes mixing for food printing a complicated yet achievable task.

Time/Speed

As discussed in Section 1.3, the target flow rate of the printing system using non-agitated mixing is 315ml/min while the target flow rate using agitated mixing is 13.2ml/min. This means that the mixing system should be able to process the same amount of mixture to avoid being the bottleneck in the process. Timing is what makes the other challenges particularly difficult to achieve.

Residue

Between the production of one voxel to be deposited and the next, there will always be some amount of residue left. This challenge has encouraged a number of solutions including: employing a cleaning cycle, designing mixing systems that have inherently minimal residue, and avoiding changing colours between voxels so that residue can be tolerated.

Viscosity

The food batter material that the food dye needs to be mixed with has a high viscosity. This has made it difficult to design a fast mixing system that also deals with the challenge of residue. The food batter does not flow well without being forced to flow, so mechanical work is required to remove the mixture from the mixing device once mixing is complete. This can either limit the type of mixing device that is feasible, or add complexity to the mixing device so that it also has extrusion actuation capability (both the Conical Surface Mixer and the Oscillating Mixer discussed in Section 5.2 incorporate extrusion actuation).

Homogeneity

The food dye must be mixed with the food batter homogeneously throughout the voxel being produced. In most situations this requires that the mixture in a mixing chamber is agitated in such a way that there are no stagnant regions in the chamber. This is particularly difficult to ensure with rotary devices where regions of mixture in different parts of the chamber have different tangential velocities.

3.1.2 Laminar Mixing

The process of laminar mixing involves increasing the interfacial area of the fluids to increase diffusion [56](p. 384). Fluid motion that allows this to happen includes slipping, fracturing, stretching and relaxing back, agglomerating and clinging to walls or impeller blades. These fluid motions allow reorientation and redistribution of the material, which eventually produce a homogeneous mixture.

3.1.3 Existing Mixing Techniques

Mixing operations are extremely common in many industries. It has been this way for a long time, which has led to a huge variety of mixing techniques. These mixing techniques vary significantly in the principles that they employ and the applications they are designed for. This makes it easier to select a technique that will perform a desired mixing operation. Even if none of the existing mixing techniques will perform the desired mixing operation to a certain standard required, the techniques can be modified to reach that standard. Some existing techniques and their principles can even be combined and modified to create new mixing techniques. The existing mixing techniques can be grouped into the following sections:

- Impellers – large variety including propeller, turbine, paddle, anchor, helical, gate, ribbon/screw, high shear teeth, rotor-stator
- Kneaders/Blade mixers (Planetary, Banbury, Sigma and Plough)
- Roll mills/mixers
- Screw Extruders
- In-line Static mixers
- In-line Dynamic mixers
- Jet mixers
- Oscillating/Reciprocating mixers

Impellers

Due to the highly viscous nature of the materials that food printing requires and the small characteristic dimensions involved with mixing one voxel, it is not feasible to work with turbulent flow [56](p. 383). For this reason, a laminar flow regime is assumed for all mixing operations, which means that little can be drawn from methods that require turbulent flow, for example turbine impellers. However, some impeller designs such as the ribbon/screw and helical impellers can introduce slow but sure movement of the fluid throughout the whole mixing chamber. Figure 3-1 shows a selection of novel impeller designs. The Paravisc and Coaxial impellers are similar to anchor and helical ribbon impellers and could be valuable to food printing if applied correctly. This would particularly involve minimising surface area to allow contrast to be achieved between voxels, but this has not been explored further due to time constraints.

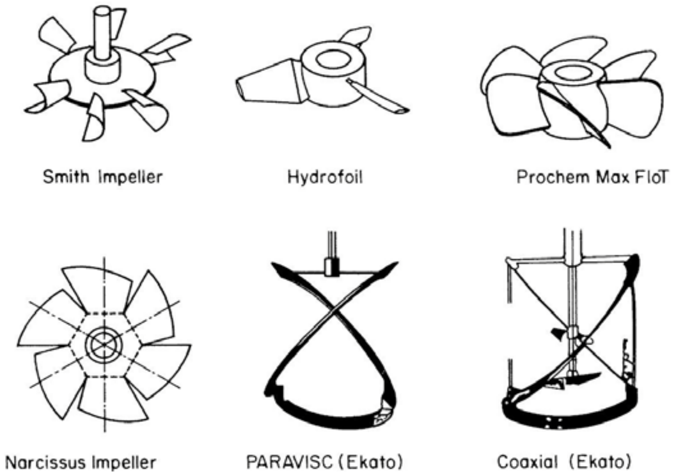


FIGURE 3-1 - NOVEL IMPELLER DESIGNS [73]

The anchor impeller uses close clearance with the wall to increase shear stress. These two mixing types can be combined by employing two helices to form a mixer such as the double helicone impeller (Figure 3-2).

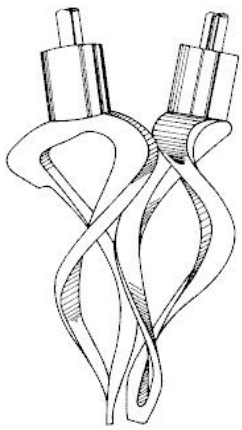


FIGURE 3-2 - DOUBLE HELICONE IMPELLER [73]

High shear impellers would result in shear thinning in the fluids we are dealing with, so are not useful by themselves, but ensuring whatever techniques are used don't result in shear thinning is a factor that needs to be considered.

Kneaders/Blade mixers

The planetary motion used by some mixers could potentially be very useful for minimising blade size. As the blade moves around the mixing chamber it agitates a larger volume than the same blade would with simple rotation. This means the blade can be a fraction of the width of the chamber diameter rather than almost the full width. A major benefit of reduced surface area of the blade is less residue on the blade. A different method to improve mixing of extremely viscous materials is employed by the Banbury mixer. This mixer employs a ram to ensure the mixing chamber is completely full and potentially pressurised. Even though the complex shape of the Banbury mixer means that it's not feasible for small batches, the concept of using a ram could be used to dynamically reduce the effective size of any mixing chamber.

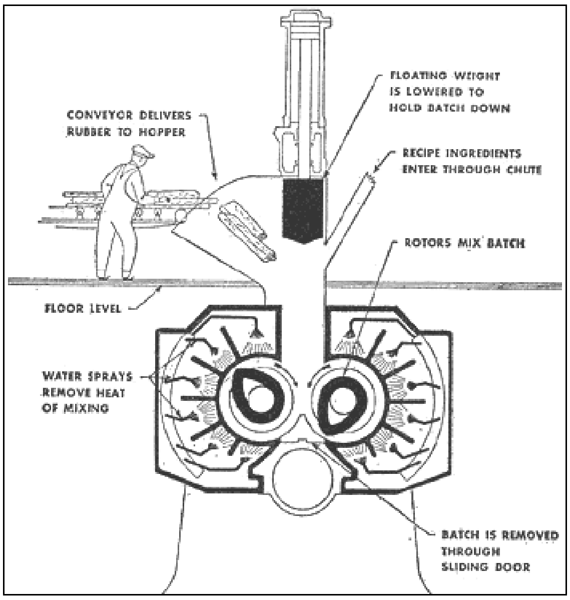


FIGURE 3-3 - INDUSTRIAL BANBURY MIXER [74]

Screw extruders both mix and pump at the same time. This has challenged the idea of separating these two processes and has encouraged research into what ways these steps can be combined to reduce waste and/or residue, minimise time between stages and avoid extra equipment.

Non blade mixers

Rolling mills and mixers show how it can be useful to use the surface of an object to transport material. It also demonstrates another way of forcing fluid through a small clearing to increase localised shear and increase interfacial surface area, hence promoting mixing. The challenge then becomes to also create axial mixing along the length of the mixer. Using gravity to feed the material along a slanted mixer or having a mixer with a varying profile could help to achieve this. More research would be needed to investigate the feasibility of this technique.

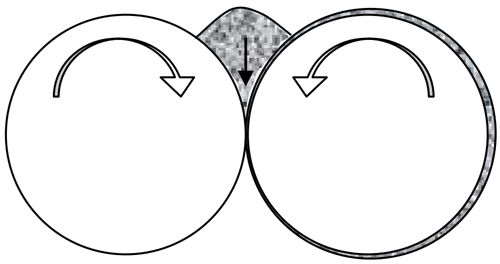


FIGURE 3-4 - ROLLING MILL/MIXER

Static Mixers

With static mixers the concepts can be directly applied by purchasing standard static mixers. There are many different types of static mixers [75], but all static mixers work by dividing the flow into different paths, stretching and recombining the flow (Figure 3-5). Static mixers are fundamentally continuous devices which employ the kinetic and pressure energy of the flowing fluid to mix its constituents.

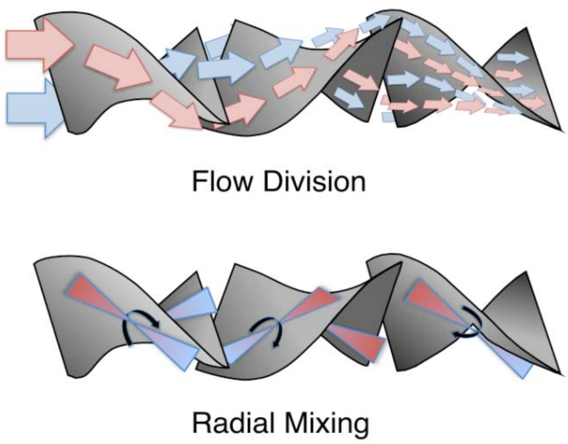


FIGURE 3-5- HELICAL STATIC MIXER OPERATING PRINCIPLE

In the literature there is a lot of work done to study the flow in static mixers [76], [77]. Particularly large amounts of work have gone into researching the Kenics helical element static mixers while a smaller amount of research has been done with other types of static mixers [78], [79]. This is partly to do with how long the Kenics mixers have been around and partly to do with the complexity of newer kinds of mixers e.g. Sulzer MX [80]. Even with this reasonable amount of ground work being done into static mixing technology, little or no research has been done in terms of dynamic mixing ratios. A dynamic mixing ratio is necessary for use in food printing because the ratio of the colours being mixed will constantly be changing. The only related research that was found was in the area of Functionally Graded Materials (FGM) and this did not focus on the capability of the static mixer being used [81]. There has been research that takes into account the effect that the ratio of mixing has on the resulting mixing coefficient, but it does not consider a dynamic mixing ratio [82]. The Residence Time Distribution (RTD) is an important measure to consider in relation to dynamic mixing ratios. Jin et al suggest that the RTD is affected by the diameter of the static mixers, the velocity of the flow and the arrangement of the mixing elements [83]. A dynamic mixing ratio is a mixing ratio between one or more components that changes as the process continues. This would mean that most of the time the system is not in steady state running conditions. This may be part of the reason that there is a lack of literature in this area of mixing. Another reason for the lack of research may be that there are few applications that require a dynamic mixing ratio. Most applications of static mixers have static mixing ratios for a consistent and uniform process output. The degree to which the components in the static mixer have been mixed is the main topic that has been researched. This is definitely applicable to food printing, but is limited in its usefulness due to the dynamic nature of our system. For most applications, it comes down to increasing efficiency of the mixing system, either by reducing the pressure drop and therefore reducing energy required to mix, or reducing the size to reduce the cost of the mixers. For any previous research to be useful, the flow regime had to correspond to the flow regime likely to be used in food printing. Due to the highly viscous nature of the food mixture and relatively low flow rates, the flow regime has been accepted to be laminar. This makes much of the existing research of little value as turbulent mixing in static mixers is very different to laminar mixing.

Because useful literature on the topic of dynamic mixing ratios was unable to be found, two options were then considered. The first option was to use Computational Fluid Dynamics (CFD) to examine the flow patterns that might occur while mixing with a dynamic mixing ratio. This option was not undertaken for reasons explained in Section 9.1. It was perceived that even though the geometry of the mixers is reasonably simple, the dynamic nature of the system would make using CFD difficult and possibly unrepresentative of the actual system.

The second option was to build a test rig to physically test this kind of mixing. This was the option selected for this research.

Oscillatory mixers

Research into oscillatory mixing has been around for many years, with the Karr column being the earliest documented reciprocating plate column (RCP) [84]. There are two common plate profiles. These two plate profiles have a ring on the outside of the wall of the column in which they operate, but differ in their actuation attachment location. Some RCPs use a central rod for the actuation, so have attachments between this central rod and the outer ring while others have rods directly on the outer ring, between each consecutive ring (Figure 3-6).

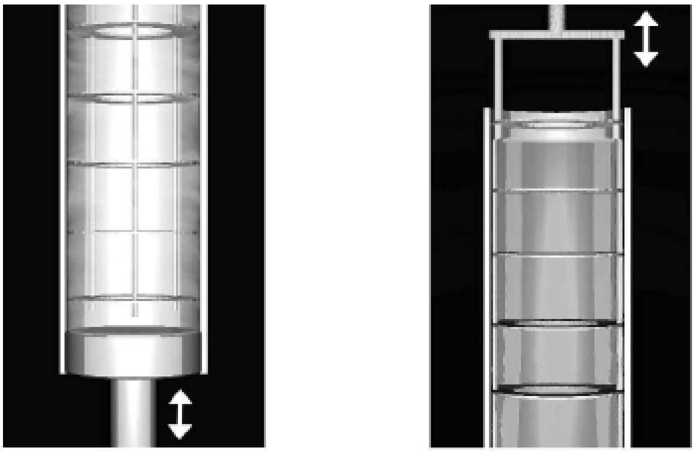


FIGURE 3-6 - PLATE PROFILES

The latter configuration means there is free space in the middle of the mixer and produces different flow patterns. Neither of these configurations would allow the mixing then ejecting action required for our application.

Although not very common, oscillatory mixers can provide more effective mixing than rotary type mixers in certain circumstances [85]. The author of [86] shows the two types of oscillatory mixing, either directly oscillating the mixing elements, or causing the fluid to oscillate past fixed baffles or mixing element. The authors of [87] suggest that the majority of the mixing that occurs in RCPs is that of vortices in turbulent flow, which occurs at high Reynolds numbers. Due to the high viscosity of the fluids our application requires, these Reynolds numbers cannot be achieved and therefore flow will be laminar. This indicates that this mixing technique is not very efficient in the laminar regime. However, modifying the technique to something more like a standard hand-held paint mixer has potential to achieve great benefits.

3.2 Pumping Systems Examined

There are many considerations when it comes to selecting an appropriate pumping system for distribution of materials. The flow generation system that is selected depends on the distribution method used. Flow is generated where there is a sufficient difference in pressure in the path of a fluid. There are many different ways to create an increase in pressure to cause flow, and many ways of measuring and/or metering flow. This is an important consideration when selecting an appropriate pump, as the functions of generating flow and metering the flow are often coupled together for accuracy and simplicity. Other significant factors that need to be considered include flow rate, proof pressure, cleanability (food grade), size, weight, price, material handling (viscosity, abrasiveness etc.), controllability, efficiency and pulsations. To help in examining all possible solutions, a table comparing all relevant pumping types was created (Appendix). As stated in Section 1.2.1, the food printer already included a peristaltic pump. Information about testing of this pump is presented in Section 8.4, which resulted in a negative outcome.

General industrial pumping systems were explored along with existing fluid dispensing systems. Standard industrial pumps such as the centrifugal, jet, reciprocating piston/plunger, diaphragm, vane, flexible member, screw, peristaltic, gear, lobe, and screw pumps are available in many variations. A good summary of standard industrial pumps is presented in [88] with a clear tree diagram of the different pump types [88](p 14.17). Table 3 shows an application matrix for rotary pumps, which can be used to rule out certain pump types and help in the selection of an appropriate pump. For example, vane pumps can be ruled out due to their low viscosity capabilities.

Pump Type	Flow, gpm	Pressure, psi	Temperature, °F	Viscocity, cP	Solids, %	Dry-run	Corrosion resistance	Pulsations	Lift ft	Price index
External gear	1 to 1000	3000	400	20 to 10,000	<1%	N	G	G	15′	110%
Internal gear	1 to 1000	3000	400	10 to 10,000	<1%	N	G	G	15′	110%
Lobe	50 to 1000	400	400	100 to 500,000	<20%	Y	G	G	10′	150%
Vane	50 to 1000	200	250	0.3 to 1,000	<1%	N	M	M	10′	100%
Diaphragm	50 to 1000	100	200	1,000 to 100,000	<20%	Y	E	B	20′	130%
Progressing cavity	100 to 1000	500	200	1,000 to 100,000	<80%	N	B	E	15′	200
Two-screw	100 to 8000	1500	650	1,000,000	<1%	N	M	G	25′	400%
Three-screw	10 to 3500	4500	550	1,000,000	<1%	N	M	E	25′	300%
Metering (diaphragm)	<1	200	400	1 to 1,000	<1%	N	E	B	5′	100%

Note: m^3/h = gpm/4.40; bar = psi/14.5; deg C = (deg F − 32)/1.8; Pa-s = cP/1000; m = 0.3048 × ft.) Values are approximate, for rough guidance only.
Code Letters: Excellent; Good; Marginal; Bad

TABLE 3– APPLICATION MATRIX FOR ROTARY PUMPS [56] (P 3.131).

Although there are many standard industrial pumps that have many advantages and potential benefits, there are other ways of generating flow, and these other options must also be considered. More specific to food applications, the author of [89] discusses a wide variety of pumping systems suited to food application.

The authors of [90] suggest the common fluid dispensing techniques include time-pressure, rotary screw and piston valve positive displacement. Taking classification of dispensing one step further, the authors of [91] classify Drop on Demand dispensing into two classes: contact dispensing and non-contact dispensing. The three fluid-dispensing techniques listed by [90] are considered contact-dispensing, while an additional dispensing method, jetting dispensing, is considered non-contact. However, jetting is not a feasible dispensing method due to the high viscosity of the food batter.

The authors of [92] suggest that time-pressure technology is void of dispensing accuracy due to material build up on the tip and although the authors of [90] admit that this technology is a challenging task, they have had success with controlling it within certain limits. MakerBot Industries have even had success with simple time-pressure dispensing using the latest version of the Frostruder - MK2 [53], which is a cheap option for dispensing. For continuous flow, time-pressure dispensing would not be suitable for multiple-material flow because the flow rates of each material would not be independent on each other. Instead the flow of each material would affect the other flows, which would make it very difficult to control.

The authors of [93] suggest that speed control of extruding piston plungers is not sufficient to sustainably control the extrusion flow rate of a high solids loading ceramic paste. 'High solids loading' is defined in this case as greater than 30% solids. The pastes used in their research range between 50-55% solids. Although the food material used in our research is lower than this, around 35%, it is still classed as high solids loading. Instead of controlling the speed of the extruding piston plunger, they suggest that the extrusion flow rate should be controlled by maintaining a constant pressure in the extrusion cylinder, which is achievable via force feedback. By maintaining a constant force on the piston plunger, a constant pressure is maintained in the syringe reservoir. During further research, a triple-extruder system has been developed [81]. In this paper, the authors suggest that using multiple materials with potentially different viscosities that are then combined and extruded simultaneously through one nozzle, means force control is not a viable option and reverting back to controlling extrusion piston plunger speed is necessary.

4 Dispensing Considerations

There are many considerations when it comes to selecting an appropriate dispensing system for distribution of materials. The materials to be printed must be stored in some type of container, be moved from there in a controlled manner to eventually be dispensed onto the printing surface. This process has many different solutions, but it's important to design a cost effective system that meets all the requirements.

4.1.1 Food batter and Food Dye Containment/Storage

In order to pump and then mix the food batter and food dye, these materials must be stored in some sort of container. The storage system is an important consideration when it comes to dealing with viscous fluids for a number of reasons mainly to do with preventing mixing with air. Problems occur when the fluid viscosity is large enough that the rate of settling under its own weight is less than the flow rate out of the container. This causes an effect known as rat-holing. A funnel forms the outlet of the storage container allowing air to be pumped out of the container (Figure 4-1).

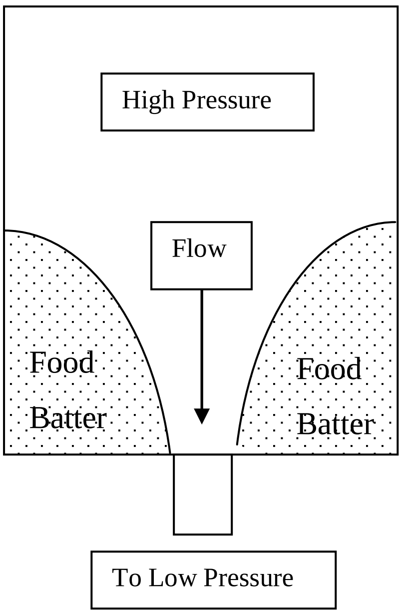


FIGURE 4-1 - RAT-HOLING

To avoid this, the container must not have shoulders for the food batter to accumulate on. A container with a conical end of appropriate angle will help overcome this problem.

Getting the food batter into the container is just as important as getting it out of the container. Both of these processes must be considered as both can introduce air into the mixture, which makes flow control very difficult.

The current food printer has made use of flexible hospital grade intravenous (IV) 1L bags while the static mixer test rig discussed in Section 8.1.1 uses acrylic tubes to store food batter to be mixed. The main attraction of using IV bags as food batter containers is that they could be used as disposable, single use storage. This would ensure hygiene and simplify any cleaning process of the system.

As the static mixer test rig discussed in 8.1.1 uses rigid containers, the rat-holing problem occurs when food batter is used. One solution to this problem is to use a floating piston. The piston sits on the surface of the fluid in the container and is forced down with the fluid as the fluid is pumped out. The piston prevents rat-holing from occurring by applying force across the whole surface of the fluid. The floating piston may not work with the static mixer test rig because of the rod that extends through the middle of the chamber to hold the end caps on.

Syringes have been used for food dye storage. Pistons and other accessories for syringe pumps can make the use of time-pressure pumps much more effective [94].

Filling a syringe or flexible container such as an IV bag requires a pump to force the fluid into the container. During this research, the process of filling IV bags has been achieved by using a peristaltic pump. This has been noted to be easily achieved [23] (See Appendix), but difficulty has been experienced with particularly viscous mixtures.

To make the process of filling more convenient, a fill-in-place method would be ideal. A two way valve would have to be included in the pumping system so that the containers would not have to be removed when refilling is needed. Another method of filling the syringes or any other rigid chamber would be to simply scoop or tip the mixture into the containers. This introduces air and often forms air bubbles so it would be desirable to then put the containers into a centrifuge to cause the air bubbles to move to one end of the container. From here, the air could be removed, or pumping could be stopped before the air bubble caused any issues.

4.1.2 Fundamental Distribution Methods

There are three fundamental distribution methods that have been explored, two using extrusion and one using Three Dimensional Printing (3DP or TDP), which uses powder and binder rapid prototyping (RP). The two extrusion methods are continuous flow and discontinuous flow (Figure 4-2).

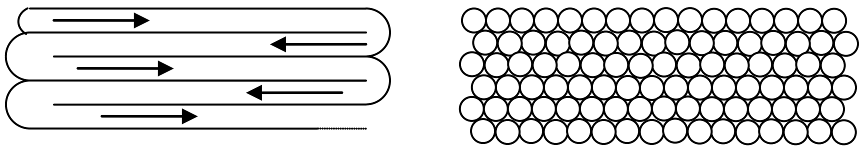


FIGURE 4-2 - CONTINUOUS AND DISCONTINUOUS DISTRIBUTION METHODS

3DP involves spreading a layer of powder on the printing surface and then depositing binder in areas that are to be solidified. This is normally done in a discontinuous manner from an ink jet printing head, but the binder could also be distributed in a continuous manner, or even with other distribution methods such as non-jet extrusion. This method has potential in some areas such as spatial colour distribution, but has been disregarded due to the complexity of the food powder and food binder that would be required. Also, a general one-part (combined wet and dry) food batter mixture has already been designed, but the powder and binder method could be the subject of future research.

The two extrusion methods for distributing material to build up layers to form a shape have been explored in more detail.

The first is a completely discontinuous distribution method where each voxel is distributed onto the printing surface one at a time, completely separate from the previous voxel. This involves starting flow in one position, stopping the flow and moving to the next position, where the process occurs again. The major benefit of the discontinuous method of distribution is that voxels can be placed in any desired order rather than geometrically ordered (line by line in a raster pattern). The major disadvantages of discontinuous flow are controlling and modelling this type of non-steady-state flow and added complexity to the system.

The second extrusion method for distributing the material consists of generating a continuous flow. Every layer is made up of one continuous flow, which has been distributed over the printing surface without flow stopping. The major benefits of the continuous method of distribution are that the flow is simpler to model, faster to deposit and easier to achieve in practice. The major disadvantage of discontinuous flow is the increased difficulty and complexity to avoid blurring between voxels.

4.1.3 Controlling Flow

There are a large number of valve types available in industry. However, for controlling the type of fluid used in this research (pseudoplastic), many valves are only suitable for ON/OFF control rather than allowing the flow to be controlled in a continuous manner. This is because pseudoplastic mixtures require a yield stress to be overcome to initiate flow. At this point the viscosity rapidly decreases, creating a practically uncontrollable flow. For this reason, either fast response ON/OFF valves need to be used with a consistent flow generation mechanism, or the flow generation mechanism also needs to control the flow. For pseudoplastic fluids, this means the mechanisms that generate flow need to also be able to rapidly prevent flow to avoid excess flow and dripping.

Many of the mechanisms used to generate flow are also capable of generating intermittent flow rather than continuous flow by stopping and starting the power/driving force. These mechanisms are favoured as they allow more flexibility for the application of pumping in this research.

4.1.4 Separation of Metering Capability from High Pressure Capability

Being able to separate accurate metering from high pressure pumping capability could be a great advantage. It would mean that two lower cost systems could be combined to perform a task that can potentially be very difficult and/or expensive. This could be achieved batch-wise with syringe pumps and/or jetting heads, an agitation cycle and a plunger mechanism or even time-pressure dispensing. Figure 4-3 shows an example of this kind of system with syringe pumps or jetting heads for the food dyes and food batter, an agitator to mix the food mixture and a plunger to force the mixture out of the chamber onto the printing surface. This kind of setup can be likened to an artist's palette, but instead of a palette, the materials are mixed in a chamber and instead of a paint brush, the materials are extruded or sucked out of the chamber.

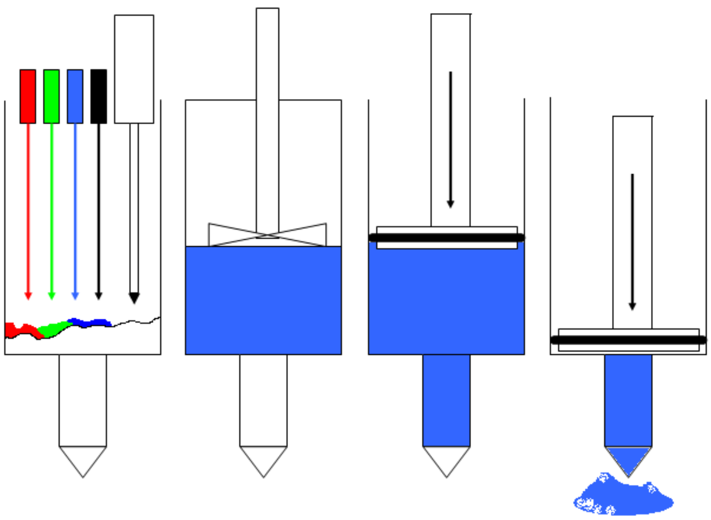


FIGURE 4-3 – SEPARATE METERING/EXTRUDING SYSTEM UTILISING PLUNGER

The fluid could be metered into a chamber at atmospheric pressure, agitated and then the high pressure flow would be achieved in a separate stage by the plunging mechanism or air pressure. The plunger system would operate similarly to the discharge stage of a piston pump, where a plunger/piston would be used to evacuate a chamber that has been filled using other pumping systems. The plunger is not required to control volume or flow rate, so a robust actuation method (such as a pneumatic air cylinder) could be applied to provide sufficient pressure to force the mixture through a static mixer or nozzle. If a static mixer is used, the fluids to be mixed would have to be evenly distributed axially throughout the chamber. This would provide a consistent ratio of constituents being forced through the static mixer. This requirement may limit the flexibility of the metering techniques used to fill the chamber.

For the plunger system to work with a static mixer or nozzle on the outlet, a method would be required to allow the plunger to be retracted without drawing excess mixture back into the chamber. This could be done in a number of ways and there are three particularly simple ways that could be relatively easily implemented. The first and possibly most simple way to ensure that mixture is not drawn back into the chamber is to completely discharge all of the mixture in the static mixer or nozzle. This could be achieved by using the plunger to force air as well as the mixture through the mixer. An injection of air at the base of the chamber would allow the plunger to be withdrawn without drawing any mixture back. The final simple method to prevent draw-back is to break the seal around the plunger. This could be achieved by tilting the plunger.

Another suggested way to transfer the material from the chamber to the printing surface once it has been mixed is back-extrusion. This requires the use of a special hollowed plunger (Figure 4-4).

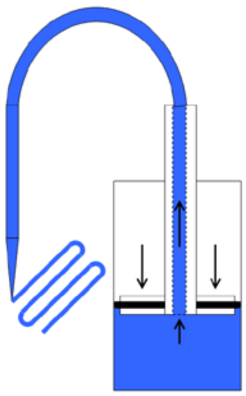


FIGURE 4-4 – BACK-EXTRUSION - PLUNGER WITH INTERNAL PIPING

The plunger would effectively have internal piping that would connect to the nozzle on the printing head. To minimise blurring between voxels caused by the dead volume of the piping, the ratio of piping volume to chamber volume should be minimised.

The plunger would also have to use the described methods to withdraw once it has removed the material from the chamber.

To allow different functions to be applied at different stages with one chamber, the chamber could be set up on a rotary table. The chamber would rotate from the injection stage, to the agitation stage and then finally to the extrusion stage.

4.1.5 Peristaltic Pumps

Although peristaltic pumps are generally self-priming, using high viscosity materials can make priming peristaltic pumps very difficult. The peristaltic pump used in this research (Section 1.2.1) works sufficiently (once primed) when the viscosity of the mixture is relatively low, but with more viscous mixtures, the pump fails to provide sufficient fluid movement.

The main advantage of peristaltic pumps is that the tubing is the only part that comes into contact with the fluid being pumped. If a disposable food storage bag was used, the tubing could be included as part of the disposable product. If cleaning of the tubes could be achieved effectively and the advantages of peristaltic pumps meant that they were selected for use, a number of additional features can improve pumping performance [23], [24] (See Appendix).

Two or more sets of peristaltic rollers could be set up to pump out of phase with each other. The combined flow would pulse less than each individual flow. This option is costly as it requires at least an additional pump head if not an additional or more powerful motor. The motor RPM could be varied to vary the pump speed to create more constant flow. Another option is varying the speed of linear movement of the printing head in synchronisation with the peristaltic pump pulses. This would result in a more constant extrusion line thickness. Both of these options would require modification to software and motor controller firmware, and could potentially be difficult due to inconsistencies in the pump.

A pulse dampener could be added to smooth out pulses, but this would make stopping and starting flow very difficult to control. Considering the poor suction it produces along with the pulsating flow, this pump is inappropriate for food printing.

5 Design of Mixing Techniques for Food Printing

After consideration of existing mixing techniques, idea generation and brainstorming generated a number of worthy techniques. The most feasible techniques were chosen based on their strengths, weaknesses, and the opportunities and threats associated with them.

5.1 Non-Agitated Mixing

Mixing techniques labelled non-agitated consist of devices/systems that have no moving parts. The ordinary distributive fluid flow is the driving force of the mixing rather than causing some system component to move. The research area of Functionally Graded Materials has offered significant insight into creating in-situ mixed multi-material objects [51], [95], [96]. With this insight, applying static mixing to producing personalised foods is a technique worth exploring.

5.1.1 Static Mixers

Design

There are many ways to use a large variety of static mixers. Designs vary in how many static mixers are used, how the fluids to be mixed are combined to be fed through the static mixer and what is forcing them through the static mixer. Even though these designs can be significantly different from one another, they all use the same principle of mixing. The Kenics type of static mixer (helical elements) has been used during this investigation, due to availability and variety of sizes (Figure 5-1). The strengths of the static mixing technique have made it a worthwhile choice to investigate. For this reason, a test rig was designed and built to allow two fluid flows to be combined and mixed in a static mixer.

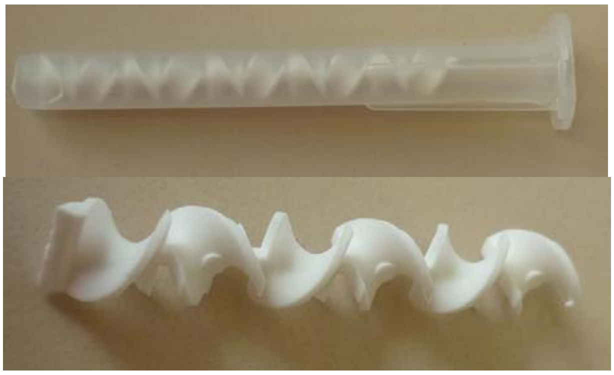


FIGURE 5-1 - KENICS STATIC MIXER AND MIXER ELEMENTS

Strengths

Static mixing has a number of strengths, which make it appealing for mixing food. It is an industry standard for many applications and much information and research is available [75]. Being a simple mixing principle, static mixing can be understood by most people, which makes it easy to work with. As there are many types of static mixers with different options, it's a versatile option that allows adjustability so that effective mixing can be obtained. Disposable static mixers are available, which means mixer parts do not need to be cleaned. Using static mixers is also an easy mixing technique to run with continuous flow, which has the advantages of no stopping and starting allowing simpler pumping and flow control. Also, static mixers can be implemented using any pumping technique.

Weaknesses

Depending on the size of the static mixer and the viscosity of the fluids being mixer, there may be a large pressure drop caused by the mixer. This means a high pressure system is needed for pumping and injecting the food dye. Static mixing is most effective when the fluids being mixed are of the same viscosity. To achieve similar viscosities for the food batter and food dye, the viscosity of the food dye would have to be increased.

Opportunities

Static mixers not only have a wide variety of commercially available variations, but there has even been research into manufacturing micro static mixers [77]. This would be very useful technology if the precision and accuracy of food printing were to be improved. The versatility of static mixers means that continuous or discontinuous flow regimes could be used. Also, the following methods could be implemented to improve the final results. A gating system could be used to ensure right colour is extruded. The mixture after exiting the static mixer could be monitored with machine vision to direct the mixture to be recycled if it is not yet the right colour, or onto the printing surface if it is the right colour. Regions of similar colour could be processed rather than using a simple raster pattern. Outlining certain regions may also improve the resulting printed food parts.

Threats

Due to large surface area of elements in the mixer, residue is retained in the mixer. This leads to axial dispersion, which limits the achievable contrast between contiguous voxels for continuous flow. A complicated system would be required to recycle the discarded mixture when using the gating method. To achieve good results in the continuous flow regime, the flow must be consistent and low pulsing.

5.2 Agitated Mixing

Mixing techniques referred to as agitated mixing techniques consist of devices/systems that have one or more moving parts. The system relies on components in the system to move in order to promote mixing.

5.2.1 Oscillating Mixer Design

A new way of mixing and distributing small batches of food (voxels) was selected to be tested in order to overcome a number of problems with previous methods. The design is similar in operation to the plunger mixer idea presented by Isidore Handler in his US Patent [97]. The idea had to be simplified so that it could be manufactured on a small scale. Figure 5-2 shows the 3D CAD model of the original concept.

Part of the motivation of the design of this mixer was that it involved an application of Mechatronics. Due to the topic of the current research, a desire to incorporate electronics and mechanical systems drove the design of this mixer.

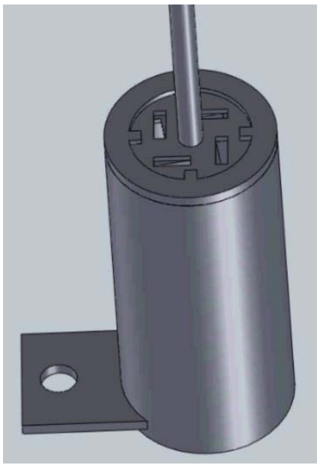


FIGURE 5-2 – ORIGINAL CONCEPT MODEL OF OSCILLATING MIXER WITH SLOT VALVE TO OPEN AND CLOSE THE CHAMBER

This method consists of an axially reciprocating mixing element inside of a chamber, which has inlets for fluid to be pumped into and an outlet for the mixed fluid to be extruded out of, on to the printing surface (Figure 5-3).

FIGURE 5-3 – ALUMINIUM AND ACRYLIC MIXING CHAMBER

The mixing element consists of a shaft with two discs, each disc with four holes equally spaced around the discs (Figure 5-4). The shaft disc is the disc that is fixed to the shaft and seals around the edge of the mixing chamber.

FIGURE 5-4 –MIXING ELEMENT WITH TEFLON SHAFT AND SHAFT DISC (WITH O-RING) AND ALUMINIUM FUNCTION DISC

The function disc is the other disc, which is able to be rotated (held in place by a circlip) so that the holes in the discs either line up, or don't overlap at all (Figure 5-5). This degree of freedom allows the system to both mix and extrude, giving it extrusion actuation capabilities. When the holes in both discs line up, the mixing element allows fluid to flow from one side of the mixer element to the other side, causing mixing. However, when the holes don't overlap at all, no direct path for fluid to flow is present, so fluid may flow out of the outlet rather than through the discs.

FIGURE 5-5– MIXING ELEMENT IN A) MIX POSITION B) IN BETWEEN C) EXTRUDE POSITION

Operation

The mechanisms for each of these concepts are quite simple, but combining them into one cohesive system can become complicated. A sequence for how the system works is as follows:

1. Position discs into Mix Position
2. Injection
3. Mixing
4. Position discs into Extrude Position
5. Extrusion

Position discs

An encoder on the shaft allows the shaft to be located in the right position. Along with the shaft positioning, the function disc gets aligned using fixed geometry in the chamber. This happens twice in a cycle. Firstly to change the orientation from extruding to mixing, then back to extruding again for the extrusion step.

Injection

Inlets at the top of the chamber allow fluid to be pumped into the chamber.

Mixing

The mixing element is oscillated up and down the full height of the chamber while being rotated continuously.

Extrusion

Once the positioning has been completed, the mixing element will then act as an extrusion device when it is plunged from the top of the chamber to the bottom of the chamber with the outlet open.

Variations

To improve the functional ability of the oscillating mixer, a number of variations of the mixing element were made. The following details the designs and the advantages and disadvantages of each.

Original Design - Fully Aluminium - Function Disc above Shaft Disc

Both of the discs of the mixing element were aluminium as well as the mixing chamber. This allowed a proof of concept for the mixing. It showed that with a few oscillations, food dye and food batter could be mixed effectively even when the viscosities of the two components were very different. However, when performing the extruding function, fluid was flowing from the underside of the mixing element to the top side of the element (not extruding out of the outlet as desired).

Teflon Function Disc

A function disc made of Teflon was manufactured to improve the seal between the mixing element and the chamber. Because the Teflon function disc was used as a seal, it was tighter and would not rotate with the shaft disc (the friction from the seal around the wall of the chamber was greater than the friction cause by the circlip holding it in place). This meant that the holes would not remain aligned while mixing. It was also more flexible than the aluminium and allowed fluid to seep through the holes while plunging.

Teflon Shaft Disc - Aluminium Function Disc

The Teflon shaft disc was used as the seal because it was attached to the shaft so it was forced to rotate along with the function disc during mixing. Fluid was still leaking from one side of the mixing element to the other side while extruding.

O-Ring Added - Teflon Shaft Disc

A thin 1mm x ϕ38mm nitrile rubber O-ring was added to further improve the seal between the mixing element and the chamber. However, even with the gap between the mixing element and the chamber being sealed, fluid was still flowing from one side of the mixing element to the other side. This was because the function disc was above the shaft disc so the fluid underneath would push up on the function disc creating a gap between the two discs that allowed fluid to flow through them rather than out of the outlet.

Reversed Orientation - Aluminium Mixing Element

Reverting back to aluminium for the whole mixing element, the orientation of the mixing element was changed so that the function disc was on the underside of the shaft disc. The intention was that the fluid would again push up on the function disc, but because it was on the underside, would seal tighter rather than leak. However, the fluid now pushed up on the shaft disc in the spaces where the holes of the function disc were. This allowed fluid to again leak up between the discs. However, with viscous enough fluid the channel between the discs closes off and seals completely.

Strengths

This oscillating mixer is a new mixing technique that not only produces good mixing results, but also combines mixing and dispensing into one operation, therefore minimising the number of parts required. The result is less surface area and therefore less residue, meaning better contrast between voxels can be achieved. The metering of components to be mixed in the mixer is performed at atmospheric pressure. This allows a wide range of metering options to be used.

Weaknesses

There are a number of drawbacks that make this system unlikely to be a feasible mixing technique. Complicated mechanisms are required to control the whole system adding cost and complexity. The mixer is not a robust system shown by the flaws/issues brought to light by the large scale prototype. One of these issues is that it does not generate enough pressure to extrude the contained fluid without leaking (only with low viscosity fluids).It also has intricate parts that may wear out from use. Being new and different to current mixing techniques, there is little understanding and support in literature to aid design. A small problem is that the Teflon bushing in the chamber cap that allows the shaft to rotate and oscillate up and down is not able to completely contain all the mixture. This results in material being left on the shaft. The oscillating mixer is a batch process that requires filling, mixing and dispensing for each cycle, which adds complexity and time.

Opportunities

Modifying the oscillating mixer so that it has a bigger opening for the outlet may mean that the extrusion process is more reliable or even allow more flexible design options to be implemented. The way the mixer is designed means it has the potential to remove the majority of the mixture in the chamber, therefore leaving minimal residue and allowing good contrast between voxels to be achieved. The concept should be possible to scale down using micro machining techniques to create very small batches.

Threats

The scale down of this concept may pose problems in terms of manufacturing, especially the moving parts and seals. Also scale down could introduce complications with control as well as food safety. In order to create a bigger opening for the outlet, non-standard control valving may be required, which will increase the complexity of the system. Voxel by voxel deposition means fusion has to occur between all voxel surfaces rather than just between layers and lines such as would be produced with continuous flow. If voxels don't bond properly the structure of the food part would fail.

5.2.2 Conical Surface Mixer Design

The Conical Surface Mixer (CSM) consists of two main parts. The first part is the body, which consists of a conical recess pointing towards the printing surface, with a small hole at the point of the cone to allow fluid to be ejected through (Figure 5-6). This gives the CSM extrusion actuation capabilities. The second part of the mixer is the mixer head. The mixer head is a shaft with a cone on the end to match the recess in the body.

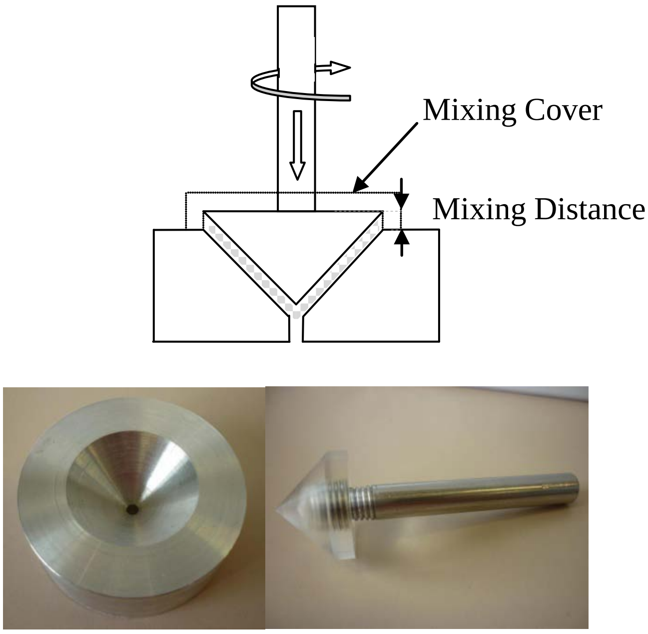


FIGURE 5-6 – CONICAL SURFACE MIXER DIAGRAM AND MIXER BODY AND MIXER HEAD

The volume of material to be mixed in the mixer is given by the offset between the two identical cones, the mixing distance. The prototype cones had a radius of 15mm, which with a mixing distance of 1mm created a mixing volume of 0.66ml.

To prevent fluid coming out the top when extruding, a cover is placed over top of the mixer head. To keep the cover in place during mixing, yet allow movement when extruding, a mechanism to apply spring compressive force to the cover has been implemented (Figure 5-7).

FIGURE 5-7 – CONICAL SURFACE MIXER HEAD AND BODY WITH CAP AND COMPRESSIVE SPRING

Operation

The CSM works on the principle of surface friction. By causing one surface to move past another with a small gap in between, large velocity gradients are present [55](p. 380). The particles in the fluid are dragged and pushed by the surface of the mixing head of the mixer. This distributes the mixture in a radial direction. The shear rate is highest at the surface of the mixing head and decreases as the distance from the mixing head increases. The velocity of the surface of the mixing head also affects the shear rate. A higher velocity will result in a larger shear rate. The velocity of the surface decreases as the radius of the surface decreases, so the tip of the cone has the lowest velocity and therefore the smallest shear rate.

Ensuring the mixture is also distributed in the axial direction is also critical. Distribution in the axial direction is achieved by a pecking motion of the mixer head. This involves a cyclic axial movement in and out of the mixing cavity.

Strengths

There are two significant advantages of the CSM. One advantage of the CSM is its simplicity. The simplicity means it is easy to understand and simple to scale down, particularly because there are no complicated parts. A peck cycle during mixing can improve mixing. Secondly, the metering of components to be mixed in the mixer is performed at atmospheric pressure. This allows a wide range of metering options to be used.

Weaknesses

A significant amount of unmixed mixture at the bottom is a result of a stagnant region. This unmixed mixture cannot be dispensed onto the printing surface. This means that it would need to be removed, adding complexity to the system. If additional features are added to improve the functionality of the conical mixer, the complexity of the system may increase significantly. This is a batch process that requires filling, mixing and dispensing for each cycle, which adds complexity and time.

Opportunities

There are a number of opportunities to improve how well the mixer operates. Using elastomeric material (for the body and/or head) could improve extrusion capability and reduce the dependency of the mixer on the mixture properties by allowing flexibility between the head and the body. Having an elastomeric head would allow the head to deform during the plunge cycle to expel all material from the mixing cavity. Mismatching mixer head and mixer body shapes could provide a cavity that reduces in size in a more defined and progressive manner (Figure 5-8).

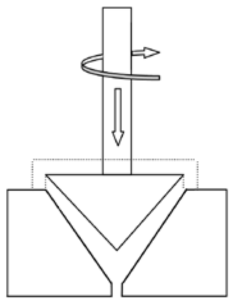


FIGURE 5-8 - MISMATCHED SHAPE ELASTOMERIC CONICAL MIXER

Different shaped mixers could be used and even incorporate extra parts that aid the mixing and extrusion process. A mixer geometry that provided more consistent shear rate throughout the mixer could be used. This would require having more mixing volume at the top of the mixing cavity than the bottom (opposite to the shape of the mixer in Figure 5-8). This would however make extrusion through the tip difficult or impossible.

Implementing nutating movement in the body or head would introduce a varying offset from the body to the head. This would create a more varied distribution of the fluid, which should cause axial as well as radial mixing.

Multiple mixers could be made to work in parallel so that production rate can be improved. To prevent leakage from under the cover over many cycles, mating slots and/or peaks/ridges in the cover and mixing body could be implemented.

Threats

This mixing technique could be relatively slow because it relies on the friction of the head and body surfaces to move the fluid. Implementing the cleaning or wiping function for unmixed mixture and/or integrating nutating movement will add extra complexity, cost and slow the process down further. The mechanism of this mixing and extruding technique may not just be slow, but it may be significantly dependant on the mixture material properties, meaning it may only work for a select group of materials. Accurate metering is required to ensure that the right amount of material is dispensed into the mixer. Too much material causes overflow and too little may result in ineffective mixing. Using elastomeric material could cause uneven mixing due to mismatching shapes of the head and body. Mixing will be different at the tip of the cone than at the base of the cone. Similar to the oscillating mixer, voxel by voxel deposition requires fusion to occur between all voxel surfaces for structural strength.

5.3 Other Mixing Techniques

A number of mixing techniques were either too complicated or did not provide enough benefits to make them worth trying to implement. These techniques however do have different strengths, weaknesses, opportunities and threats and may be appropriate in different situations.

5.3.1 Visual Mixing

Visual mixing works in a similar way as an LCD screen. Different coloured light sources placed very close together appear as one pixel of one colour. To achieve something similar for food printing, food of each ink colour (CYMK) could be deposited in very small amounts directly onto printing surface, with no physical mixing. Contrast sensitivity of human colour vision depends on a large number of factors including to colours of the object being observed, the illumination source, the background that the object is on and the distance from the object [98], [99]. The authors of [100] state the centre-to-centre distance between RGB phosphor groupings in CRT monitor displays (0.25 to 0.31mm) is sufficient to ensure reliable spatial-additive colour synthesis. Although this uses additive colour synthesis rather than subtractive, as printing methods use, this could still be a target for dot size of individual food colours.

Visual mixing is a simple concept that does not require any physical mixing system. The apparent mixing comes from human visual colour synthesis. Although the concept is simple, a very accurate and precise dispensing of the mixture required. Depending on the capability of the dispensing system, the consumer may see that it’s not actually mixed if they look up close. It may also be a slow technique as many small dots of mixture are required to be dispensed. Also four times as many dots are required to be dispensed as there are four ink colours per voxel. If an appropriate dispensing system is used, high resolution printing could be achieved. The opportunity to introduce static mixers into this technique could decrease the size of the material set if a distinct material set is used making it easy to supply materials for. It may be difficult to get the ratios of colours right to create the appearance of a combined voxel of desired colour.

5.3.2 Agitate in place

Food of each colour (CYMK) could be deposited on the printing surface and subsequently be agitated. This means that no mixing chamber is required, meaning the system can be smaller and less residue (only on the agitation device).

Once the first layer has been printed, the printing surface becomes somewhat uncertain and less rigid. This would make mixing without a chamber difficult as there would be no boundaries for the material. This system would require a mixing head as well as a printing head, which would increase cost and complexity. To improve mixing reliability, methods of solidification such as freezing or cooking after each layer could be incorporated to create a stable printing surface. Also, this method allows the use of any type of agitator, provided they don't spread the fluid excessively (horizontally or vertically). This method may not be able to create effective mixing without containment from a chamber and may only work for one layer due to unwanted inter-layer mixing.

5.3.3 Powder and Binder

3DP™ technology originally invented, patented and developed by Massachusetts Institute of Technology, which binds layers by depositing colour and binder selectively onto deposited powder could be used for food printing if the powder was substituted with dry food mixture.

This technique only requires mixing between low viscosity inks that are jetted from ink jet print heads. The ink disperses into the powder layer, which means no additional agitation required. High spatial and colour resolution can be relatively easily achieved using powder and binder technology. To utilise this technology for making personalised foods, a complete redesign of the food batter mixture would be required. A different batter mixture could allow the dry and wet parts to be separated so the dry parts were used as the powder and the wet parts were jetted onto the printing surface to colour and bind the appropriate portions. Only allows liquid components could be distributed in a customised way as all dry parts are present in the homogeneous powder. This method is very material dependent and would potentially allow only a very limited material set of powdered material. Also licensing of the technology may be expensive. In addition, Selective Laser Sintering of powder/binder printed parts has been explored, but with limited success [101].

6 Image Processing, Machine Control and Data Logging

A number of programs were written or modified as part of the research into food printing (these programs can be found in the Appendix). LabView (National Instruments) was used to make a program to analyse mixed samples from mixing tests. Two programs were written in Visual Basic.net and one in Matlab to process images so that colour distribution information could be determined. The Visual Basic.net machine control program was improved, but many issues with the program fell outside of the scope of this research and therefore recommendations have been made for future development. Finally, to allow flow rate measurement during mixing tests, a mass data logging program was developed using LabView (National Instruments).

6.1 Mixing Sample Image Processing

A sample LabView (National Instruments) program was modified to allow the variance and standard deviation of a selected area of an image to be acquired. This meant that a circle region in a dish or even an arbitrary shaped region could be selected for analysis. The values of each primary colour could also be obtained individually, but the average variance and standard deviation provided the most useful measure of the effectiveness of mixing.

This program was also used for two different tests used in Section 8. Photos were taken during the tests and were later analysed using this software. It was used to measure the mixedness of the mixture in the oscillating mixing chamber as mixing progressed. It was also used to analyse photos of the colour variation of along the open top tubes of extruded mixture (or directly as it was extruded out of the static mixer).

6.2 Colour Distribution Image Processing

If a discontinuous flow regime is used as discussed in Section 4.1.2, there is a valuable opportunity to distribute voxels in any order, rather than in a raster pattern. This means that voxels of similar colour could be printed in sequence to avoid changing colour so much. This would allow blurring between voxels to be avoided or at least reduced significantly. Establishing how far it may be between voxels of the same or similar colour would enable us to determine how far the three-axis CNC food printer would have to move if this technique was used. This will allow an estimation of the extra time it may require to operate this way rather than continuous distribution.

Predictions about the relationships being tested are simple and obvious, but quantifying these relationships to some extent will be valuable. When creating groups of pixels of the same or similar colour, two factors will determine the spread of the pixels in that group. Increasing the range of allowable colours is expected to decrease the distance required to search to create a group of pixels. Also, increasing the required size of the group is expected to result in increasing the distance required to search.

6.2.1 Algorithms

If a discontinuous flow method is chosen, printing voxels in order of colours that are similar can be advantageous. This means that less contrast is required to be achieved by the mixer.

In order to estimate the extra time required to move between voxels of similar colour, rather than voxels right next to each other, a sample of images was selected and tested. Three approaches were taken to estimate the distance between certain pixels in order to estimate extra time required.

The first approaches were tested by using programs that were written in Visual Basic.net while the third approach was tested using Matlab.

Spiral Search Algorithm

The Spiral Search Algorithm (SSA) scans through the image pixel by pixel, and for each pixel, it searches in a spiral (as shown in Figure 6-1) to locate a group of pixels that have colour values within a certain range of colours. The algorithm spirals out to the right in a clockwise direction.

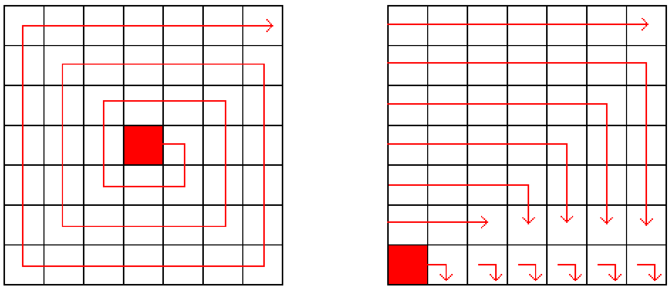


FIGURE 6-1 - SPIRAL SEARCHING (RED SQUARE = CURRENT PIXEL)

The range of colours that are acceptable for pixels to be included in the group is determined by the allowed difference value, given in units of RGB colour values (RGB units ranging from 0-255), specified for each test. An example of some of the colours in a range with allowed difference of 30 is shown in Figure 6-2.

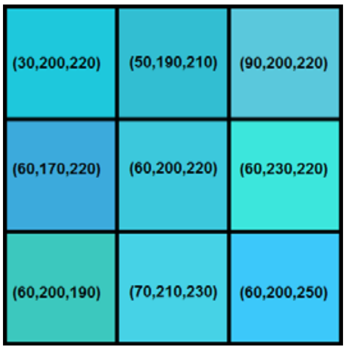


Figure 6-2 – Colour Range with Allowed Difference of 30 units (Combined R, G & B) Centred Around Pixel with RGB Values 60,200,220

These colours would represent a sample of the colours of voxels that would able to be printed consecutively by the food printer. The contrast ratio or allowable difference that the food printer will be able to achieve will depend on which mixing system is used, but tests in Section 8.1 help to give an indication of what is achievable with static mixers. The group size (number of pixels to be found) is also specified for each test. Once the algorithm has located the specified number of pixels to form the group, it finds the distance between the current pixel and the furthest pixel in the group. Please refer to the Appendix (Other Documentation) for more detailed examples.

If the algorithm cannot find enough pixels to fill a group of the required size, it is termed a 'fail' and a 'worst case scenario' distance is assigned as the distance for the current pixel. The average of the length and width of the image is used as this 'worst case scenario' distance. The average of all the distances for the groups found for each pixel is then calculated.

The aim is to find the relationships between the distances calculated, the allowed difference, and the group size.

Open Path Travelling Salesman Problem Genetic Algorithm

The Genetic Algorithm (GA) that was implemented was created by Joseph Kirk [102]. From the details Kirk gave when the algorithm was released, this algorithm finds a near optimal solution to a variation of the Travelling Salesman Problem (TSP) by setting up a GA. The Open Path Travelling Salesman Problem (OP TSP) variation searches for the shortest route of an open path rather than a closed loop. In the context of image processing for food printing, the open path is the path that the printer head ('travelling salesman') needs to travel from a fixed point (current pixel) to all the other pixels of the same colour ('cities') exactly once, without returning to the starting pixel (‘city’). Figure 6-3 shows a selection of black pixels, a distance matrix for that group of pixels and the best solution path and history.

For every colour group the GA performs a set number of iterations to converge to the shortest open path. The average distance between the pixels along this path is calculated. These average distances for each colour group are then averaged for all of the colour groups in the image.

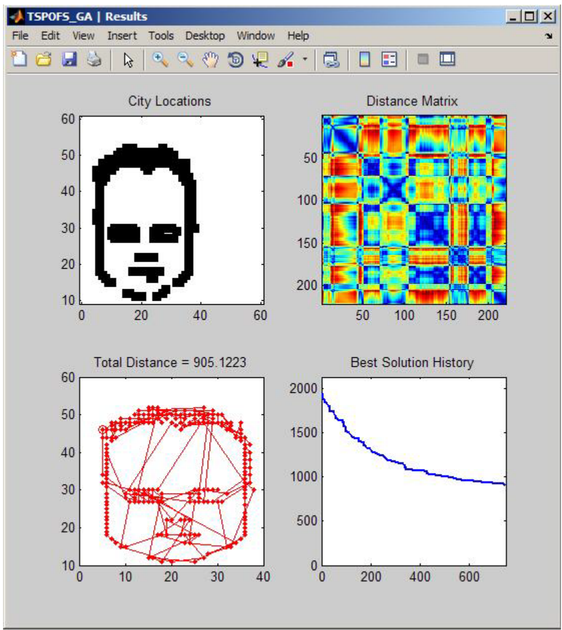


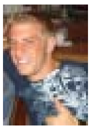
Figure 6-3 - Sample Output showing the group of black pixels, Final Route and Best Solution History of the OP TSP GA

6.2.2 Experimental Setup and Procedures

Test Images

The size of images to be used for testing and analysis was chosen based on an A4 sized image at the resolution target of the food printer. The voxel sizes at the target resolution are 5x5x5mm, which means the size of an A4 picture is 42x60 pixels. All test images were found by using Google’s image search with a size filter of exactly 42x60 pixels. The images were then saved using Microsoft Paint as 256 colour bitmaps, which gave them a bit depth of nine levels (8 groups) per colour (0, 32, 64, 96, 128, 160, 196, 224 and 255).This meant that the colours of the images were separated into 512 groups (8^3) with 256 of these groups being filled for each image. Although this is the case with the majority of the colours, some colours present after saving as 256 colour bitmaps were in groups additional to the defined 512 groups (e.g. Some pixels had colour values such as (R-192, G-220, B-192) and (R-255, G-251, B-240), which are additional to the 512 groups). The reason for this occurrence is unknown, but was corrected in the algorithm. The results of using both of these algorithms on these images are reported in Section 8.6.

Thumb Up



This is a photograph of a young man in a blue and white shirt with his thumb up. The main significance of this image as a test image is that it is a photograph. This means it has a variety of colours and substantial gradients between colours.

Wine

This is a poster for a family day at a winery. With a green wine bottle on a green background and a little bit of green text on a white banner, the few colours present are grouped together.

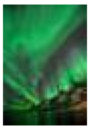
Cartoon

This is the head and shoulders of a cartoon man. This image consists mostly of well-defined areas of colours.

Text

Consisting of a poster with nine lines of text, this image has defined colour regions, which have been blurred when reducing its size and colour depth.

Aurora



This is a photograph of the aurora borealis. Although it's a photograph, it has relatively few colours ranging from black to dark green through to light green. There is little contrast between the colours, with colour changing slowly throughout the image.

Magazine

This is a magazine cover with a main title, image in the middle and very small writing down the bottom. This is a combination of types of images with some defined colour regions and some regions of gradual change as well.

6.2.3 Colour Group Information

Two properties of the images are particularly important when it comes to processing the images for printing. If the pixels of the images are separated into groups of pixels of the same colour, the number of groups and the size of these groups can help to clarify the outcomes of following tests. Figure 6-4 shows the average size of colour groups for each of the test images. There is an inverse relationship between the average colour group size and the number of colours present in the images: Group Size = No. Pixels in Image (2520) / No. of Colours Present (Figure 6-5).

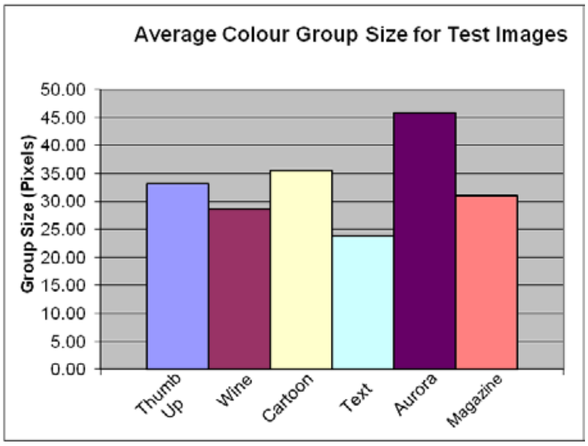


FIGURE 6-4 - AVERAGE SIZE OF COLOUR GROUPS FOR TEST IMAGES

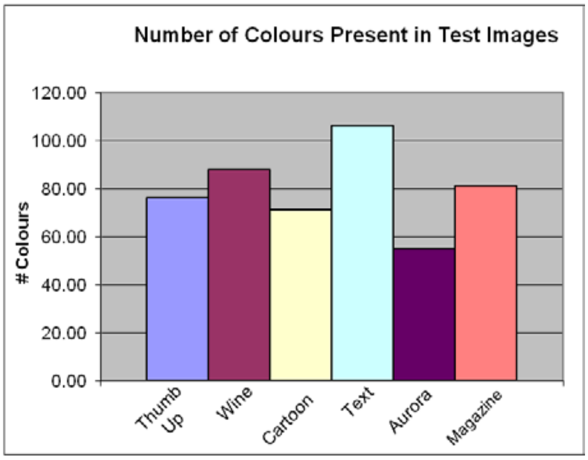


FIGURE 6-5 - NUMBER OF COLOURS PRESENT IN TEST IMAGES

6.3 Machine/Printer Control

The details about the software, firmware and hardware were given in Section 1.2.2.

6.3.1 Improvements Made

The program to communicate between the computer and the motor controller was very well set up to allow each component to be altered and tested easily. However, in some situations it was not very robust when it came to communication between the two systems. The first instance of the robustness being an issue was with the communication confirmation protocol. The program never established whether the serial port that was selected for communication was actually connected to the food printer, as it could easily be any other serial device. To make this confirmation, part of the existing communication protocol was utilised. When a ‘5’ character was sent to the printer, it was required to send a ‘5’ character in return. Therefore to confirm that the serial port selected for communication was the food printer, a ‘5’ character was sent and if a ‘5’ character was received within a small time-out time (10ms), then it was confirmed that the printer robot was connected. This was of great importance if connection was ever lost or incorrect serial communication ports were selected when an abort command needed to be sent.

Extra robustness was also added for when the user was selecting the serial port for communication to avoid program errors.

6.3.2 Improvements Suggested

Transforming or adding to the software/firmware so that it includes a G-Code interpreter could potentially be a very useful feature potentially. There are many software packages that take digital 3D models and slice them into layers for printing 3D models. This would allow the 3D printer to print any model in a flexible manner rather than hard coding printing routines. The other alternative would be to create software that is able to directly process digital 3D colour models and bypass the G-Code generation step. This is possibly a good idea as at some point in the development of the food printer, colour (and potentially flavour and nutrition) information will need to be included in the digital 3D models. Most existing software packages relating to 3D printing do not allow for this kind of information to be included so additional processing and control would be required. Research into what file formats may be appropriate for including colour information is well under way [57]. The authors of [81] have designed and implemented a useful approach to process planning and control in order to print Functionally Graded Material (FGM). By using G-Code generated from STL files by proprietary software and combining material gradient and transport delay factors, fully defined and cohesive demands were able to be loaded into the Freeze-form Extrusion Fabrication (FEF) machine. By using a similar approach, control commands for the 3D food printer’s motion control could be coupled with deposition and mixing ratio commands to produce multi-coloured food objects.

An issue of robustness has also been found with the motor controller. After certain movement commands (more detail in Section 8.7.2), the food printer performs some movement, sends a confirmation of movement, but then continues to cyclically perform some continued movements at increasing amplitude. This occurs when speed calculation errors are made, which is noted by a fast flashing status LED on the motor controller. This required improvements or modifications in the motor controller firmware and/or communication software.

While testing the printer's ability to extrude lines of batter, it was particularly noticeable that improvements in the motor controller need to be made. The testing and difficulties are discussed in more detail in Section 8.5.

6.4 Mass Data Logging Software

A digital electronic scale was set up to measure the mass flow rate of material exiting a number of systems. The scale used in this research was a Precisa 30000 D SCS (Figure 6-6). The scale was connected up to a computer to monitor the mass and calculate the flow rate. To achieve this, a LabView (National Instruments) program (Figure 6-6) was created to acquire, process and display the mass data that was sent from the electronic scales, then use this data to calculate, display and save mass flow rate data. The connection between the electronic scales and the computer was made using RS232 serial connection.

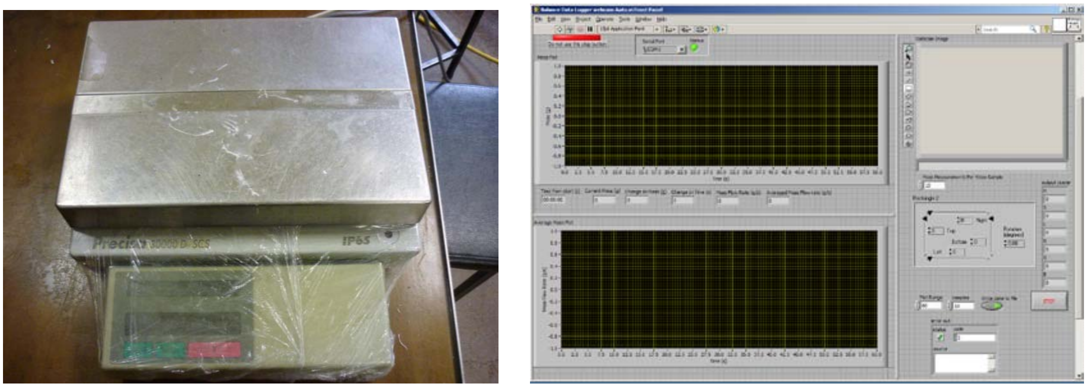


FIGURE 6-6 - DIGITAL ELECTRONIC SCALE AND SCREENSHOT OF MASS DATALOGGING PROGRAM

7 Hardware Design

In order to test selected mixing techniques, test rigs were designed and built. The purpose these test rigs was to demonstrate the advantages and expose the disadvantages of each mixing technique.

7.1 Non-Agitated Mixing

Because non-agitated mixing consists only of devices/systems that have no moving parts, and the fluid flow is the driving force of the mixing, the pumping technique used is highly important. Rather than causing a system component to move, the fluid flow generated by the pump must provide enough force to not only transport the fluid, but to mix it as well. Static mixing is the only non-agitated mixing technique and a test rig utilising compressed air as the pumping mechanism was designed and built to examine the usefulness of static mixers for food printing.

7.1.1 Static Mixer Test Rig

The static mixer test rig (SMTR) allows a secondary flow to be joined with a primary flow at an angle of 45 degrees. This is achieved with a custom made combination chamber with various sized insertion tubes (Figure 7-1). The combined flow is then forced through a static mixer. The SMTR uses regulated compressed air (up to 105psi) to force the fluids from two separate chambers through the static mixer (Figure 7-2). More detail on the set up of the SMTR can be found in [103] (See Appendix).

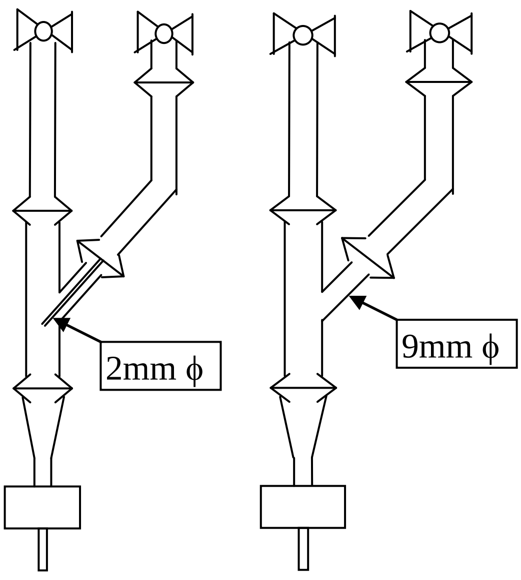


FIGURE 7-1 - COMBINATION CHAMBER CONFIGURATIONS: A) 2MM INSERTION TUBE B) 9MM INSERTION TUBE

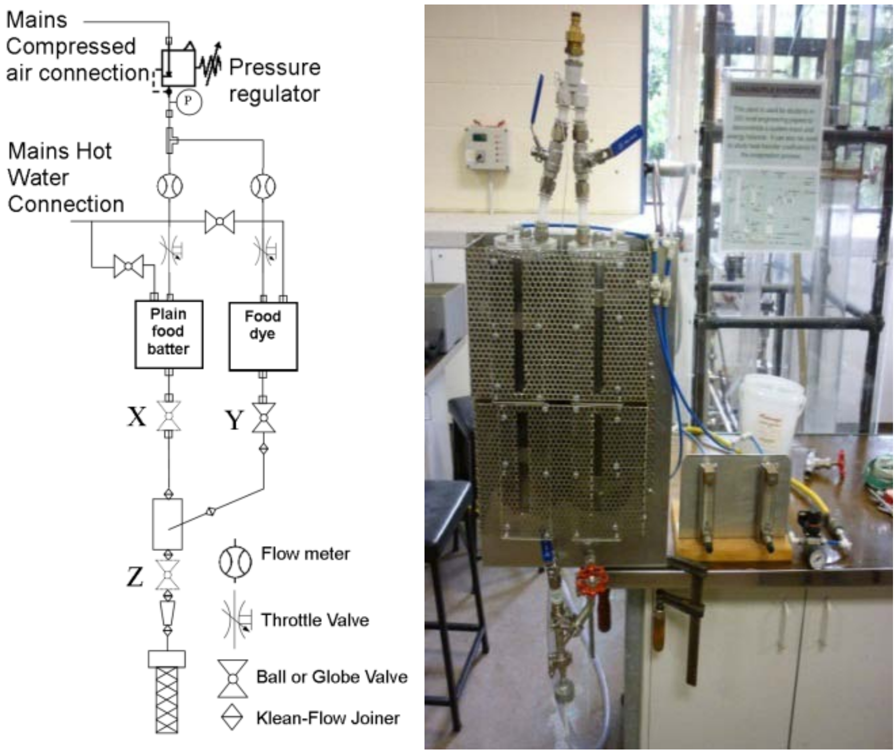


FIGURE 7-2– STATIC MIXER TEST RIG SCHEMATIC AND FUNCTIONAL TEST RIG

Design

There were a number of design changes throughout the design process resulting in a functional SMTR. For the design iterations, please refer to Appendix. The initial idea for clean in place (CIP) functionality was abandoned and replaced with just water flushing capabilities for simplicity. Throttle valves on the air lines were added to allow the regulated air line to be isolated from the pressure chambers. The types of valves had been limited to ball valves (1/4" stainless steel), but to allow for easier control, globe valves (3/8" stainless steel) were used in some locations. The positioning of the valves was also modified to facilitate control over more aspects of the flow and make them easy to access.

The process of manufacturing the components for the SMTR were as follows:

- End caps – A simple configuration for the end caps was designed. With a 12mm steel rod through the middle to hold the end caps together and 2mm x ϕ97mm nitrile rubber O-rings to create a seal around the inner diameter of the chambers.
- Mounting configuration – The chambers were mounted side by side for simplicity of operation and connectivity

- Valves – Ball valves were used for ON/OFF service and Globe valves were used when modulated flow control was necessary.
- Purge welded combination tube and associated fittings – The combination tube and associated components were all fabricated from stainless steel with KleenFlow parts and standard tubing parts being purge-welded together. Fittings to connect the one touch plastic tube fittings to the stainless steel components were also fabricated in this manner.
- Static mixer holder – The static mixer holder was machined out of aluminium for ease of fabrication. A 2mm x ϕ10mm O-ring was used to create a seal between the static mixer and the holder.

Safety Testing

1st safety test

The SMTR was set up in a safe environment, with the rig's safety shield as well as additional shielding (Figure 7-3). The additional shielding consisted of a Perspex safety shield with plywood containment panels to prevent water or pieces of the rig flying off in the case of a rupture.

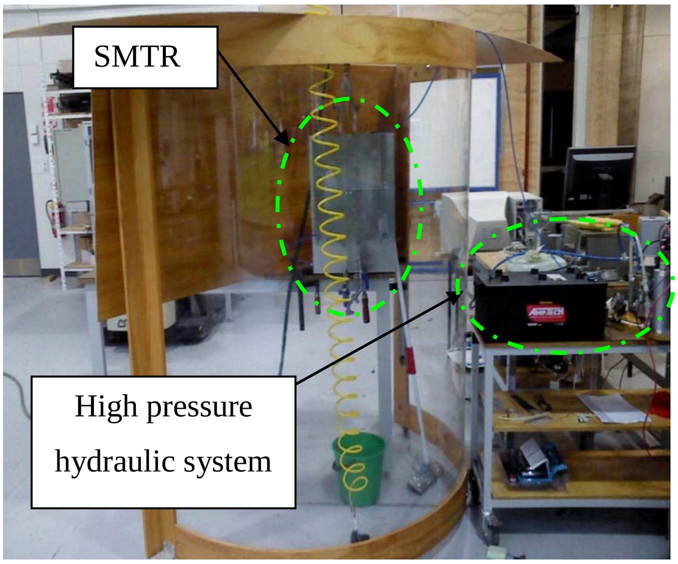


FIGURE 7-3 – STATIC MIXER TEST RIG SAFETY TEST

Filled with water, the chambers were tested hydraulically to 250psi for a few seconds before one of the end caps popped up enough (about 6mm) to allow water to spurt out of the top. The reason that the end cap was able to pop up was that the flexible washers used to seal around the end cap rods were not stiff enough. One of the flexible washers stretched right out and over the steel washer, allowing the end cap to rise enough to let water out. To overcome this problem, a washer with a 2mm x ϕ15mm nitrile rubber O-ring in the bottom was made. This allowed a seal between the washer and the top of the end cap while being rigid so as to not allow any movement of the end cap. Teflon thread tape is used to create a seal between the threaded rod and the nut, with an M10 vulcanised fibre washer providing a seal between the nut and the steel washer.

2nd safety test

The SMTR was setup in the same way as for the 1st safety test with the only change being the new washer setup. Again, while filled with water, it was tested hydraulically at 200psi for one minute, along with momentarily testing it at 240psi. Two conclusions were reached from this test. The first conclusion was that the chambers are strong enough to withhold double the maximum operating pressure and therefore are safe to use with the mains air pressure line. The second conclusion, which is an assumption, is that the first components on the rig to fail would most likely be the one touch fittings, which are only rated to 150psi. If these fittings were to fail, it is unlikely that any components would be propelled uncontrollably away from the SMTR. This is because it is assumed that if one of these fittings fails, in most circumstances, every component is attached to the SMTR by another fitting. However, if two fittings failed simultaneously, or the failure of one fitting led to the failure of another, components may be propelled away from the SMTR in a dangerous manner. This is particularly unlikely as the fittings are pointing up or down, so they would be propelled at the roof or the floor rather than toward a user. As an additional safety feature, a wire has been wrapped around the valve that would most likely cause damage if the fitting failed. In this case, the wire, which is attached to the safety shield, would retain the valve that the fitting is connected to.

Mass flow rate measurement

A comprehensive review of standard flow rate measurement systems was carried out to establish the most appropriate system(s). A table summarising this review is presented in Appendix.

Two systems were put in place for flow rate measurement during initial testing. The first was a post system mass flow measurement. It used electronic scales connected up to a computer to monitor the mass and calculate the flow rate. A LabView (National Instruments) program was created to acquire, process and display the mass data that was sent from the electronic scales, then use this data to calculate, display and save mass flow rate data. More detail about this system is presented in 6.4.

The second system to allow measuring of the flow rates was simple visual inspection of the change in height of the fluid in the chambers. A transparent ruler was attached to the sides of the two chambers, which allowed height measurements to be taken over time. The corresponding mass flow rate was calculated manually or in a spread sheet. Using a video camera to monitor the rulers proved unsuccessful [103] (See Appendix).

7.2 Agitated Mixing

Agitated mixing techniques consist of devices/systems that have one or more moving parts. This means the test rigs must have at least one actuation mechanism. In the case of the test rigs for testing the Oscillating Mixer and the Conical Surface Mixer (CSM), the actuation methods used are rotation and linear actuation. Both mixer test rigs have used motors to directly drive shafts, while the linear actuation methods differed. The oscillating mixer test rig used a pneumatic linear actuator while the CSM used the linear displacement of a manual drill press for axial movement and geared motors for rotary movement.

7.2.1 Oscillating Mixer Test Rig

The oscillating mixer test rig setup consists of a number of parts to allow the oscillating mixer to be controlled. The mixer effectiveness was verified by analysing images of the mixture through a transparent acrylic chamber. The test rig performs the following tasks:

Mixing

Oscillation of the mixing element is achieved by a linear pneumatic air cylinder with reed switches to control the positions at which the oscillation reverses. This produces a square wave speed profile rather than a sine wave speed profile that a crankshaft would produce. The rotation is achieved by having the mixing element shaft attached to a gear motor, which spins at approximately 60RPM with no load.

Positioning of the discs

The mixing element shaft has a positioning system, which consists of a two position rotary encoder. The encoder has two magnets positioned 135° away from each other around the shaft (Figure 7-4). These two positions are detected by a Hall-Effect device mounted on the air cylinder shaft. This allows the shaft to be located in the right position.

FIGURE 7-4 – TWO POSITION ENCODER

Along with the shaft positioning, the function disc gets aligned using one of two methods. The first method uses the ceiling of the chamber, the chamber cap, which has four protruding pins (80% countersunk hex screws) to mate with the disc's holes (Figure 7-5).

FIGURE 7-5– CHAMBER CAP WITH HEX SCREWS FOR SHAFT POSITIONING

This way is used for the mixing element with the function disc on the top. The second method consists of an external locating pin that protrudes through the chamber wall at the top of the chamber in a hole/slot in the disc. This method must be used with the mixing element that has the function disc on the bottom.

The positioning step happens twice per cycle. The first position step is required to change the orientation from mixing to extruding. The second positioning changes the orientation back to mixing again for the next cycle.

Extrusion

Once the positioning has been completed, the mixing element will then act as an extrusion device when it is plunged from the top of the chamber to the bottom of the chamber with the outlet open.

All aspects of the operation of the oscillating test rig are controlled through a LabView (National Instruments) program. The air cylinder is controlled with solenoid valves. The solenoid valves, reed switches, motor and Hall-Effect device sensor are all interfaced with the computer using an input/output breakout board.

7.2.2 Conical Surface Mixer Test Rig

The mixer head and body were machined using reciprocal machining operations to ensure the geometries matched. The mixer head was made out of acrylic stock, with a stainless steel shaft and the mixer body was turned from aluminium stock. To ensure the material remained in the mixing zone while mixing and came out of the nozzle when extruded a cap was put over/around the mixer. To hold the cap in place yet allow for movement during extrusion, a spring and washer provided compressive force on the top of the cap. This whole assembly was mounted in a drill press for testing.

FIGURE 7-6 - CONICAL SURFACE MIXER TEST RIG

8 Testing and Results

Testing of mixing techniques, food printer systems and components as well as image processing software was carried out. Three mixing techniques were determined as the techniques offering the most potential out of all of the mixing techniques considered. These three mixing techniques were static mixing, oscillating mixing and conical surface mixing. In order to establish how effective each of these mixing techniques were, test rigs were designed, fabricated and testing procedures were carried out. Samples were mixed and photographed (using a Panasonic DMC-F2 point-and-shoot digital camera), and then analysed using image processing to determine how effective the techniques were. The testing performed also gave insight as to how appropriate each technique would be for food printing.

Testing the food printer's pumping and movement capability was achieved by utilising the existing hardware and machine control software. The peristaltic pump, syringe pump and three-axis CNC machine were tested so that their appropriateness could be evaluated. Both the Spiral Search Algorithm and the Open Path Travelling Salesman Problem Genetic Algorithm were tested in a number of ways and the algorithms compared and contrasted.

8.1 Non-Agitated Mixing Testing

Non-agitated mixing is a continuous-flow mixing technique, so determining the effectiveness of mixing involved collecting mixing samples. Two techniques of obtaining samples were used to obtain the most reliable information.

8.1.1 Static Mixing

Experimental Procedure Setup

Testing of the validity of the test rig and examination of many different factors affecting mixing effectiveness has already been done to a certain extent [103] (See Appendix). The author concludes that a number of problems are evident, but these issues haven't rendered the SMTR useless.

Materials

Four mixtures were made up to be used for testing. Each mixture had the same composition besides the addition of colours to three of the mixtures.

A mixture of xanthan solution was prepared, which consisted of 98 parts water, 2 parts Tex.Smooth Pro xanthan and 1 part Potassium sorbate (preservative) (purchased from Hawkins Watts, New Zealand).

Each of the four mixtures consisted of 5 parts xanthan solution, 1.5 parts water, 3.5 parts rice flour and 0.25 parts food dye solution.

The red mixture had red food dye, the blue mixture had blue food dye, the green mixture had green food dye and the white mixture had water in place of the food dye solution.

The mixtures were all left in the testing environment so that the temperatures of the mixtures would stabilise. Over the course of the testing, the temperature of the environment changed from 24.4°C to 24.9°C, so it was assumed that the temperature of the mixtures remained in this range.

Setup

The SMTR was setup with a ball valve in position X and a globe valve in position Y (refer to Section 7.1.1 and [103] (See Appendix)). Initially a globe valve was expected to be more useful due to the progressive flow control it allows, but when dealing with xanthan, which is a viscoplastic fluid, the flow was too hard to progressively control. This is because the mixture would go from not flowing at all to suddenly flowing very quickly even with very small adjustments of the valve. To reduce the flow once it had begun, the valve had to be adjusted to almost back at the closed position. For this reason it was determined that it was easier to run the tests with a ball valve to start or stop the flow completely by quickly moving the control lever on the ball valve rather than rotating the hand-wheel on the globe valve. White mixture was placed in Chamber 1 on the left, while one of the coloured mixtures was placed in Chamber 2 on the right.

Method

The first method involved collecting the mixture in an open top tube as it was extruded from the static mixer nozzle (Figure 8-1). Photographs of the collected mixture were analysed to examine the colour content of the mixture along the length of the open top tube. The mass of material extruded was recorded to give an overall contrast, but the image was also used to obtain a section by section contrast recording.

FIGURE 8-1 – OPEN TOP TUBE SAMPLE – WHITE TO GREEN

The second method required the flow to be stopped a number of times part way through the run to take a photo and record the mass of extruded mixture so far. Figure 8-2 shows a sample of a photo that was taken part way through a run.

FIGURE 8-2 - MIXER TIP PART WAY THROUGH RUN (MASS RECORDED AT SAME TIME)

This allowed a more accurate way of measuring change in colour as the change in mass extruded changed. However, it produced fewer data points for analysis.

Steps

Step 1: For the first run, open valve Y to allow the coloured mixture to flow into the static mixer until it is completely filled with mixture. Completely close valve Y.

(From the second run onwards, this step would then become a part of the rest of the method, meaning that Step 1 would no longer be carried out.)

Step 2: Depending on the method of analysis, either a photo would be taken of the static mixer or the electronic scales would be zeroed.

Step 3: Open valve X to allow the plain mixture to come through the static mixer while the extruded mixture is collected in the open top tube or a container on the scales (depending on the method of analysis).

Step 4: (For method 2 only) When the colour begins to change significantly, close valve X to stop flow and take a photo of the static mixer. Re-open the valve X to allow the mixture to continue to flow. Repeat two or three times until the colour looks like it has finished changing.

Step 5: Close valve X and record mass of extruded mixture.

Step 6: (For method 1 only) Take a photo of open top tubes alongside a ruler for scale.

The red mixture was used to test the operation of the SMTR and to find the right operating conditions. Initial conditions that were used with the red mixture were 60psi for the cylinders, smallest (2mm) insertion tube and a static mixer that was 85mm in length, 6.3mm ID and 5mm nozzle size with six elements (purchased from Sulzer Chemtech) as suggested would provide complete mixing [103] (See Appendix). Two methods for measuring the contrast able to be obtained by the static mixer system were used. For both methods, the coloured mixture was allowed to flow so that it filled the static mixer. At that point, the coloured flow would be stopped and the white mixture would then be allowed to flow to flush the coloured mixture out. This would then happen in reverse with the coloured mixture flushing the white mixture out.

The pressure was reduced to 40psi and then 20psi as the mixture was flowing too quickly to collect. Also the static mixer was not mixing completely with six elements, so to be sure of mixing, a further four elements were added. Chamber pressure of 20psi and ten elements were used for the tests with blue and green mixtures. The test with the blue mixture used the 2mm insertion tube while the test with the green mixture used the 9mm insertion tube.

Measurement of Mixture Colour Properties

A sample LabView (National Instruments) program was heavily modified to allow the variance and standard deviation of an image's colour properties to be acquired. The values of each primary colour and the hue, saturation and luminosity could be obtained individually. For method 1, sections at various points in the open top tubes were selected, while for method 2, the mixture dripping out of the tip was selected (Figure 8-3). These sections were analysed to give plots of Saturation vs. Distance (a loose measure of mass extruded).

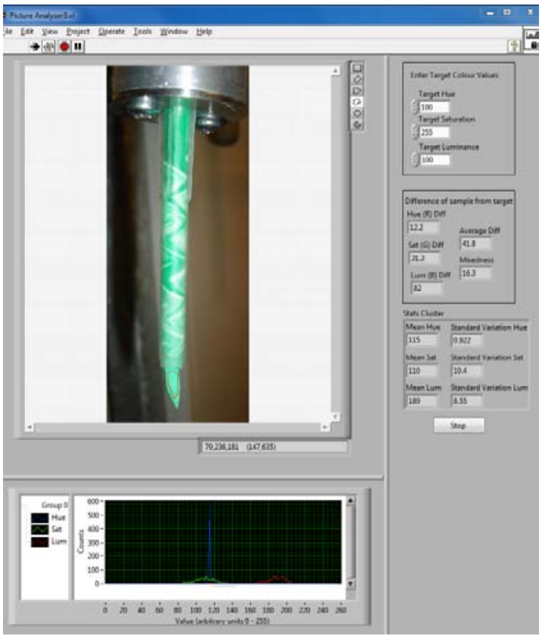


Figure 8-3 - Screen Shot of LabView Image Analysis Software

Results

The Method 1 tests established the significant difference in performance between the contrasts that could be achieved with different insertion tubes. From Figure 8-4 it can be see that saturation is the best indicator of colour change.

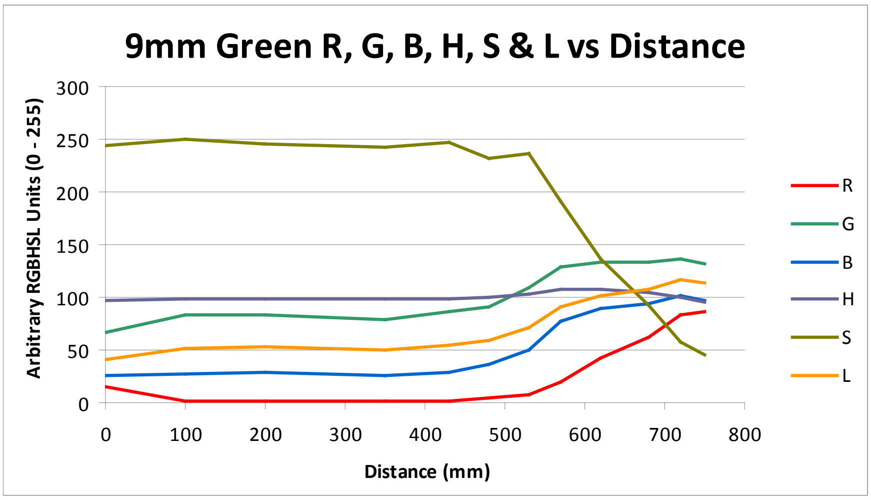


Figure 8-4 - R, G, B, H, S & L Values' Usefulness

The R, G and B values do not directly increase or decrease with the change from coloured to white or vice versa. The Hue is mostly unaffected by the change from coloured to white and the luminosity only changes a small amount. It can be seen by the difference between the profiles of colour change for the 2mm Blue test (Figure 8-5) and the 9mm Green test (Figure 8-6) that the size of the insertion tube is very important.

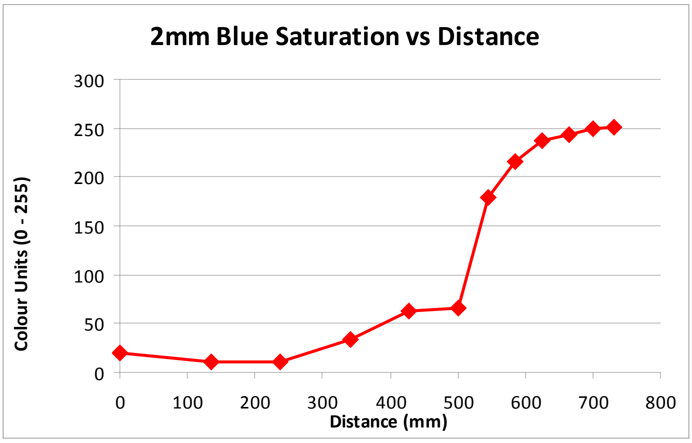


FIGURE 8-5 – 2MM BLUE SATURATION VS. DISTANCE WITH SLOW INCREASE IN SATURATION FROM 237MM

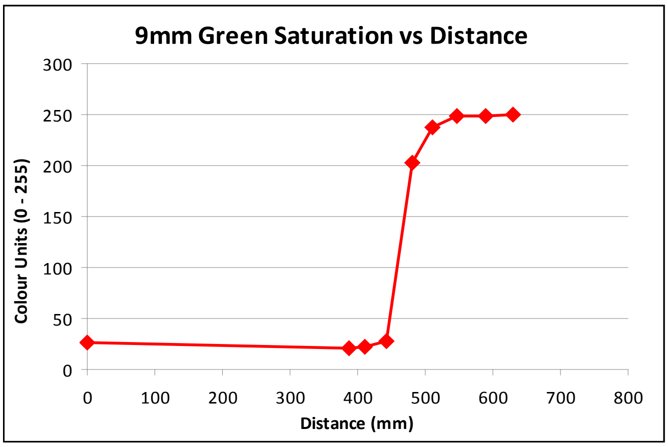


FIGURE 8-6 – 9MM GREEN TEST - SATURATION VS. DISTANCE WITH RAPID INCREASE IN SATURATION FROM 442MM

These figures show the two different rates of change in saturation over the distance (mass). They both have reasonably large dead times before saturation starts to change significantly, but the change in the 9mm Green test saturation is much more rapid than the change in the saturation during the 2mm Blue test. This is most likely completely to do with the size and position of the insertion tube, where the coloured and the plain flow are combined. The 9mm Green test used the 9mm insertion tube, which caused the green mixture to join the combination chamber from the side (refer to Section 7.1.1). This would cause the green mixture to flow in and displace the majority of the white mixture in a flushing manner. This would explain the sudden change because once the green mixture reached the static mixer, there would be little white mixture left in the combination chamber. However, because the 2mm Blue test used the 2mm insertion tube, it positioned the flow of blue mixture in the centre of the combination chamber, the flow would propagate from the centre of the chamber and be forced down the centre of the static mixer while white mixture remained in the static mixer. This may be what allowed a reasonably quick change from white to blue. However, this cannot be confirmed without further investigation. Until the way the mixture comes out of the 2mm insertion tube is confirmed, the reasons behind the slow change from blue to white cannot be determined. Two ways that these flow patterns may be determined could include clear plastic or glass combination tube for visual inspection or Computational Fluid Dynamics (CFD).

The other significant observation was the difference in the rate of change of saturation depending on the order of mixtures used. There was a significant difference between the change from the coloured mixture to the white mixture and the change from the white mixture to coloured mixture. This was particularly evident with the green mixture while using the 9mm insertion tube. When changing from white to green, the saturation changes twice as quickly than when changing from green to white.

The flow patterns were highly dependent on whether the mixture was coming out of the 2mm insertion tube, the 9mm insertion tube or the main flow straight from the top of the mixing chamber. This shows how important the configuration of the combination chamber is for mixing.

The Method 2 tests produced very few data points, which made it difficult to draw conclusive results from (Figure 8-7).

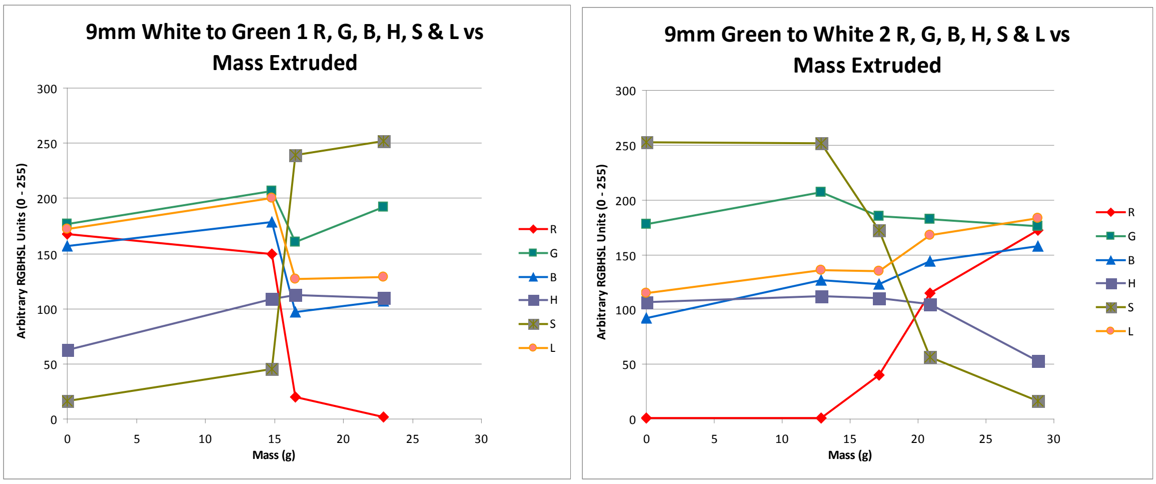


FIGURE 8-7 - METHOD 2 RESULTS FOR 9MM TESTS

Although these results are not as clear as those from Method 1, differences such as the different rates of change in saturation can still be observed.

Mixing Improvements

To improve the capabilities of static mixers for use in food printing, it is necessary to decrease the dead volume of fluid in the piping leading to the static mixer. This will allow a quick change-over of colour from one voxel to the next making reasonable contrast achievable.

8.2 Agitated Mixing Testing

The agitated mixing techniques used in this research are discontinuous-flow mixing techniques, so determining the effectiveness of mixing involved mixing sample voxels. The oscillating mixer was evaluated on how quickly it could mix a voxel, while the Conical Surface Mixer was evaluated on the variation of colour throughout the voxel. This means that these results don't allow the two agitated mixing techniques to be compared and contrasted directly. Instead, the results are intended to aid in the selection of these mixing techniques for certain applications.

8.2.1 Oscillating Mixer Testing

Experimental Setup and Procedures

Water Leakage Test

Testing with water was carried out initially for simplicity and to test functionality (Figure 8-8). The testing showed that there are technical issues with the mixer that were thought to be detrimental to the mixer design. The issue that caused the most concern was how quickly water would leak through the closed mixer.

FIGURE 8-8 - LEAKAGE WATER TEST SETUP

Food Batter Leakage Test

To test how quickly an actual batter mixture would leak through the mixer, 25g of xanthan, rice flour and water mixture was placed into the chamber. The pressure in the air cylinder was increased from 30psi to 87psi and results recorded.

Mixing Capability Test

To test the effectiveness of mixing created by the oscillating mixer, two small tests were carried out. First a simple operational test was conducted, which demonstrated the value of performing a follow up test. For both tests, 68g (enough to fill ¾ of the chamber) of xanthan mixture was placed into the chamber along with 20 drops of standard food dye. The mixer element was then oscillated and photographs of the fluid in the chamber were taken as each oscillation took place. One photograph was taken after the mixer plunged to the bottom of the chamber (1/2 a plunge) and another after the mixer was withdrawn to the top of the chamber (a full plunge). This was repeated until a homogeneous mixture was obtained. Rotation of the mixer element only occurred on the downward plunge during the initial test, resulting in about 0.2 rotations per plunge. During the second test, the mixer element was rotated during the downward plunge and the upward retract, resulting in about 0.4 rotations per plunge. The photographs were then analysed with the LabView (National Instruments) program described in Section 6.1 to determine how mixed the mixture was after successive plunges. Mixedness was measured by finding the RMS value of the difference between each pixel's RGB values and the target colour's RGB values. The scale is 0-100% with 0% being all white and 100% being all pixels the exact right colour.

Results

Water Leakage Test

An arbitrary pressure of 32psi in the air cylinder was used to allow the tests to run long enough for results to be unaffected by timing issues (4-5 seconds). This meant the actuator applied 156N to the mixer shaft, which resulted in a pressure of 18psi in the water in the chamber. The water leaked back in between the mixer discs at a flow rate of 6.7ml/sec.

Batter Leakage Test

For the test to examine leakage of mixture through the mixer element, no identifiable leakage occurred at all within 2 minutes. From this it was assumed leakage of the mixture is negligible.

Mixing Capability Test

The oscillating mixer worked well in the first test with almost turbulent looking flow patterns being created. Figure 8-9 shows the mixture in the chamber after the first plunge and withdraw, with distribution of the food dye throughout the chamber. When the shaft is inserted into the chamber, the added volume of the shaft increases the pressure in the chamber so that air and/or mixture is forced through the Teflon bushing around the shaft.

FIGURE 8-9 - MIXTURE AFTER A) FIRST PLUNGE B) FIRST WITHDRAW (ALSO RESIDUE ON SHAFT)

Figure 8-10 shows that the mixedness rises rapidly for the first few plunges as the blue food dye is spread throughout the chamber. However, after 4 plunges the mixedness stays within 80-90% as the majority of the mixture has been mixed with the dye to some extent. At 5.5 plunges, the last small white clump is seen, so by 6 plunges, there are no significant unmixed clumps (Figure 8-11). From 6.5 to 12 plunges, the mixture is becoming more homogeneous, with no significant white or dark blue bits of mixture.

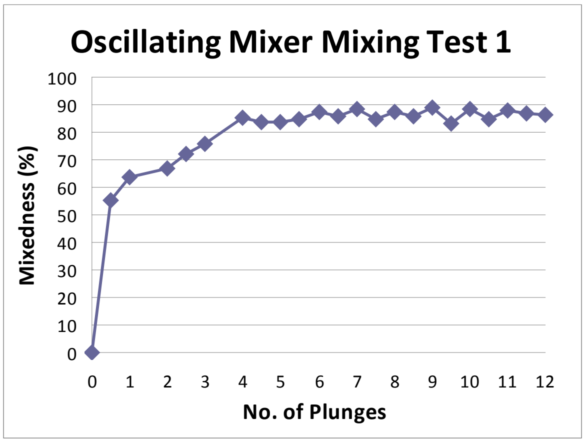


FIGURE 8-10- MIXEDNESS VS. NO. OF PLUNGES

FIGURE 8-11 - MIXTURE AFTER A) 4 PLUNGES B) 5.5 PLUNGES

By the end of the 12 plunges, there was a small amount of mixture on the shaft (Figure 8-12).

FIGURE 8-12 - AFTER 12 PLUNGES A) MIXTURE B) RESIDUE ON SHAFT

Following on from the first test, the second test confirmed the effectiveness of the oscillating mixer. Similar mixing was obtained with mixedness values of around 90 being achieved by 5 plunges, and then fluctuating while slowly increasing. Figure 8-13 shows the sequence of plunges as the second mixing test progresses. It can be clearly seen that the majority of the mixing occurs in the first few oscillations.

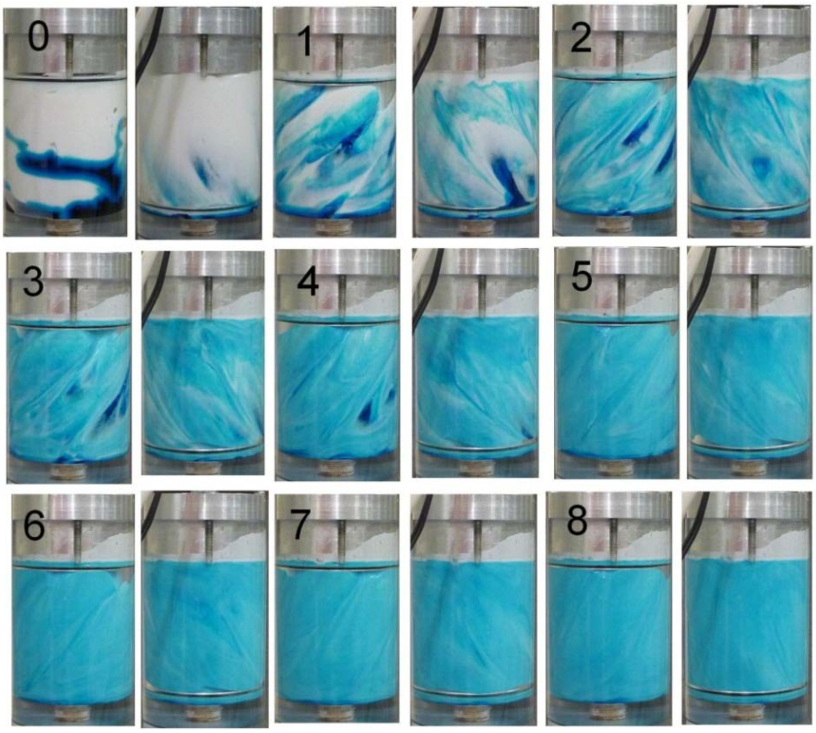


FIGURE 8-13 - OSCILLATING TEST SEQUENCE

More development would be required to bring the mixer up to an operating state where further testing could be completed. This may require improving the motor control, improving the mixer element location mechanism and miniaturising the system.

8.2.2 Conical Surface Mixer Testing

Experimental Setup and Procedures

The system was set up in a drill press to allow variable speeds and feed rates and to monitor the mixing (Figure 8-14). The mixing body was clamped to the work table and the mixer head shaft was tightened into the drill head chuck.

FIGURE 8-14 – CONICAL SURFACE MIXER TEST SETUP

Three tests were undertaken as the testing method was refined further. Two fluids were used throughout these tests. The fluid used for the first test was a rice flour mixture, with liquid food dye to visualise the mixing mechanisms. This helped get a basic understanding of the mixing, but the extrusion results were somewhat poor. To examine the mixing and extrusion performance of the mixer with a fluid more like the actual food batter, the second and third tests used a xanthan and rice flour mixture.

1st Test

<u>70RPM– visualisation</u>

Initially, to examine the way that surface mixing drags and pushes the fluid, a spindle speed of 70RPM was used. This speed allowed the movement of particles and dye paths to be noticed and observed quite clearly.

To improve the uniformity of the mixing, a cyclic axial movement in and out of the mixing cavity (pecking) of increasing depth meant that the dye (deposited in the middle) would get more evenly distributed throughout the whole recess.

<u>270-540RPM – increase mixing</u>

The spindle speed was increased to examine the effects on the mixing. At 270RPM, the mixing happened more quickly and also caused some transfer of fluid from the tip of the cone to the base. However, when the speed was increased to 540RPM, the fluid was transferred from the tip of the cone to the base much faster and when it reached a certain point, was thrown of the mixer in a radial manner. This increase in transfer from the tip of the cone was assisted by the fluid clumping. The clumps would almost roll and ‘climb’ up the cone.

2nd Test

During the second test, the xanthan and rice flour mixture was used, with a spindle speed of 270RPM. This test was mainly to examine how well the mixer could extrude the xanthan and rice flour mixture. It was also useful to improve the mixing technique, by getting a balance between pecking time and full mixing.

3rd Test

The third test also used the xanthan and rice flour mixture with the aim of obtaining consistent results with a consistent method. It was decided that the photographs of the extrusions should be taken in the controlled environment of a light box. From previous testing it was concluded that 10 seconds of the pecking cycle and 10 seconds of full mixing should produce consistent results. An auto-pipette was used to deliver a relatively consistent amount of mixture into the mixer. The high viscosity of the mixture meant that the auto-pipette was not 100% reliable, but by operating the auto-pipette in a consistent way, it was still able to deliver a consistent mass of mixture (6.5g). This was achieved by inserting the tip of the auto-pipette into the mixture for 10 seconds while it sucked up mixture.

Results

Uneven mixing/Stagnant region

Although about the top 80% of the cone created effective and homogeneous mixing, the bottom 20% and the extrusion hole were areas where mixing was ineffective. Due to the small surface area of the tip of the mixing head, there is little drag force exerted on the fluid and there is nothing driving food dye down to this region in the mixer. No matter how long, how fast or whether pecking was used, there would be some unmixed volume of fluid that would be extruded first. Figure 8-15 shows an extrusion sample, with highlighted sections showing where the image was analysed.

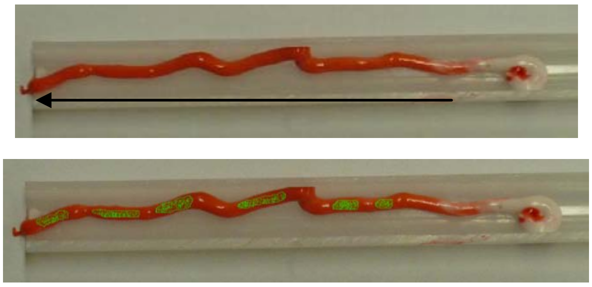


FIGURE 8-15 – A) EXTRUSION FROM THE SECOND TEST OF THE CONICAL SURFACE MIXER WITH WHITE UNMIXED MIXTURE ON RIGHT (ARROW SHOWS DIRECTION OF EXTRUSION) B) HIGHLIGHTED AREAS SHOW REGIONS ANALYSED

Figure 8-16 shows that the colour values at the six selected positions are fairly consistent over the length of the extrusion, with only relatively small change from one end to the other. The G and B values do show a noticeable increase in the middle, but is quite a minor change in colour. Saturation is again the most important measure of mixedness and it can be see that the mixture only had a slightly higher saturation towards the end.

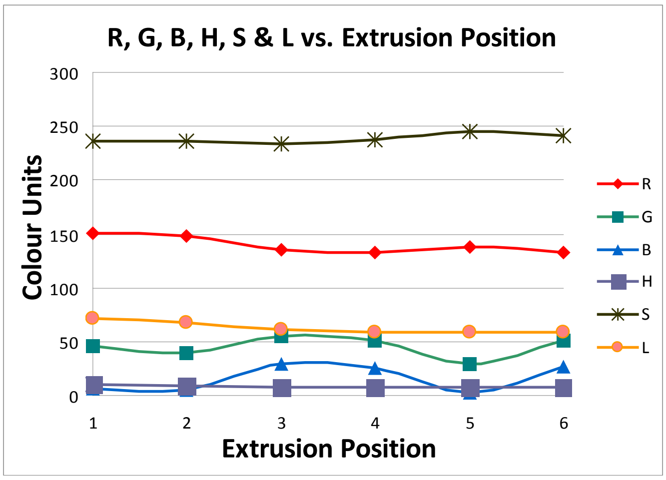


Figure 8-16 - Colour Values at Extrusion Positions

Extrusion

The first testing showed that after extrusion there was a significant amount of residue left on the mixing head and mixing body. This may have been caused by the nature of the rice flour mixture, which allows the moisture to be forced away from the mixture leaving mainly starch remaining.

The second and third tests used the xanthan and rice flour mixture. Two noteworthy observations were made during these tests. Firstly, the food dye, which was again deposited on top of the plain mixture came into contact with the mixer head before the mixture did, which created a sort of lubrication layer between the mixer head and the plain mixture. This layer, which prevented the mixing head from mixing effectively, was overcome when a deeper plunge into the mixer body was made. Once this lubrication layer was overcome, the plain mixture and the food dye mixed effectively. The second observation, which was very promising was that the extrusion process seemed easier than during the first test and there was very little residue left on the mixer head and body, only residue due to overflow (Figure 8-17).

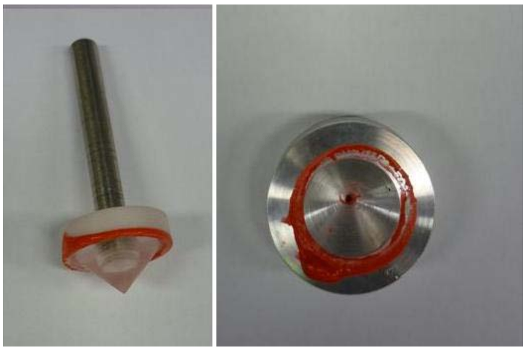


Figure 8-17 – Conical Mixer Body and Head after extrusion (over flow caused by too much mixture)

This would be due to the viscoplastic fluid properties of the xanthan solution, which allow the mixture to flow once a certain yield stress is reached. This testing helped to show what kind of materials may behave well when used in the CSM. For a material to behave well in the mixer, it must allow two processes to happen. Firstly, the material must allow the friction of the mixing head to distribute it throughout the mixing volume to facilitate mixing. Second, it must also allow the mixing head to force it out of the mixing body while leaving minimal residue. For the mixing process to occur, the material must remain in the mixing chamber while being mixed. This indicates the material must have a viscosity within a certain range. It must be viscous enough to not leak out of the mixing body, but not be too viscous to prevent extrusion. Lubrication is also essential to allow the mixture to slip out once the mixer head is forced into the mixer body. As xanthan is a lubricating agent with viscoelastic properties [104], it makes it very suitable for this application. More materials should be tested with the CSM to determine how versatile the mixer is and if there are any other suitable materials.
This test also tested the functionality of the spring to apply appropriate compressive force on the cover. The spring applied sufficient force to contain the mixture, and allowed easy extrusion. As seen in Figure 8-17, some overflow was present, so the following tests targeted this problem. More testing with a more appropriate amount of mixture is required to confirm the effectiveness of the spring loaded cover.

The third test demonstrated the functionality of the spring loaded cover, but also showed that a more controlled method is required. This is because even with consistent timing, the height of the mixing head during pecking cycle and full mixing is controlled by hand and therefore inconsistent. This is evident when the mixture is extruded after mixing (Figure 8-18).

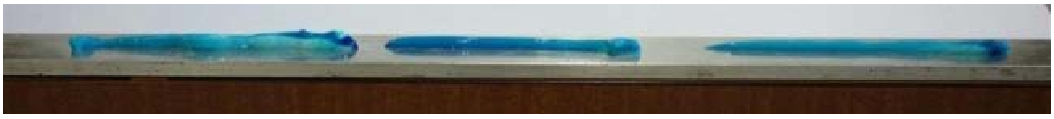


FIGURE 8-18 - INCONSISTENT MIXING

Improvements

The residue problem can be dealt with in two ways. Either avoid changing colour between one voxel and the next (leaving the residue in place), or have a cleaning cycle between making each voxel. Using an elastomeric material for the mixing head and implementing nutating movement are two ideas that may improve mixing. These are explained in Section 5.2.2.

8.3 Reliability of Results

For all three of the mixing techniques examined, image processing was implemented to aid visual inspection. This involved taking photographs of mixture samples and analysing them with software. There were two major inconsistencies relating to photographic methods used during the initial tests. The camera angle as well as lighting source allowed variation of the environment to affect the image acquisition process. The camera for all initial tests was held by hand and the flash used was a small camera mounted flash that would create more light in the middle of an image than at the edges. To improve these inconsistencies the ideal situation would be to take all photographs in a light box. However, as many of the photographs need to be taken in a remote position (e.g. in the mixing chamber or as it is extruded from the static mixer), a tripod would allow for far more consistent results for those images not able to be acquired in a light box. The tripod would ensure the photographs are taken from the same position each time and the light box would provide consistent lighting, independent of the position in the image. Using a DSLR camera would most likely also improve the quality of the photos, but a digital colour meter would be the most accurate way to acquire the required data.

While trying to improve the image analysis process the photos of sample extrusions were taken using a light box. However the camera could not focus resulting in Figure 8-19. This may have been due to the unnatural lighting or light coloured extrusion sample.

FIGURE 8-19 - BLURRY LIGHT BOX PHOTO OF EXTRUSION

The next suggestion to improve this process would be to use an instrumental colour meter. Most of the results have been obtained in less than ideal circumstances and therefore should only be used as a guideline. Further testing with more consistent methods would be required to obtain more reliable data.

8.4 Peristaltic Pump Testing

The peristaltic pump used in this research was a MasterFlex Easy-Load II Model 77200-62. The mass balance described in Section 6.4 was used to monitor the mass flow rate of fluid discharged by the peristaltic pump. Experimenting with how the pump operated allowed conclusions about its feasibility to be made. Besides the highly pulsating flow that was generated by the pump, incomplete occlusion meant that flow rate was not directly proportional to pump RPM, but was also dependent on other factors. The pressure due to fluid head was the most significant factor that influenced flow rate. This made obtaining any results very difficult because the level of fluid in the container that the fluid was being pumped from constantly changed (Figure 8-20). This meant that the fluid head pressure also changed throughout use of the pump. The head pressure affected flow rate much more with low viscosity fluids such as water, than with high viscosity fluids such as xanthan gum, but was significant with both fluids.

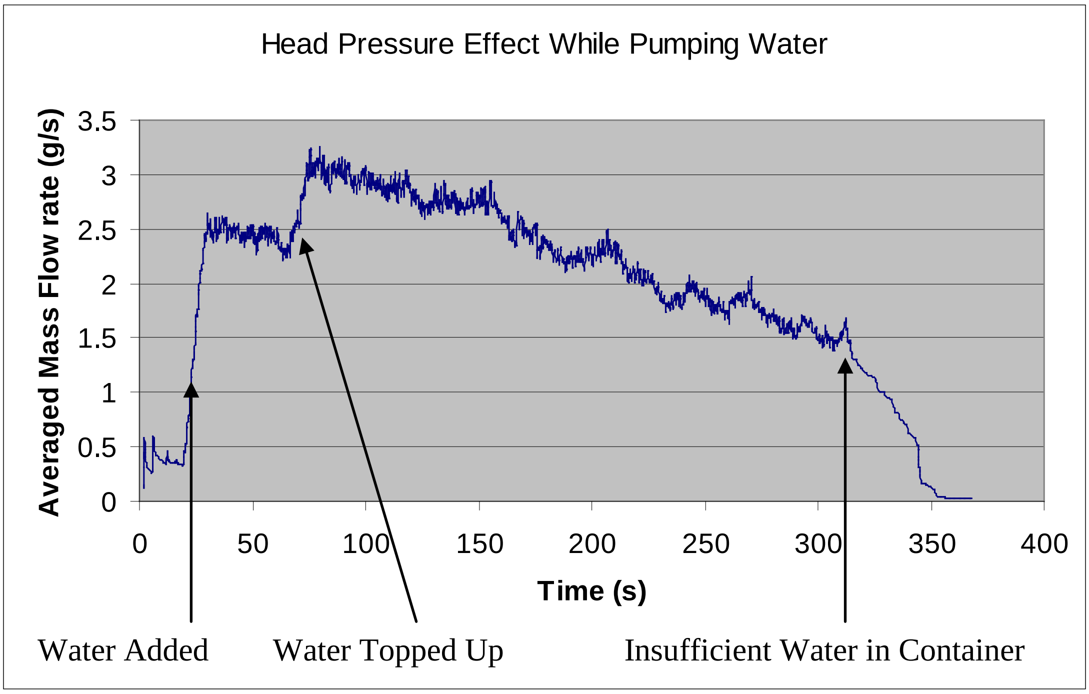


FIGURE 8-20 - HEAD PRESSURE EFFECT WHILE PUMPING WATER

The positioning of the flexible tube inside the pumping head also influenced the flow rate, with inconsistent results. When tested with viscous fluids, the flow rate would continually vary during testing, most of the time decreasing.

These inconsistencies along with incomplete occlusion mean that the peristaltic pump used in this research is not suitable for food printing. It is not able to be used as a metering pump nor does it provide consistent flow rate. The tubing that was supplied with the pumps was assumed to be the correct tubing, but this may not have been the case. Ensuring the correct tubing is used may help to reduce or even eliminate some of the issues discussed.

8.5 Syringe Pump Testing

The syringe pump holster usually mounted on the cover of the Y axis of the Cartesian CNC machine was moved and mounted on the printer head. The cover only moved in the X axis so full movement was not possible. Moving the syringe pump allowed movement of the syringes in all three axes, which meant the syringe pump could be used as an extrusion head (Figure 8-21).

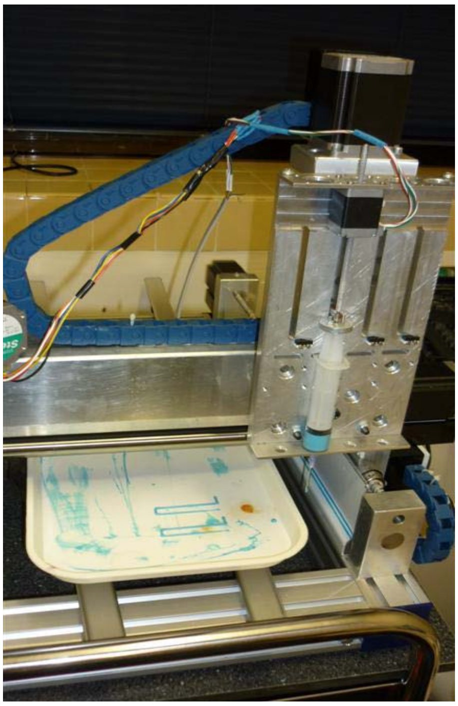


FIGURE 8-21 - FOOD PRINTER WITH SYRINGE PUMP ON PRINTING HEAD

Some adjustments to the control program were made to allow a line with three corners to be extruded to test the effectiveness of syringe extrusion. The diameter of the line varied between 2mm and 4mm during testing depending on speed of extrusion and movement.

The motor controller is set up in such a way that there is no way to stop the syringe pump once it has been sent a command to start, besides sending an abort command to the printer. This is highly undesirable as it potentially creates positioning errors when all motors are stopped in an uncontrolled manner. As this is the case, it was not possible to gain complete control of the syringe pump so varying the speed of pumping could not be achieved easily while printing.

The syringe used was a ϕ20mm 25mL syringe with ϕ1mm tip, with speed setting of 200μm/sec providing good extrusion performance. This gives a volumetric flow rate of 6.3×10^{-3}ml/sec. With larger syringes and larger linear actuators, this flow rate could be increased to allow faster print times.

Significant draw back (1.3mm was sufficient) was required to prevent flow in between separate sections of extrusion. This meant that an initial downward movement of the syringe plunger was required to reinitialise flow after any draw back.

Although significant effort was made to reduce the amount of air present in the food batter in the syringe, some bubbles were still present. From time to time a gap in the extrusion line would be present due to a lack of material where an air bubble was present (Figure 8-22). This significant issue was discussed in further detail in Section 4.1.1.

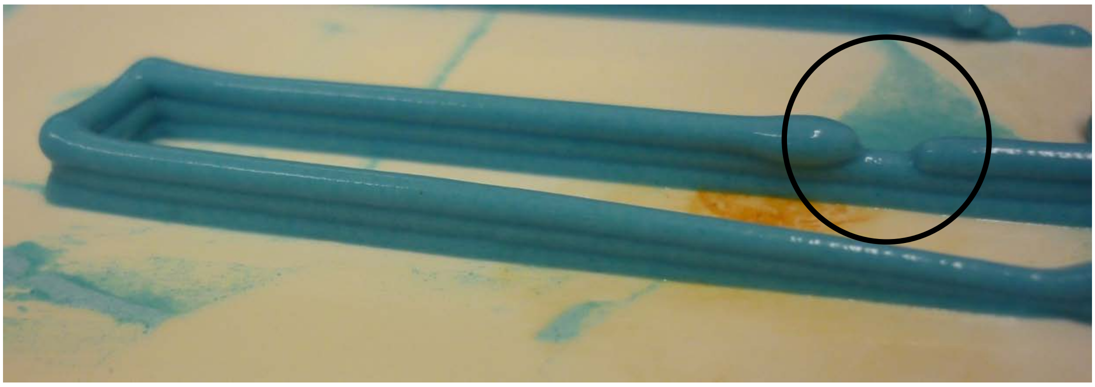


FIGURE 8-22 - EXTRUSION LINE SHOWING GAP FROM AIR BUBBLE

With these difficulties poor results during starting, stopping and cornering could not be overcome, even with significant modification of machine control. A blob would be formed at the beginning of the extrusion followed by a slightly thinned extrusion line, which would then thicken to normal thickness. On cornering, the machine decelerates one axis then accelerates the other axis resulting in a slower movement speed. The syringe pump would continue to pump the same amount of mixture as normal, which resulted in a build-up of material on the corners. When the movement was complete the machine would stop and there would be a delay before the syringe was stopped and withdrawn to prevent flow. This resulted in a blob at the end of the extrusion also. Figure 8-23 shows two extrusion lines performed with the same movement speeds and distances. The blobs and varying line thickness is clearly evident.

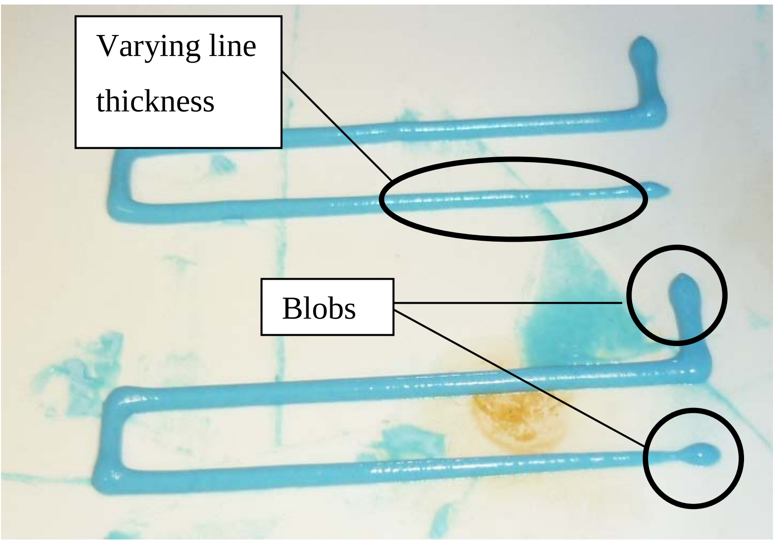


FIGURE 8-23 - EXTRUSION LINES SHOWING BLOBS AND INCONSISTENT LINE THICKNESS

The results showed that more control is necessary in order to produce a consistent extrusion line while stopping, starting and cornering. More complications would be encountered when multiple syringe pumps are used especially with the additional element of a static mixer. A revision of the motor controller firmware is required if the syringe pumps are to be used for flow control. The motor controller firmware should allow the current control method of sending a command with a set distance and speed, but should also allow speed to be controlled without stopping in between. It should also allow the syringe pumps to start and stop with no specified distance because the distance is not the important factor during extrusion. The speed of the syringe pump should be able to be changed without stopping the pumping or stopping the movement of any of the axes.

During this testing filling of the syringes has been achieved using a mastic gun and even parts of the Static Mixer Test Rig (SMTR discussed in Section 7.1.1) to try to avoid creating air bubbles. The tip of the mastic gun was inserted into the combination chamber of the SMTR and air pressure was used to force the mixture into the mastic gun. The tip of the syringe was then inserted into the tip of the mastic gun to fill the syringe. The filling was done this way to minimise the amount of air introduced while filling the syringe. A standard way to fill a syringe with viscous fluid is to pump the fluid from a larger storage container through a nozzle positioned at the bottom of the syringe. As the syringe is filled up, the nozzle is withdrawn so that the tip of the nozzle is always just submerged.

8.6 Software Testing

The two image processing algorithms described in Section 6.2.1 were used for estimating the average distance between pixels of similar colour for images to be printed were tested with a number of test images. A number of different tests were carried out to establish a broad understanding of the distribution of colour throughout images and how that distribution would affect printing.

8.6.1 Spiral Search Algorithm Testing

Testing of the SSA was achieved by performing four tests with different variables. Either the group size was held constant while the allowed difference in colour between the pixels was changed or the allowed difference in colour between the pixels was held constant while the group size was changed. Group size is a control variable and it is set as the number of pixels to be found to create the group (e.g. Group size = 3 means 3 pixels had to be found to form a group).

During the two tests in which the group size was held constant, it was firstly held at a size of 3, then 8. These group sizes were chosen as they represent squares of size 2x2 and 3x3 respectively (Figure 8-24).

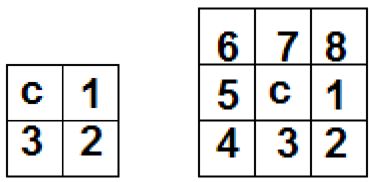


FIGURE 8-24 - GROUP SIZES OF 3 (2X2) AND 8 (3X3) WITH CURRENT PIXEL MARKED 'C'

For these two tests, the allowed difference, with units Red, Green, Blue Colour Units (RGB units), was varied between 0 RGB units and 96 RGB units at steps of 8 RGB units.

During the two tests in which the allowed difference was held constant, it was held at 0 RGB units. For the first of these two tests, the group size was varied between 2 pixels and 16 pixels at steps of 1 pixel. To get a broader view, the second test varied the group size between 4 pixels and 64 pixels at steps of 4 pixels.

8.6.2 Travelling Salesman Problem Testing

The genetic algorithm used a population size of 45 with 750 iterations. These values were selected to get a balance between computing time and solution quality. As the genetic algorithm has a random nature, results were replicated five times for each sample image to ensure the variability was tolerable.

Part of the implementation of this algorithm involved making sure every pixel fitted in one of the standard 512 groups of colours rather than additional ones. To make sure every pixel was in one of these groups, the colour values were rounded to the closest 32 (e.g. 251 was rounded to 255). As it is uncommon for the 256 colour bitmaps to have any pixels out of the standard colour range, this process would have a minor effect on any results. It would decrease number of colours present and increase size of colour groups by small amounts, but the exact extent of this issue has not been explored.

8.6.3 Results

Two main overall relationships have been tested using the algorithms described in Section 6.2.1. These relationships are between average distance and allowed difference, and between average distance and group size. Both of these relationships are simple and results showed trends that are easily predictable. As group size increased and allowed difference decreased the average distance increased. However, the results that are hard to interpret accurately are the differences in the results of the different images.

Spiral Search Algorithm

Increasing Allowed Difference

As is expected, the average distance decreases as the allowed difference increases (Figure 8-25). As these images have been reduced to a set of colours separated by 32 RGB units (0, 32, 64…224, 256), the average distance doesn't decrease significantly until the allowed difference reaches this 32 RGB units threshold.

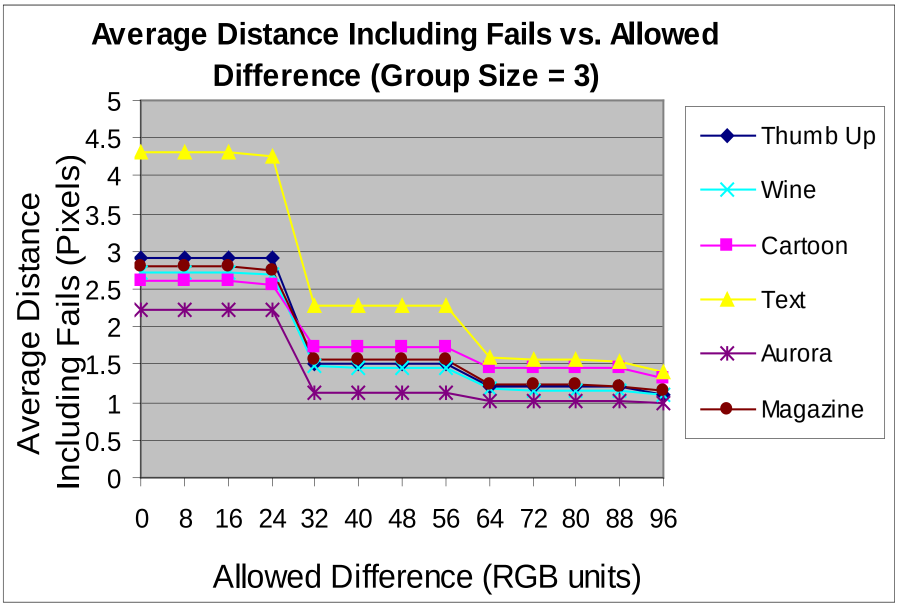


FIGURE 8-25 - AVERAGE DISTANCE INCLUDING FAILS VS. ALLOWED DIFFERENCE (GROUP SIZE = 3)

Also expected are the overall larger distances for the data for the test done with group size of 8 pixels rather than 3 pixels (Figure 8-26).

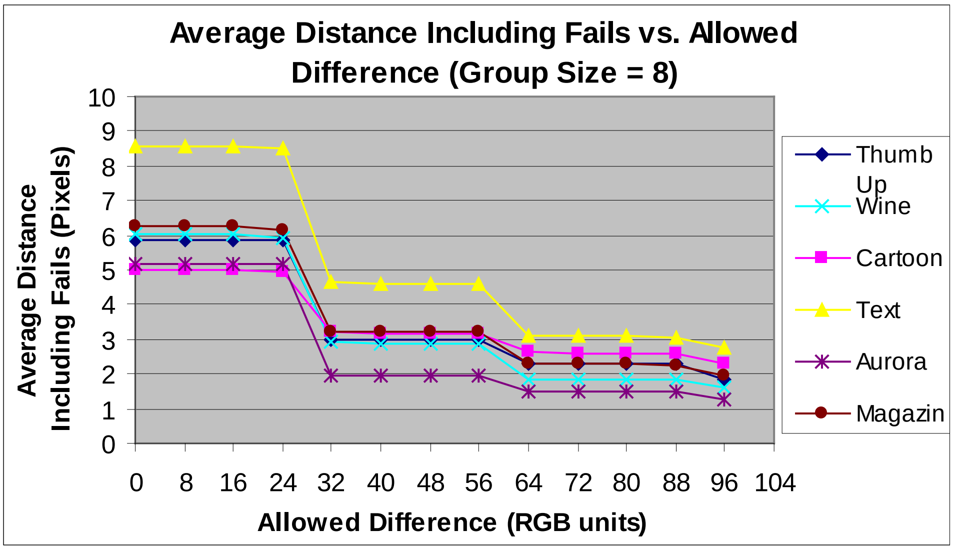


FIGURE 8-26 - AVERAGE DISTANCE INCLUDING FAILS VS. ALLOWED DIFFERENCE (GROUP SIZE = 8)

An interesting point to note is the convergence of all images as the allowed difference gets large enough. The convergence point could be a useful measure of where the differences in the images no longer make a significant difference to the distance. This would only be useful if the food printer was able to change the colour of the voxels it printed consecutively at the rate at the specific allowed difference. At an allowed difference of 64 RGB units (group size of 3 pixels) the distance values of all of the images are within 36% of each other. The implications of these values will be expanded on in Section 8.6.3.

Also notable is the way that the test with group size of 8 pixels seems to spread the data on the Y axis, with the distances of the images being in similar order to that of those in the test with group size of 3 pixels.

Increasing Group Size

As is expected, average distance increases as group size increases (Figure 8-27).

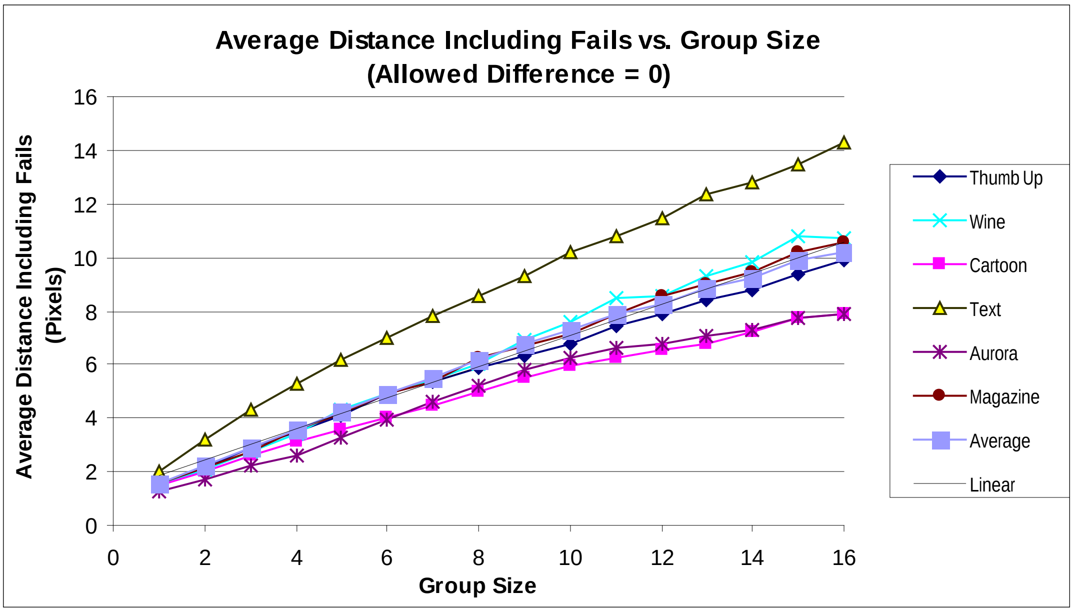


FIGURE 8-27 - AVERAGE DISTANCE INCLUDING FAILS VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

The equation of the trend line applied to the average of the distances is given as y = 0.58x + 1.29 (R^2 = 0.995). This means that along with an offset of 1.29 pixels, as group size increases by 1 pixel, distance increases by 0.58 pixels. The R^2 value indicates that the relationship over a range of group size from 1 pixel to 16 pixels is very close to a linear.

Interesting results were produced with regard to the large variability in number of fails (Figure 8-28). It can be seen that the number of fails for the Wine image increased significantly more than most, with 'Thumb Up' only showing a marginal increase over the 1 pixel to 16 pixel range.

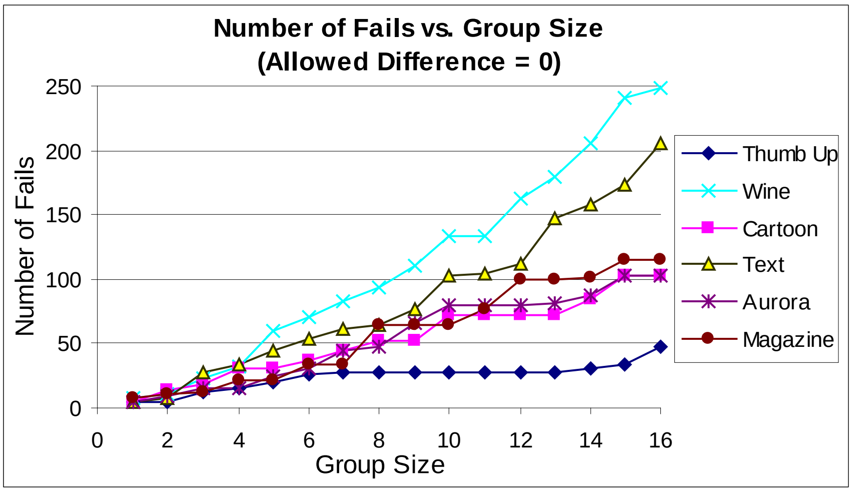


FIGURE 8-28 - NUMBER OF FAILS VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

The number of fails in the Wine image increased so much from group size 11 pixels to 12 pixels that the distance not including fails actually decreased (Figure 8-29).

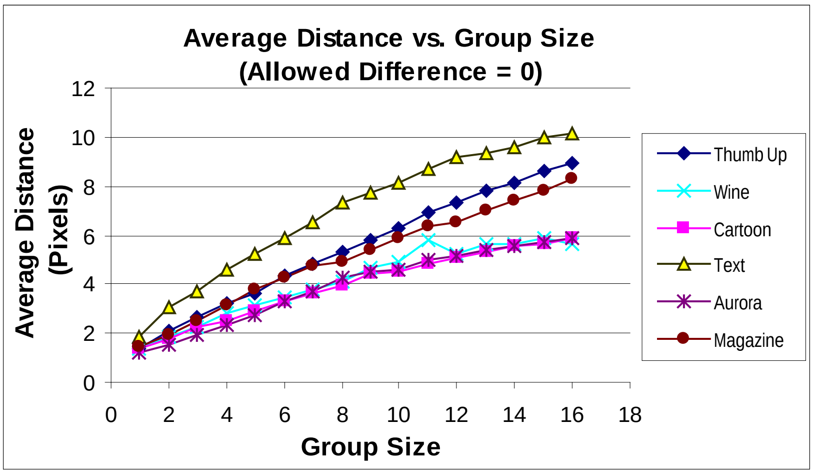


FIGURE 8-29 - AVERAGE DISTANCE (NOT INCLUDING FAILS) VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

To examine how these relationships behaved over a larger range, the distance was obtained for group sizes up to 64 pixels. The larger range showed very similar results, with an overall trend of increasing distance with increasing group size as well as inconsistent gradients of number of fails (Figure 8-30, Figure 8-31 & Figure 8-32). However, the equation of the trend line applied to the average of the distances was different from the result of the test using group size of 1 pixel to 16 pixels. The equation for group sizes ranging from 1 pixel to 64 pixels was $y = 0.37x + 4.02$ ($R^2 = 0.987$). This indicates that the rate of increase in distance is smaller for the larger group sizes. The R^2 value indicates that over the larger range of group sizes, the relationship is less linear and more variable.

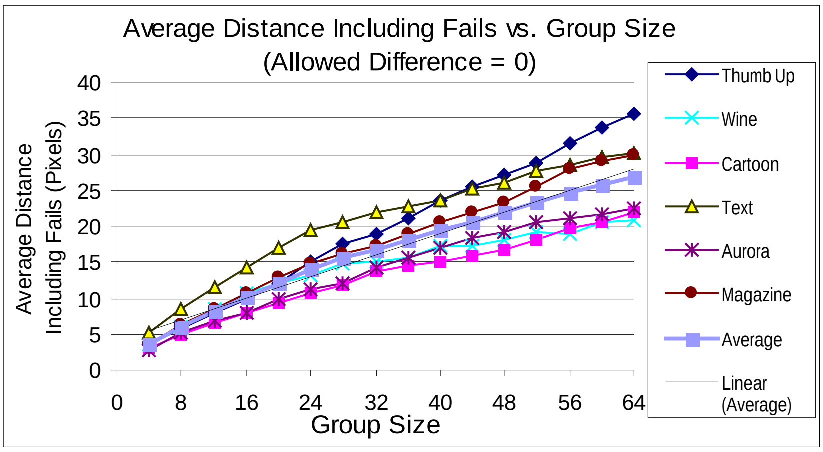


FIGURE 8-30 - AVERAGE DISTANCE INCLUDING FAILS VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

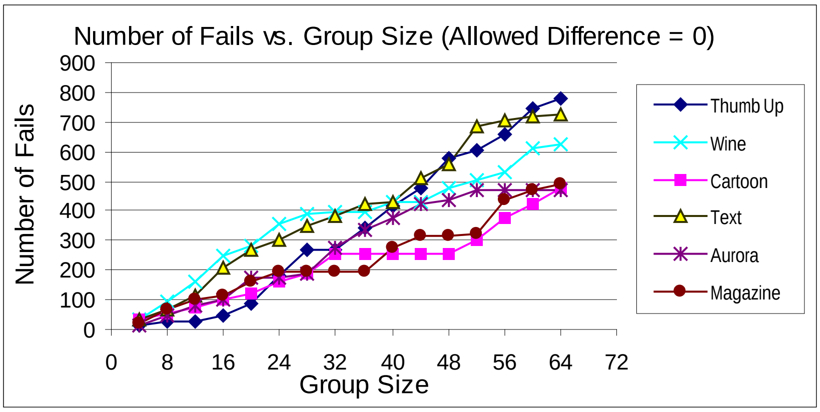


FIGURE 8-31 - NUMBER OF FAILS VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

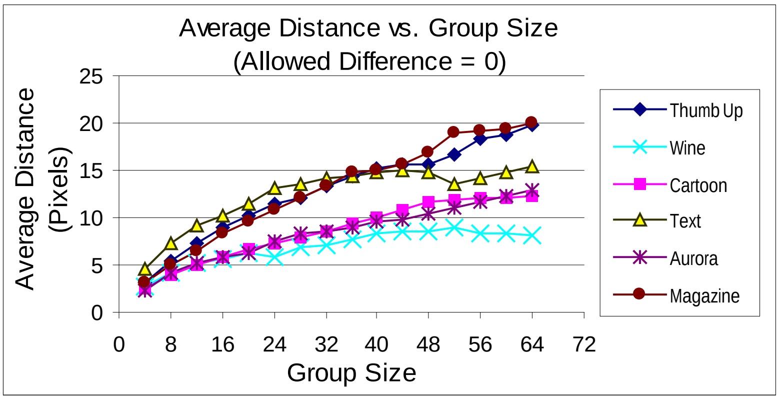


FIGURE 8-32 - AVERAGE DISTANCE (NOT INCLUDING FAILS) VS. GROUP SIZE (ALLOWED DIFFERENCE = 0)

Although the overall trends are the same, it can be seen that the way number of fails change is not consistent of the range of group sizes tested. 'Thumb Up' began with very small increase in distance for group size up to 16 pixels, but then rose rapidly to overtake all other images in number of fails. At around group size 28 pixels, Wine, which was the most rapidly increasing image in Figure 8-28, slowed its rate of increase, allowing 'Thumb Up' and Text to overtake it.

It seems from Figure 8-32 that Wine's trend could be explained because it has many smaller group sizes (average 28.6 pixels), so once it gets above that point, more fails continue to occur, with only a few larger groups actually being completed. Text behaves in a similar way. Text has the smallest average group size (23.8 pixels) and so can be expected to behave similarly to Wine. This is somewhat the case, with Text's number of fails increasing consistently, while at the point between the group sizes of 24 pixels and 32 pixels, the average distance not including fails stops increasing significantly and even decreases for a period.

Open Path Travelling Salesman Problem Algorithm

The GA that solves the TSP becomes less efficient and fails to find shortest routes when the number of 'cities' (pixels) in the group to be traversed becomes large. For this reason increasing the allowable difference when forming groups of pixels (which would create larger groups) would cause poorer efficiencies. Therefore only pixels of the exact same colour were used to form groups to perform the TSP on. The result of the OP TSP GA is therefore equivalent to using the SSA to find the distance for a group of one extra pixel with no allowed difference. For this reason the data for group size 1 pixel were taken from Figure 8-29, allowing comparison of the two algorithms.

The OP TSP GA results in significantly larger distance values than those from the SSA (Figure 8-33).This OP TSPGA data consists of the minimum of the 5 runs. Importantly, the proportions and order of the average distances for the images were the same for both algorithms.

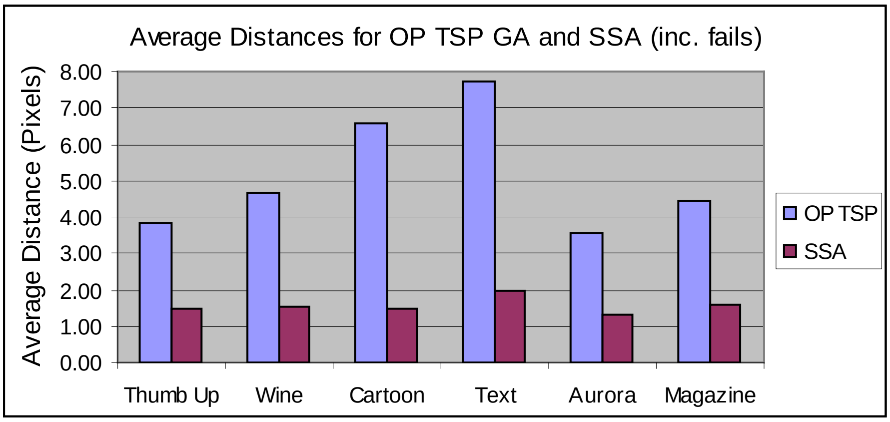


FIGURE 8-33 – COMPARISON OF AVERAGE DISTANCES TO CLOSEST PIXEL OF SAME COLOUR FOR TEST IMAGES USING OP TSP GA AND SSA

It can also be seen from Figure 8-33 that the distances obtained using the OP TSP GA are more spread out, ranging from 3.58 pixels to 7.75 pixels (range - 54%) compared to 1.29 pixels to 1.98 pixels (range - 35%). There was a noticeable difference in average distance values for all of the test images. The difference ranged from 1.2% up to 5.6%.

750 was deemed appropriate for the number of iterations for the GA to run. The standard deviation over the five replications of the average distances for all of the test images was 0.01 pixels. This was deemed sufficiently low to provide reliable results. By comparing results obtained by running 5000 iterations, 750 iterations was accepted as a good trade-off between calculation time and good results. Although the average distances themselves were reduced with more iterations, the proportions and order of the average distances for the images did not change. The results obtained using 5000 iterations were used or further calculations.

Discussion

The data from the SSA testing is not conclusive in the relationships it presents. Deciding what factors in the images determines how the fails and average distances behave cannot be concluded without further testing, possibly looking at different images and different statistics of the images. However, the overall trends do provide insight into what kinds of trends there may be and what to look out for when applying these techniques to food printing. The most valuable data obtained by using the SSA is therefore the data that allows the SSA and the OP TSP GA to be compared and then even combined.

Convergence of Distance with Increasing Allowed Difference

The findings from the allowed difference test showed a convergence of the average distance values of all the images. The distance values converged to within 36% of each other, which if this variation between the images is considered small enough to be ignored, can allow the following conclusion to be made. If the food printer could change the colour of the voxels it printed consecutively by 64 RGB units, then it could be assumed that the average distance of any image using the same conditions would be around the average of the test image distances (1.28 pixels). This would allow a prediction of the time taken to print an image using the food printer, irrespective of the image to be printed.

Comparison of SSA and OPTSP GA

There are significant differences between the two algorithms. The SSA has no bias with regards to order; the same result will be obtained every time. The OP TSP GA on the other hand will return different results based on the starting pixel and the order the GA determines is the shortest path. This leads to the second difference, which is that the SSA will always return the minimum average distance while the OP TSP GA will almost never find the same average distance twice. Even if the GA finds the shortest path for the OP TSP, the average distance will likely be larger than that found by the SSA. The SSA finds ‘number of pixels’ distance values and then averages them while the OP TSP GA finds ‘number of pixels’ – 1 distance values to average. This is demonstrated in Figure 8-34, which shows how the algorithms would determine the average distances. When finding the average distance between red pixels, the SSA would find a total of four distances (1, 1, 1 & 1) as each pixel has another pixel right next to it. This would give an average distance of 1. However, solving the OP TSP would result in three distances (1, 3 & 1) as it needs to create a path between pixel 2 and pixel 3. This is why the OP TSP GA gave average distances greater than the SSA did for all test images.

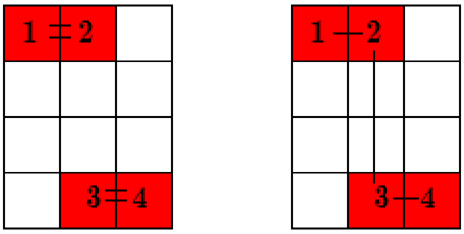


FIGURE 8-34 - A) SSA DISTANCES B) OP TSP GA DISTANCES

The OP TSP GA must always result in a continuous tool path while the SSA has no orientation requirements at all. This becomes particularly noticeable with larger group sizes or when there are small groups of pixels of the same colour spread out throughout the image.

Increasing the resolution of the image being tested will result in a slower solution with a smaller distance if the SSA is used, but not only will the OP TSP GA be slower, it may also result in larger distance values. This is because a higher resolution image will have more pixels, which will mean larger group sizes. The GA can produce poor results if the number of iterations isn’t large enough or the population size is inappropriate. For different sized images the population size and number of iterations would have to be re-examined to ensure that an appropriate balance between computation time and solution quality is achieved.

The two algorithms used have disadvantages and advantages. Both have limitations and both should be used for approximation only.

The SSA does not account very well for how the extrusion process may need to work and ignores the idea of a tool path. However, the OP TSP GA takes the tool path approach to the extreme and assumes all pixels of the same colour have to be printed in succession. The actual printing would much more likely be a combination of both concepts. It would most likely select colours that are close and in an achievable contrast range from the previous voxel that had been deposited.

Application to the Food Printer

To obtain a result that factors in all the considerations mentioned, it is assumed that an average of the two methods would provide the best estimation of the distance between pixels of the same colour (Figure 8-35). As a clear distinction between the distances for the different types of images cannot be made, an overall average of the distances for all the images is the most useful result (3.26 pixels). This 'distance' value can then be used with machine statistics data to determine the time required to print an image. Tests were carried out to determine the time required to move this 'distance' with the existing three-axis CNC machine being used in this research. The time for the machine to move 16.3mm (3.26x5mm voxels) moving only on one axis was 0.38 seconds. This would mean it would take just under 16 minutes to print a 42x60 pixel cake assuming the deposition of the material could be achieved at the same time.

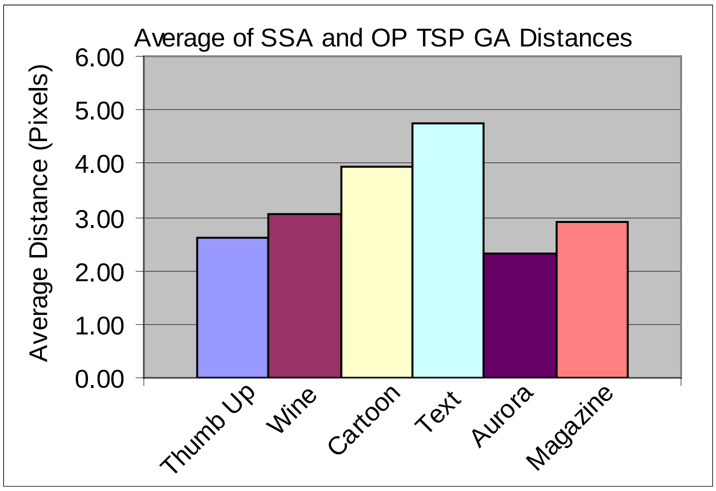


FIGURE 8-35 - AVERAGE OF SSA AND OP TSP GA DISTANCES FOR TEST IMAGES

Additional Testing

One variation of the research presented here that may be useful would be to search for groups of pixels of similar Hue, Saturation and Luminance values rather than Red, Green and Blue values.

Also, rather than using 256 or 512 colour sections, using the colours that appear in the LCH colour space may be more valuable [105]. This is because the LCH colour space includes only colours that are reproducible in four-color offset printing without great deviation and might be more representative of colours that could be achieved in food printing.

8.7 CNC Machine Control and Speed Testing

To determine how the printer would behave when requested to perform certain printing tasks and to find out the maximum speed and time taken these certain tasks, a number of tests using the three-axis CNC machine were performed. The control software and motor controller described in Section 1.2 was used for this testing. To determine the maximum speed and the correlation between the set speed in software and the actual speed achieved by the machine a number of movements were timed. These movements were timed using timing in the control software to get accurate and precise timing measurements. Six movements were timed. These were single axis movement along the X axis in both directions, single axis movement along the Y axis in both directions, and simultaneous X and Y axis movements, either both away from the origin or both towards the origin. These were all tested to ensure any differences in the axes or directions the machine was moving was accounted for. Each movement was tested five times to ensure consistency and avoid error due to variation.

8.7.1 Operation and Measurement

Figure 8-36 shows the movement cycle and how it is initiated and when messages are sent from the motor controller to the computer. To monitor the different parts of the movement cycle, three times were recorded per movement. The first time that was recorded was when the move command was sent from the computer program to the motor controller firmware. The next time recorded was when the motor controller firmware sent a return axis move complete message to the computer indicating the deceleration cycle had started. The final recorded time was when the motor controller firmware sent a move complete message to the computer indicating that all axes' deceleration cycles were completed. The deceleration time was used to approximate the acceleration time so that cruise time could be calculated.

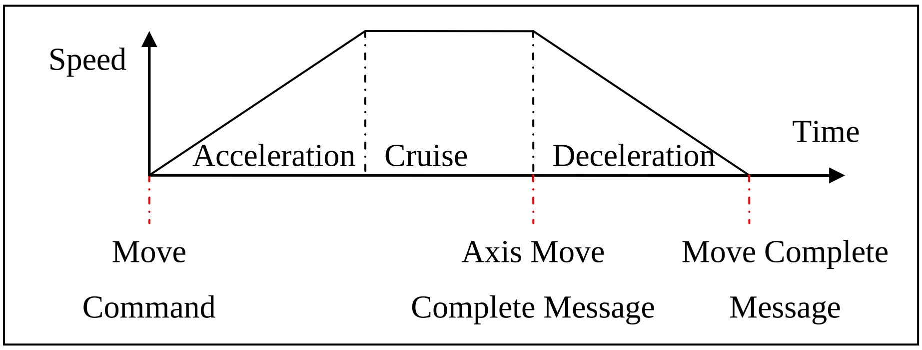


FIGURE 8-36 - MOTOR CONTROL COMMAND AND MESSAGE SEQUENCE

Cruise time was calculated by the following formula:

(movComp – movComand) – 2 * (movComp – axisMovComp) i.e. ‘total move time’ – 2 * ‘deceleration time’

Where movComand was the time when the Move Command was sent to the motor controller, movComp was the time the Move Complete Message was received from the motor controller, and axisMovComp was the time the Axis Move Complete message was received from the motor controller. Logic was used to prevent errors caused by overflow from the time changing from 60 seconds back to 0 seconds as the minute changed over.

8.7.2 Malfunctioning

It was discovered that certain combinations of speed, acceleration and distance input into the control software, caused the motor controller to malfunction from errors in the speed calculations. The stepper motors would make strange noises and jitter in a periodic manner, which meant the requested speed and distance would not be achieved. The status light on the Motor Controller Box would remain in normal mode (slow flash) for a short time while part of the malfunctioning move was carried out, but would then change to the speed calculation error mode (fast flashing) when the jittering began.

Any input speed value above 99000µm/sec would cause the machine to malfunction. Although this was the maximum speed over a certain range of distances, it could not be achieved for small distances. It was determined that the minimum distance that can be moved at this maximum speed of 99000µm/sec with the acceleration set to 500, was found to be 9.5mm. If the acceleration was reduced below 490 with these settings, the machine malfunctioned.

This may indicate that the errors in the speed calculations occur when the machine cannot reach its cruising speed before it needs to decelerate. With this explanation, the situation where speed calculation errors occur should be avoidable. It seemed that smaller travel distances would require small speeds to remain operational. With a distance of 5mm and acceleration of 500, the largest speed value that didn’t result in a malfunction was only 58000µm/sec.

These errors and the resulting malfunctioning governed the boundaries in which the following tests were performed.

8.7.3 Single 50mm Movement – Cruise Speed Test

A distance of 50mm was selected for the single movement test as it provided a relatively long travel time and allowed five replicates to be recorded successively on one axis without changing direction. This test allowed a maximum speed value to be obtained and this was compared with product documentation.

When compared with the overall travel time and distance during the 50mm travel test, the acceleration and deceleration only take a very short time and distance when the acceleration is set to 500.

8.7.4 Five 5mm Movements – Neighbour Depositing Test

The 5mm multiple movement test allows an estimation to be made for the time required to move between voxels (of size 5x5x5mm) if they were printed in order of orientation. This would mean they were printed line by line and subsequent voxels were deposited right next to one another (neighbours). When performing the tests over small distances, the acceleration, deceleration time and distance become significant. To ensure this didn't become a problem, the Five 5mm Test was made to consist of five start stop cycles. This meant there were five acceleration and deceleration cycles to minimise measurement errors. The test had to be carried out over a limited range (up to 58000µm/sec) due to malfunctioning at higher speeds.

8.7.5 Five 16.3mm Movements – Average Same Colour Distance Test

The 16.3mm multiple movement test allows an estimation of the time required to move the average distance calculated in Section 6.2. The average distance between voxels of the same colour was determined to be 3.26 pixels so the distance required to move is 16.3mm (3.26x5mm). 16.3mm was considered small enough that the acceleration and deceleration time and distance was significant. To ensure this didn't become a problem, the test was again made to consist of five start stop cycles. With a distance of 16.3mm and acceleration still 500, the machine operated perfectly fine at a maximum speed of 99000µm/sec.

8.7.6 Documentation

Documentation about the High Z 400T three-axis CNC machine has varying details. The name tag on the machine specifies that the model is a High Z 400 not including the T character, which indicates that the X and Y axis linear actuators use ball screws rather than trapezium spindles. This has a large impact on the maximum movement speeds. Although the name tag on the machine doesn't have the 'T', the main sticker on the machine includes a 'T' and the machine does have ball screws. Specified speeds for the High Z 400T model range from 6500mm/min or 108mm/sec up to 7000mm/min or 117mm/sec (refer to Appendix). How these values were determined is uncertain as it is not specified. The results showed that the machine is operating just below these maximum speeds, but is sufficient for the purposes of this project.

8.7.7 Results

General relationships

For the single movement test over 50mm, it can be seen that there is a linear relationship between the selected speed setting and the actual speed achieved by the machine (Figure 8-37). The actual value measured was close to the set value. The equation of the trend line applied to the data points had an equation of y = 1.09x - 3.41 (R^2 = 0.9994). This indicates that, with an offset of 3.41mm/sec, for every 1mm/sec the set speed is increased, the actual speed will increase by 1.09mm/sec. This is a very tolerable result, and if very accurate speeds are required, this equation could be used to adjust the set speed.

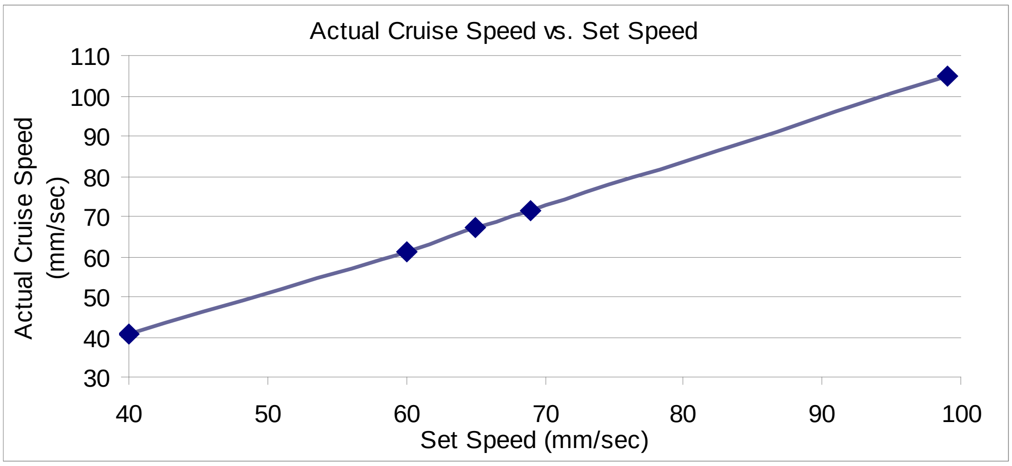


FIGURE 8-37 - ACTUAL CRUISE SPEED VS. SET SPEED

For the five 5mm movements, as the set speed approached the maximum speed that would not produce malfunctioning, the movement time stopped decreasing as much as with the lower set speeds (Figure 8-38).

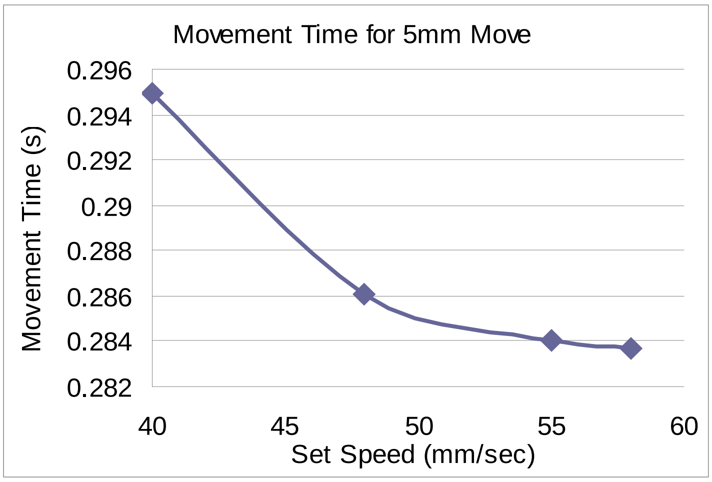


FIGURE 8-38 - MOVEMENT TIME FOR 5MM MOVE

This could be due to poor efficiency of the stepper motors and/or the motor controller at these operating conditions. Similar to the multiple movements of 5mm, the multiple movements of 16.3mm the movement time decreased less as speed increased (Figure 8-39).

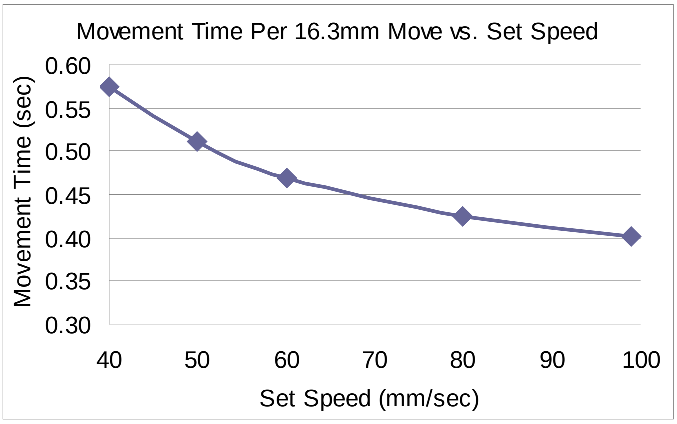


FIGURE 8-39 - MOVEMENT TIME FOR 16.3MM MOVE

This indicates that efficiency was not a big influence at these distances, but only acceleration and deceleration times. The relationship is no longer linear because an increase in set speed doesn't affect the achievable acceleration (unless the motor controller becomes less efficient) and most of the travel time is spent accelerating and less time cruising.

Maximum Speed

If the values in the documentation are referring to speed per axis, then there may be minor problems in the software, firmware or hardware that have prevented these values being achieved. The maximum speed that was able to be achieved in one axis direction was 105mm/sec. This was the cruise speed achieved over a distance of 50mm with a speed setting in the software of 99000µm/sec and did not include acceleration and deceleration. If the maximum speed value listed in the documentation is referring to the combined speed of both axes, the machine can achieve beyond this value. The maximum speed was achieved by having both axes move 50mm at the same time. This meant a distance of 70.7mm was covered in approximately the same amount of time as each axis moving 50mm. This resulted in a speed of 148mm/sec.

If the speed values at the lower end of the range are correct, good operation of the machine may be jeopardised. This is suggested because the datasheet says "In order to achieve a durable economic life of the mechanical components, the max. express speed should be not higher than 80% of the stated figures." This would mean running the machine at 61-93mm/sec depending on which maximum speed is correct and whether the maximum speed is per axis or two axes speed.

9 Conclusions, Recommendations and Discussion

The market for food products is constantly evolving and new products are required to keep customers buying. Food trends have led to customers wanting more customised products and it has been predicted that Technofoods will be able to satisfy this demand. This research has covered the broad topic of food printing. The existing food printer at Massey University was the focus of the research, with development of the printer and additions to improve capability. Several areas that are of particular importance to food printing have been explored and examined: including mixing, pumping, rapid prototyping, associated software and electronic and mechanical hardware.

There have been four major outcomes as a result of this research. These outcomes have clearly achieved the intended research objectives. The first major outcome is a broad and firmly rooted base from which future research can continue to build on many different areas of technology and engineering associated with food printing. Secondly, improvements to the existing food printer have been made and a number of improvements out of the scope of this research are suggested for future work. Third, image processing of sample images has determined that the spread of colour throughout an image is such that printing in a discontinuous flow regime can be achieved in an acceptable time frame. Finally, research into mixing the food batter with food dye, the main focus of this work, has allowed four mixing-dispensing options to be recommended. These options could be applied in a number of ways, depending on goals of future research.

Research into pumping and metering of flow has allowed a number of recommendations to be made for future development. The static mixing test rig used time pressure dispensing and showed there are a number of problems with this setup. If the storage chamber was redesigned so that a floating piston could be used, a better result could be achieved. If more control is required, stepper motor driven syringe pumps could be used for all pumping/metering operations. This would most likely require more powerful motors and larger syringes. If even more control over dispensing is required, rotary screw extruders would provide high pressure controlled flow. This is a more expensive option with more difficult cleaning required.

With these recommendations, the following options combine the lessons learned into a number of paths that could be taken for future research.

Syringe Pump Driven - Static Mixed - Discontinuous Dispensing

If discontinuous flow is acceptable, the most feasible and achievable method of producing a working prototype colour food printer would be using five syringe pumps and a static mixer. Four would have food dyes in them (cyan, yellow, magenta and black) and the fifth syringe pump would have a white food batter. Each syringe pump should be able to generate enough pressure to force fluid through a static mixer at the desired operating flow rate. To achieve a good contrast ratio so that any image printed is clearly identifiable, image processing would most likely be necessary. This would be a relatively cheap solution that would provide a good base to work from. Additions like force/pressure feedback and regional colouring could be explored with this setup.

Plunger Driven – Static Mixed – Discontinuous Dispensing

The second option worth exploring if discontinuous flow is acceptable is a plunged static mixer. A static mixer would be used to mix the fluids in a voxel sized chamber connected on top of the static mixer. The fluids would be added preferably by syringe pumps and/or jetting heads depending on their viscosity, but would need to be evenly distributed axially throughout the chamber. A plunger would then force the fluids through the static mixer onto the printing surface. A release system to allow the plunger to be withdrawn without drawing excess mixture back out of the mixer would potentially be required.

Mixer Head Driven – Conical Surface Mixed – Discontinuous Dispensing

The third option, conical surface mixing, also requires discontinuous flow to be acceptable. This option is likely to only be feasible with a limited range of materials due to the nature of the mixing and extruding mechanism. The method used to place the fluids to be mixed into the conical recess is open to any method. It would again preferably be achieved by syringe pumps and/or jetting heads depending on the materials' viscosities. The conical mixer head then rotates within the conical recess causing the fluids to mix. Once the fluids are mixed, the conical mixer head is forced into the conical recess to extrude the mixture out a hole in the tip of the recess.

Pressure (compressed air or syringe pump) Driven – Static Mixed – Continuous dispensing

If continuous flow is required, the first option worth exploring would be a computer vision monitored gating system. The system would divert flow away from the printing surface until the desired colour is achieved when it would be routed to the printing surface. This would be a relatively cheap and simple solution. However, the flow that is diverted away while the colour is changing would have to be dealt with appropriately. Either it would have to be justifiable to waste that mixture (for a prototype this may be acceptable) or it would have to be recycled.

9.1 Computational Fluid Dynamics

Although it is outside the scope of this research, Computational Fluid Dynamics (CFD) is potentially highly relevant. This makes it prudent to consider its' impact with respect to food printing.

"The physical aspects of any fluid flow are governed by the following three fundamental principles: (1) mass is conserved; (2) F = ma (Newton's second law); and (3) energy is conserved" [106]. CFD is when these equations are applied to certain situations with set parameters and then advanced in space and/or time.

CFD has the power to provide many benefits in mixing research, but it's not a simple tool to use. CFD, along with experimental results, can be used to aid visualising flow paths, establishing residence time distribution, estimating the variation throughout the mixers and optimising design parameters [79]. However, to perform CFD analysis on static or agitated mixers would require a number of obstacles to be overcome. A computer software package would have to be purchased or open source software could be used. This would require determining what outcomes are expected from the software. Learning how to operate the software package would be the next challenge. Once the software was mastered, deciding all the input parameters and geometries would need to be completed [78]. Any results obtained using CFD would then have to be verified with functional testing as well. Due to time constraints and the field of study CFD is in, it has been reviewed but a decision has been made to not pursue the use of CFD in this current research. However, if future research was to be done by someone working in the area of process engineering, there are some important things that CFD could be used for this context.

1. Type of static mixer
2. Size and number of elements of static mixer
3. Disc profile for oscillating mixer
4. Height to width ratio of oscillating mixer chamber
5. Estimation of number of oscillations required to achieve desired mixing using the oscillating mixer

9.2 Model Representation Data Formats

Also outside the scope of this research, model representation data formats are also highly relevant for end user application. Considering relevant research can help guide future work so that a complete solution incorporating hardware and software can be achieved significantly more seamlessly.

A significant amount of research has been published with regard to computer modelling of 3D objects with variable composition. Three main techniques have been used to overcome this modelling challenge. The first technique uses mathematical equations to vary the composition of the material throughout the model [95]. Using a combination of orientation and gradients, Functionally Graded Materials (FGM) can be modelled effectively. The second technique adds colour functionality to the existing standard method of storing face information [57]. Each face is given colour information, whether it is a single colour, gradients, patterns or even bitmap images. The last technique uses regions with boundaries to enclose sections of the model with the same composition [34]. If this technique is used with every voxel assumed to be its own unique region, a voxel representation of a 3D model [22], [96]. A comprehensive examination of a number of different methods has been completed in [107].

10 References

[1] M. Nichols and K. Reagan, “Not by Bread Alone: America’s Culinary Heritage,” *Division of Rare & Manuscript Collections*, 2002. [Online]. Available: http://rmc.library.cornell.edu/food/default.htm. [Accessed: 15-Dec-2011].

[2] K. Herbes, “Dietary Trends, American,” *Diet.com*. [Online]. Available: http://diet.com/g/dietary-trends-american. [Accessed: 14-Dec-2011].

[3] R. Archer et al., “From the F-Files : Technofoods – printed with your choice of image!,” *Food New Zealand*, vol. 10, no. 4, pp. 20-21, 2010.

[4] “About - Charm City Cakes.” [Online]. Available: http://www.charmcitycakes.com/about. [Accessed: 17-Dec-2011].

[5] R. I. McIntosh, J. Matthews, G. Mullineux, and a. J. Medland, “Late customisation: issues of mass customisation in the food industry,” *International Journal of Production Research*, vol. 48, no. 6, pp. 1557-1574, Mar. 2010.

[6] J. B. German and H. J. Watzke, “Foods for Health and Delight,” *Comprehensive Reviews In Food Science And Food Safety*, vol. 3, no. 4, pp. 145-151, 2004.

[7] Z. Tang, R. Chen, and X. Ji, “Operational tactics and tenets of a new manufacturing paradigm ‘instant customerisation’,” *International Journal of Production Research*, vol. 43, no. 14, pp. 2873-2894, Jul. 2005.

[8] L. Hao, D. Raymond, G. Strano, and S. Dadbakhsh, “Enhancing the sustainability of additive manufacturing,” in *Responsive Manufacturing - Green Manufacturing (ICRM 2010), 5th International Conference on*, 2010, pp. 390-395.

[9] T. F. Wegrzyn, M. Golding, and R. H. Archer, “Food Layered Manufacturing: A new process for constructing solid foods,” *Trends in Food Science & Technology - Under Review*, 2011.

[10] N. Gray, “Looking to the future: Creating novel foods using 3D printing,” *Food Navigator*, 2010. [Online]. Available: http://www.foodnavigator.com/Science-Nutrition/Looking-to-the-future-Creating-novel-foods-using-3D-printing/?c=BI2vYOpnuau9XFIMenxeXA==&utm_source=newsletter_daily&utm_medium=email&utm_campaign=Newsletter+Daily. [Accessed: 13-Dec-2011].

[11] A. Vesco, H. Lipson, D. L. Cohen, J. I. Lipton, M. Cutler, and D. Coulter, “Hydrocolloid Printing: A Novel Platform for Customized Food Production,” in *Twentieth Annual International Solid Freeform Fabrication Symposium*, 2009, pp. 807-818.

[12] J. Lipton et al., “Multi-Material Food Printing with Complex Internal Structure Suitable for Conventional Post-Processing,” in *Twenty-First Annual International Solid Freeform Fabrication Symposium*, 2010, pp. 809-815.

[13] N. F. Kinzie, “Method and apparatus for constructing a three-dimensional surface of predetermined shape and color,” U.S. Patent 50153121991.

[14] J. Jang, “Process and apparatus for creating a colorful three-dimensional object,” U.S. Patent 6129872Oct-2000.

[15] J. Jang, W. C. Huang, and B. Z. Jang, “3-D color model making apparatus and process,” U.S. Patent 6165406Dec-2000.

[16] J. Yang, L. Wu, and J. Liu, “Method for rapidly making a 3-D food object,” U.S. Patent 6280784Aug-2001.

[17] J. Yang, L. Wu, and J. Liu, “Rapid prototyping and fabrication method for 3-D food objects,” U.S. Patent 6280785Aug-2001.

[18] E. M. Sachs, J. S. Haggerty, M. J. Cima, and P. A. Williams, “Three-dimensional printing techniques,” U.S. Patent 52040551993.

[19] E. M. Sachs, J. S. Haggerty, M. J. Cima, and P. A. Williams, “Three-dimensional printing techniques,” U.S. Patent 53406561994.

[20] M. Cima et al., “Three-dimensional printing techniques,” U.S. Patent 53873801995.

[21] J. Hiller and H. Lipson, "Design and analysis of digital materials for physical 3D voxel printing," *Rapid Prototyping Journal*, vol. 15, no. 2, pp. 137-149, 2009.

[22] V. Chandru, S. Manohar, and C. E. Prakash, "Voxel-based modeling for layered manufacturing," *Computer Graphics and Applications, IEEE*, vol. 15, no. 6, pp. 42-47, 1995.

[23] G. Ramsay, "FINK Printer, Part B," Massey University, 2009. (See Appendix)

[24] J. Pemberton, "FINK Printer, Part A," Massey University, 2009. (See Appendix)

[25] "Nanotek Instruments Inc." [Online]. Available: http://www.nanotekinstruments.com/index.htm. [Accessed: 22-Feb-2012].

[26] "Interview with Nico Kläber (Moléculaire) Electrolux Design Lab finalist | Electrolux Group." [Online]. Available: http://group.electrolux.com/en/interview-with-nico-klaber-moleculaire-electrolux-design-lab-finalist-2040/. [Accessed: 09-Feb-2012].

[27] "Electrolux Moléculaire 3D Molecular Food Printer by Nico Kläber» Yanko Design." [Online]. Available: http://www.yankodesign.com/2009/08/26/surreal-food-is-real-and-printed/. [Accessed: 16-May-2012].

[28] "Philips - Design Probes." [Online]. Available: http://www.design.philips.com/about/design/designportfolio/design_futures/design_probes/index.page. [Accessed: 22-Feb-2012].

[29] "Philips - Design Probes - image downloads - FOOD." [Online]. Available: http://www.design.philips.com/philips/sites/philipsdesign/about/design/designportfolio/design_futures/design_probes/downloads/food.page. [Accessed: 09-Feb-2012].

[30] A. Zoran and M. Coelho, "Cornucopia: The Concept of Digital Gastronomy," *Leonardo*, vol. 44, no. 5, pp. 425-431, 2011.

[31] "Cornucopia: Prototypes and Concept Designs for a Digital Gastronomy." [Online]. Available: http://web.media.mit.edu/~marcelo/cornucopia/. [Accessed: 23-Feb-2012].

[32] "3D Candy Printing: An Interview with Designer Marcelo Coelho - Lifestyle - GOOD." [Online]. Available: http://www.good.is/post/3d-candy-printing-an-interview-with-designer-marcelo-coelho/. [Accessed: 09-Feb-2012].

[33] J. I. Lipton et al., "Fab @ Home Model 2 : Towards Ubiquitous Personal Fabrication Devices," in *Solid Freeform Fabrication Symposium (SFF'09)*, 2009, no. 2, pp. 70-81.

[34] W. K. Chiu and S. T. Tan, "Multiple material objects: from CAD representation to data format for rapid prototyping," *Computer-Aided Design*, vol. 32, no. 12, pp. 707-717, Oct. 2000.

[35] "Main Page - Fab @ Home." [Online]. Available: http://www.fabathome.org/wiki. [Accessed: 16-May-2012].

[36] D. Periard, N. Schaal, M. Schaal, E. Malone, and H. Lipson, "Printing Food," in *Proceedings of the 18th Solid Freeform Fabrication Symposium*, 2007, pp. 564-574.

[37] "Fab@Home:Materials." [Online]. Available: http://www.fabathome.org/wiki/index.php/Fab@Home:Materials. [Accessed: 24-Feb-2012].

[38] "About Evil Mad Science." [Online]. Available: http://evilmadscience.com/about. [Accessed: 23-Feb-2012].

[39] "About Evil Mad Scientist Laboratories - Evil Mad Scientist Laboratories." [Online]. Available: http://www.evilmadscientist.com/staticpages/index.php/AboutEMSL. [Accessed: 24-Feb-2012].

[40] "Solid freeform fabrication: DIY, on the cheap, and made of pure sugar - Evil Mad Scientist Laboratories." [Online]. Available: http://www.evilmadscientist.com/article.php/candyfab. [Accessed: 09-Feb-2012].

[41] "CandyFabWiki." [Online]. Available: http://wiki.candyfab.org/Main_Page. [Accessed: 24-Feb-2012].

[42] N. Sewell, J. Henderson, M. Sloan, L. Hao, S. Mellor, and O. Seaman, “Extrusion behavior of chocolate for additive layer manufacturing,” in *Innovative Developments in Design and Manufacturing*, CRC Press, 2009.

[43] “Fabaroni: a homemade 3D printer.” [Online]. Available: http://fab.cba.mit.edu/classes/MIT/863.07/11.05/fabaroni/process.html. [Accessed: 11-Feb-2012].

[44] D. Southerland, P. Walters, and D. Huson, “Edible 3D Printing,” in *Digital Fabrication 2011 Conference, NIP 27, 27th International Conference on Digital Printing Technologies*, 2011, pp. 819-822.

[45] “Centre for Fine Print Research 3D Printing : Edible 3D Printing.” [Online]. Available: http://www.uwe.ac.uk/sca/research/cfpr/research/3D/research_projects/edible_3d_printing.html. [Accessed: 25-Feb-2012].

[46] “About Bits from Bytes.” [Online]. Available: http://www.bitsfrombytes.com/usd/content/about-bits-bytes. [Accessed: 25-Feb-2012].

[47] “RepRap - RepRapWiki.” [Online]. Available: http://reprap.org/wiki/Main_Page. [Accessed: 25-Feb-2012].

[48] “TNO Mission and Strategy.” [Online]. Available: http://www.tno.nl/content.cfm?context=overtno&content=overtno&item_id=30&Taal=2. [Accessed: 25-Feb-2012].

[49] K. V. Bommel, “The Future of Food.” 2010. [Online]. Available: http://www.earto.eu/fileadmin/content/10_Hidden_Pages/EUROTECH_2010/TNOfoodprocessingOct22010.pdf. [Accessed: 25-Aug-20].

[50] “FoodJet Printing.” [Online]. Available: http://foodjet.nl/index.html. [Accessed: 01-Apr-2012].

[51] M. C. Leu et al., “Freeze-Form Extrusion Fabrication of Composite Structures,” in *Solid Freeform Fabrication Symposium*, 2011, pp. 111-124.

[52] “Welcome to the MakerBot Wiki - MakerBot Industries.” [Online]. Available: http://wiki.makerbot.com/start. [Accessed: 29-Feb-2012].

[53] “Frostruder MK2 - MakerBot Industries.” [Online]. Available: http://wiki.makerbot.com/frostruder-mk2. [Accessed: 29-Feb-2012].

[54] “Food ingredients - Hawkins Watts New Zealand - Products - Hydrocolloids - Xanthan.” [Online]. Available: http://www.hawkinswatts.com/prod_stabs12.htm. [Accessed: 16-Jan-2012].

[55] R. P. Chhabra and J. F. Richardson, *Non-Newtonian Flow and Applied Rheology: Engineering Applications*, 2nd ed. Elsevier, 2008.

[56] R. R. Hemrajani and G. B. Tatterson, *Handbook of Industrial Mixing: Science and Practice*, vol. 8, no. 3. John Wiley & Sons, Inc, 2004, pp. 345-390.

[57] L. W. Ming and I. Gibson, “Specification of VRML in Color Rapid Prototyping,” *International Journal of CAD/CAM*, vol. 1, no. 1, pp. 1-9, 2002.

[58] S. Kim, M. Golding, and R. Archer, “Matching target colours in a food system using the Allen colorimetric algorithm,” in *AIC 2010 Color and Food, Interim Meeting of the International Color Association*, 2010, no. Berns 2000, pp. 104-107.

[59] C. K. Chua, K. F. Leong, and C. S. Lim, *Rapid Prototyping: Principles and Applications*, 3rd ed. World Scientific, 2010, p. 512.

[60] S. Crump, “The extrusion of fused deposition modeling,” in *Proc. 3rd Int. Conf. Rapid Prototyping*, 1992, pp. 91-100.

[61] “3D wax printers for lost wax investment casting | Solidscape.” [Online]. Available: http://www.solid-scape.com/products/solidscape-3d-wax-printers. [Accessed: 06-Jul-2012].

[62] “3D Systems Unveils its Plan to Launch the InVision LD 3-D Printer — a New Affordable Desk-Top 3-D Printer,” 2005.

[63] "MultiJet-Modeling (MJM)." [Online]. Available: http://www.3d-labs.de/en/products/multijet-modeling-mjm. [Accessed: 06-Jul-2012].

[64] A. Kamrani and E. A. Nasr, Eds., *Rapid Prototyping Theory and Practice*. Springer, 2006.

[65] Roland DGA Corporation, "Rapid Prototyping Technologies | Rapid Prototyping Machines | RP Solutions | Roland DGA." [Online]. Available: http://www.rolanddga.com/solutions/rapidPrototyping/. [Accessed: 18-May-2012].

[66] Z. Corporation, "3D Printing White Paper," 2006. [Online]. Available: http://zcorp.com/documents/108_3d printing white paper final.pdf. [Accessed: 06-Jul-2012].

[67] "From CAD to Cast in Hours - ProMetal." [Online]. Available: http://www.prometal-rct.com/eng/process.html. [Accessed: 06-Jul-2012].

[68] D. C. . Monkhouse, C.-C. Wang, and C. W. . Rowe, "TheriForm Technology," in *Modified-Release Drug Delivery Technology*, 2002, pp. 77–87.

[69] M. Greulich, M. Greul, and T. Pintat, "Fast, functional prototypes via multiphase jet solidification," *Rapid Prototyping Journal*, vol. 1, no. 1, pp. 20-25, 1995.

[70] "EnvisionTEC 3D-Bioplotter." [Online]. Available: http://www.envisiontec.de/index.php?page=machines&id=41. [Accessed: 06-Jul-2012].

[71] R. Landers, U. Hübner, R. Schmelzeisen, and R. Mülhaupt, "Rapid prototyping of scaffolds derived from thermoreversible hydrogels and tailored for applications in tissue engineering.," *Biomaterials*, vol. 23, no. 23, pp. 4437-4447, 2002.

[72] W. Zhang, M. C. Leu, Z. Ji, and Y. Yan, "Rapid freezing prototyping with water," *Control*, pp. 139-145, 1999.

[73] R. P. Chhabra, "Fluid Mechanics and Heat Transfer with Non-Newtonian Liquids in Mechanically Agitated Vessels," *Advances in Heat Transfer*, vol. 37, no. C, pp. 77-178, 2003.

[74] "Rubber Processing." [Online]. Available: http://www.bouncing-balls.com/chemistry_tech_conservation/rubprocess.htm. [Accessed: 22-May-2012].

[75] R. Thakur, C. Vial, K. Nigam, E. Nauman, and G. Djelveh, "Static Mixers in the Process Industries—A Review," *Chemical Engineering Research and Design*, vol. 81, no. 7, pp. 787-826, 2003.

[76] K. J. Myers, A. Bakker, and D. Ryan, "Avoid Agitation by Selecting Static Mixers," *Chemical Engineering Progress*, vol. 93, no. 6, pp. 28-38, 1997.

[77] A. Bertsch, S. Heimgartner, P. Cousseau, and P. Renaud, "3D micromixers-downscaling large scale industrial static mixers," in *Micro Electro Mechanical Systems, 2001. MEMS 2001. The 14th IEEE International Conference on*, 2001, pp. 507-510.

[78] A. Bakker, R. D. Laroche, and E. M. Marshall, "Laminar Flow in Static Mixers with Helical Elements," *The Online CFM Book*, 2000.

[79] O. Byrde and M. . Sawley, "Optimization of a Kenics static mixer for non-creeping flow conditions," *Chemical Engineering Journal*, vol. 72, no. 2, pp. 163-169, Feb. 1999.

[80] M. K. Singh, P. D. Anderson, and H. E. H. Meijer, "Understanding and Optimizing the SMX Static Mixer.," *Macromolecular rapid communications*, vol. 30, no. 4–5, pp. 362-76, Feb. 2009.

[81] B. Deuser, L. Tang, J. Geldmeier, R. G. Landers, and M. C. Leu, "Process Planning and Control for Functionally Graded Material Fabrication Using Freeze-Form Extrusion Fabrication," in *Solid Freeform Fabrication Symposium*, 2011, pp. 415-426.

[82] J. M. Zalc, E. S. Szalai, and F. J. Muzzio, "Mixing dynamics in the SMX static mixer as a function of injection location and flow ratio," *Polymer Engineering & Science*, vol. 43, no. 4, pp. 875-890, Apr. 2003.

[83] D. Jin, D., Fu, H.-L., Wu, J.-H. , Sun, “Analysis for the effect of factors on residence time distribution in kenics static mixer,” *Shiyou Huagong Gaodeng Xuexiao Xuebao/Journal of Petrochemical Universities*, vol. 24, no. 3, pp. 70-74, 2011.

[84] A. E. Karr, “Performance of a reciprocating-plate extraction column,” *AIChE Journal*, vol. 5, no. 4, pp. 446-452, 1959.

[85] Y. Komoda, Y. Inoue, and Y. Hirata, “Mixing Performance by Reciprocating Disk in Cylindrical Vessel,” *Journal of Chemical Engineering of Japan*, vol. 33, no. 6, pp. 879-885, 2000.

[86] X. Ni, M. Mackley, A. Harvey, P. Stonestreet, M. Baird, and N. Ramarao, “Mixing Through Oscillations and Pulsations - A Guide to Achieving Process Enhancements in the Chemical and Process Industries,” *Chemical Engineering Research and Design*, vol. 81, no. 3, pp. 373-383, Mar. 2003.

[87] Y. Hirata, T. Dote, T. Yoshioka, Y. Komoda, and Y. Inoue, “Performance of Chaotic Mixing Caused by Reciprocating a Disk in a Cylindrical Vessel,” *Chemical Engineering Research and Design*, vol. 85, no. 5, pp. 576-582, 2007.

[88] L. Nelik, R. A. Platt, C. W. J. Little, T. Dahl, and V. Patel, *Pump Handbook*, 4th ed., vol. 22, no. 6. McGraw-Hill, 2008.

[89] L. Coucoulas, *Pump selection guide for food industry applications*. Leatherhead Food R.A., 1997, p. 79.

[90] X. B. Chen, W. J. Zhang, G. Schoenau, and B. Surgenor, “Off-Line Control of Time-Pressure Dispensing Processes for Electronics Packaging,” *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 26, no. 4, pp. 286-293, 2003.

[91] L. Jianping and D. Guiling, “Technology development and basic theory study of fluid dispensing - a review,” in *High Density Microsystem Design and Packaging and Component Failure Analysis, 2004. HDP ’04. Proceeding of the Sixth IEEE CPMT Conference on*, 2004, pp. 198-205.

[92] B. Li, P. A. Clark, and K. H. Church, “Robust Printing and Dispensing Solutions with Three Sigma Volumetric Control for 21st Century Manufacturing and Packaging,” in *Materials Research Society - Symposium N – Printing Methods for Electronics, Photonics and Biomaterials*, 2007, pp. 1-7.

[93] M. S. Mason, T. Huang, R. G. Landers, M. C. Leu, and G. E. Hilmas, “Aqueous-based extrusion of high solids loading ceramic pastes: Process modeling and control,” *Journal of Materials Processing Technology*, vol. 209, no. 6, pp. 2946-2957, Mar. 2009.

[94] “Dispensing Accessories.” [Online]. Available: http://www.fisnar.com/accessories_barrels. [Accessed: 17-Feb-2012].

[95] J. Y. Hascoet, P. Muller, and P. Mognol, “Manufacturing of Complex Parts with Continuous Functionally Graded Materials (FGM),” in *Solid Freeform Fabrication Symposium*, 2011, pp. 557-569.

[96] G. E. Knoppers, J. Dijkstra, and W. P. V. Vliet, “The design of graded material objects,” in *RM-Platform #02*, 2006.

[97] H. Isidore, “Plunger type cartridge mixer for fluent materials,” U.S. Patent 4676655Jun-1987.

[98] J. Yao, “Measurements of human vision contrast sensitivity to opposite colors using a cathode ray tube display,” *Chinese Science Bulletin*, vol. 56, no. 23, pp. 2425-2432, Jul. 2011.

[99] K. T. Mullen, “The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings,” *Journal of Physiology*, no. 359, pp. 381-400, 1985.

[100] B. Wandell, J. Hall, and L. D. Silverstein, “Digital Color Reproduction,” in *The Science of Color*, 2nd ed., S. K. Shevell, Ed. Elsevier Ltd, 2003, pp. 281-316.

[101] L. Ming and I. Gibson, “Experimental investigation of ink on powder used for selective laser sintering,” *Journal of Materials Processing Technology*, vol. 174, no. 1–3, pp. 91-101, May 2006.

[102] “Fixed Start Open Traveling Salesman Problem - Genetic Algorithm - File Exchange - MATLAB Central.” [Online]. Available: http://www.mathworks.com/matlabcentral/fileexchange/21198. [Accessed: 28-Jan-2012].

[103] F. Elie-Michel, “Evaluation of a test system for mixing high-viscosity food pastes,” Massey University, 2011.

[104] J. de Vicente, J. R. Stokes, and H. a. Spikes, “Soft lubrication of model hydrocolloids,” *Food Hydrocolloids*, vol. 20, no. 4, pp. 483-491, Jun. 2006.

[105] J.-P. Homann, “Color Theory with Realistic Colors,” in *Digital Color Management*, Springer Berlin Heidelberg, 2009, pp. 32-57.

[106] J. F. Wendt et al., *Computational Fluid Dynamics*, 3rd ed. Springer, 2008, p. 5.

[107] T. R. Jackson, “Analysis of Functionally Graded Material Object Representation Methods,” Massachusetts Institute of Technology, 2000.

11 Appendix (On CD)

Please refer to accompanying CD for appendix contents.