MDI

Investigation into integration of digital manufacturing
with ceramics

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ABSTRACT

Within the territory of crafts, it has long been thought that individuals' proficiency and adeptness, which take long to attain or are presumably innate abilities, determine the quality, delicacy and value of the products, and the common perception has often acted as a barrier to accessibility and penetration. It is more apparent in the pottery and ceramics where special equipment and facilities, such as wheels and kilns, in addition to skilfulness and dexterity are considered essential for creation. Advances in digital technology represented by 3D printing, however, are changing the way objects are designed, produced and distributed, instigating attempts to view traditional crafting processes and practices from a different perspective. Among various branches of crafts, this research specifically explores introduction of digital technology to pottery and challenges the limitations that the conventional methods have, by eliminating the hardware restrictions and lowering the barriers. The outcome offers not only transcendent possibilities of creation to craftspeople and artists but also unprecedented accessibility and apprehensible process to the public. Technically, Liquid Deposition Modelling (LDM) building upon material optimisation and tool redesign was employed in conjunction with digital design process. In addition, functional additives were trialled to incorporate multilevel translucency and electrical conductivity into the new types of ceramic objects.

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RODUCTION

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INTRODUCTION

This research seeks to expand design knowledge through an iterative process of exploration.

It examines the traditional production of ceramics and the use of clays and will investigate how these can be implemented and integrated with emerging digital technology. Digital technology such as 3D printing represents a powerful tool for product designers as well as a paradigm shift for manufacturing across a range of industries.

Designed objects have always been heavily influenced and constrained by the method used in producing them. This has always been acknowledged in the pottery and ceramics industry where makers are heavily limited by their own hand crafting skills, which can take many years to develop. The limitations of the production process whether its hand turning or molding greatly influence the ability to innovate with ceramics. Because of this, developing new techniques or uses for the material has been something only possible by expert artisans with a lifetime of experience in the craft. This has prevented any major breakthroughs or advancements in this field until now. With rapid advances in 3D printing technology expanding the material opportunities it is changing the way many industries view traditional manufacturing and creation processes (Lipson & Kurman, 2013). Digital tools now lower the barrier to entry for these materials to make it possible for designers to access and control them.

This research paper aims to challenge the perception people have surrounding the way we look at ceramic objects, what they can be used for and the way they are produced through the use of new digital technology. Material exploration was carried out in order to optimise it for the Liquid Deposit Modeling (LDM) printing process. This helped further align the material with the digital process, showcasing properties and functions that are not possible through any other means of production. Finally this thesis suggests scenarios where the introduction of digital technologies such as multi-property 3D printing can allow for new manufacturing opportunities for functional object (Barnatt, 2014).

BACKGROUND

Ceramics is one of the most ancient industries on the planet (Rice, 2015). Once humans discovered that clay could be dug up and formed into objects by first mixing with water and then firing, the industry was born.

Pottery is our oldest handicraft (Rice, 2015). It is believed that in prehistoric times water was carried in woven baskets lined with clay from the rivers where they collected. Once all the water was poured out of the container the layer of clay would dry and shrink separating from the sides of the basket. The dry clay would now be shaped like a pot and could be removed and dried in the sun. It was then discovered that they could harden the molded pottery in hot ashes and make sturdy containers to transport and store food. From these would have been extended the pots formed by hand and decorated with crude tools (Lakeside Pottery, 2017).

From a very early date in history people in many parts of the world produced earthenware ceramics on a mass scale. In Egypt kilns were constructed to place clay pots in for firing, they were insulated with a brick made from a straw and clay mixture that had been dried in the sun. Later, finer clay was used with a much higher quartz content for their delicate pottery, pieces would be rubbed with smooth stones to give them a surface sheen or a coating with a different colour of clay.

With further development the Egyptians were able to produce an early form of glaze to coat porous containers, composing of quartz, soda, and a mineral containing copper. When fired the green substance would coat the objects with a glass like surface. Experts estimate that it was not until 1500 BC that glass was produced independently of ceramics and fashioned into separate items (De Guire, 2014).

Around the middle of the thirteenth century German potters started to produce stoneware. This type of pottery was made from a much finer clay that could be fired at a much higher temperature. Unlike earthenware clay stoneware is not porous so it does not require a glaze coating to seal it.

Light, transparent porcelain was first produced in China. Porcelain was made from a very plastic

and pure clay called kaolin mixed with feldspar. The colourful decoration of the porcelain was accomplished by firing each colour individually after it was applied. These delicate china dishes and figurines were in demand all over Europe. In their efforts to unravel the secret of the composition of the Chinese porcelain, European and other Asian potters developed many variations in their glazing techniques (De Guire, 2014).

Despite advancements in materials and processes that are used with ceramics improving there has still yet to be a major technological or digital advancement in the industry. The pottery industry is still largely dominated by handcraft but with rapid development in digital manufacturing technology designers and artists are beginning to look at ways these can be adapted to process ceramics.

MATERIALS

Clays & Ceramics

Clay is made up of the finest particles of rock eroded by wind and rain. Historically most clay-based materials are composed primarily of alumina (Al_2O_3) and silica (SiO_2) (Rice, 2015). These particles are carried off by running water and gather at the bottom of rivers or streams where they stick together and are compacted. Clay can be found almost everywhere and it is cheap. It has several transitional states; it is squishy and elastic when it is wet, and you can make any shape you like. When it dries slightly it becomes the consistency of chocolate and can be carved or scraped. It dries quickly depending on its thickness and the humidity, as the water evaporates out into a brittle state. At this point, it can be made soft again by getting it wet. So whatever shape the clay is made, it will not be permanent until it is heated to high temperatures.

When a potter is researching which type of clay is appropriate for their application there are many factors that need to be considered including the end product, cost and skill level. There can also be other technical factors involved in the decision including what type of clay they have access to and its temperature limits, each clay has a specific temperature range. It is not uncommon to need more than one variety of clay to achieve multiple construction methods such as a potter's wheel or hand building.

The three most commonly used clay bodies are earthenware, mid-fire stoneware and high-fire porcelain.

Earthenware

Earthenware clays are the oldest known to ancient potters and it is the most common naturally found. These clays are highly plastic easy to work with. Earthenware clays contain iron and other mineral impurities, which cause the clay to reach its optimum hardness at lower temperatures (between 950 °C and 1100 °C). The result is softer, unvitrified (not turned into glass) yielding porous ceramic that is not watertight, this also enable the piece to be stained easily. Earthenware clay is generally more forgiving than finer particle clays and is therefore more suitable for beginners, along with its low shrinkage factor. Earthenware clay is used primarily for bricks, tiles and planting products, this type of clay will not be well suited for vessels that hold liquids unless it is glazed. Typical colours for most earthenware clays are red, orange, yellow, and light grey.

Porcelain

Porcelain clay is used for high-quality ware including laboratory equipment. Porcelain and kaolin clays are virtually identical and are considered the best clays available for making pottery. They are a largely silicate clay and are resistant to high temperatures. If you want to make high-quality ware, then this type of clay is best for you. The pottery will likely be white or pale in colour unless you buy clay that has been mixed with iron oxide to make it redder.

Because it's composed of such tiny particles, porcelain offers optimum qualities of smoothness, and can be manipulated even when extremely thin to achieve translucent, delicate forms. However, it is difficult to work with during the throwing stage because of its low plasticity. It cracks and deforms easily during the drying and firing stages, because its optimum density isn't achieved until nearly the melting point of the clay.

Ceramic

Ceramic is heat-resistant, non-metallic, insulators (does not conduct electricity), corrosion-resistant, hard, but brittle (like glass), inorganic solids made out of clay that has been fired to high temperature. Once the clay is fired to high temperature, its chemical composition permanently changes and becomes ceramic which will never dissolve in water again. Anything that is made from fired clay is ceramic including tableware, pots, ovenware, brick, tile, roof tile, bathroom fixtures (e.g., sinks), etc. The following terms all fall under ceramic: Pottery, china, porcelain, stoneware, and earthenware ("What is Ceramic", N.D.).

TECHNOLOGY

3D printing

3D printing separates itself from other manufacturing techniques by being an additive process as it uses only the material needed for the final object in the building process. Digitally-driven additive processes define the term “rapid prototyping”. Applying cross-sectional data from a CAD model, rapid prototyping systems build three-dimensional objects layer-by-layer. Results are fast as well as accurate, this also differs from other subtractive technologies, where the process of building an object is severely linked to cutting, molding, or other manipulation of raw materials (Campbell, Williams, Ivanova, Garrett, 2011). Applications vary from conceptual visualisation to the functional analysis, depending on the system type and material used. The following are the most common types of 3D printing.

Stereolithography (SLA)

Widely used for visualising design concepts, SLA enables users to construct complex, three-dimensional models one layer at a time. During operation, an ultraviolet laser, driven by successive slices of the CAD model, systematically solidifies a photopolymer resin. Developed by 3D Systems in 1984, Inc. (2017), SLA accommodates a wide range of photopolymer materials to approximate the characteristics of thermoplastics like polypropylene, polyethylene, nylon, ABS and even ceramics with porcelain impregnated resin (Dimitrov, Schreve, & De Beer, 2006).

Selective laser sintering (SLS)

SLS creates three-dimensional objects from powdered materials, including plastics and metals for a wide latitude of material properties. Driven from a CAD part heat from a CO₂ laser fuses or sinters the powder layer-by-layer within a strictly controlled environment chamber. This method was first introduced by DTM Corp in the mid-1980s (2012), SLS offers parts that are suitable for functional analysis and prototype applications (Dimitrov, Schreve, & De Beer, 2006).

Fused Deposition Modelling (FDM)

Developed and manufactured by Stratasys, Inc. in 1989 (2017), FDM offers functional plastic prototypes with materials such as ABS, polycarbonate and other thermoplastic materials. Extruded as a semi-molten filament, these thermoplastics are deposited layer-by-layer to construct a 3D object based of the 3D CAD data (Bak, 2003). FDM printers generally do not require any controlled built environment or post processing on parts they produce making them the most common type of printer used by designers and maker. The simple design of this style of printer and their relatively low cost makes them the perfect platform for hobbyists to hack and modify. Due to FDM printers unique method of depositing material it also makes this one of the only styles of printing that allows for a multi-material/ duel-extruder setup. Finally the accessibility to a wide range of materials compatible with FDM printers makes them the most popular choice adopted.

Liquid Deposition Modeling (LDM)

LDM extrusion is a recent branch off FDM printing that replaces the thermal print head and extrusion system with a syringe and plunger. This technology can be used to print with any paste-like material that can be pushed out of a syringe; materials typically used are silicone, concrete, clay and edible materials like chocolate, cheese and dough.

AIMS AND OBJECTIVES

First Aim

Background research/ precedent analysis: This stage is to explore the potential of 3D printing within the field of ceramics.

- Identify the possibilities presented by previous designers in the field of 3D printed ceramics and clays. This objective was largely be completed through an in depth literature review and precedent analysis of the current design space within the field. This method is used to develop a broader scope of all the design work that has been carried out and helps solidify connections between concepts. A literature review can also help organise the material by research categories. For example the literature in this thesis has been largely categorised by the type of digital technology manufacturing process the designer used in their work.
- Develop a strategy to investigate how digital manufacturing processes can achieve a dramatic change to the way we look at manufactured ceramic objects. This objective has been completed with the use of Research Through Design (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146) this approach utilised the entire range of skills at a designers disposal, sketching, iterative ideation, CAD modeling and prototyping. This method was utilised for the majority of the design section, moving through the iterative process of techniques to develop the final solution.
- Test and identify which materials and machine setup will allow me to achieve desired properties in the later stages of development. This stage was also carried out with the use of Research Through Design (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146) more specifically the technique that was utilised within this method was prototyping (Houde & Hill, 1997). Prototyping is the tangible creation of artifacts at various levels of resolution, for development and testing of ideas within the design process (Martin & Hanington, 2012, p. 138). This stage encompassed creating a series of tests looking at various materials and their compositions. Creating test rigs of syringe extruders to measure their ability to be extruded also tested this. Low-fidelity prototypes are effective at generating fast results while high-fidelity prototypes are used to test more complex or crucial sections of the process.

Second Aim

To design and print a series of lighting devices that express a range of properties only achievable through the use of digital technology. Two of these objectives were:

- Further investigate different properties that can be applied to clay and ceramic material to help align it with the digital process as well as its use in lighting design. This stage continues to follow the Research Through Design (Martin & Hanington, 2012, p. 146) process but has a heavier focus on evaluating the tests based on the overall goal of the objective. As the information gathered from this objective directly informs the objects created in the next stage it is important to critically evaluate all the work produced. Evaluative or evaluation research attempts to gauge expectations against the designed artefact in question, determining whether something is useful, usable, and desirable. (Martin & Hanington, 2012, p. 74)
- Test the ability of multi material 3D printing to allow for advancements in the production of lighting design. As Research Through Design (Martin & Hanington, 2012, p. 146) was used as the core approach for the second half of the thesis, it was used to complete the final objective as well. This stage involved sketching, iterative idea generation and prototyping, resulting in the creation of a final series of high-fidelity prototypes. This final series has been evaluated against the guidelines and standards put in place for the previous objectives and from the findings of the literature review. These criteria include:
 - Designs should explore the range of qualities and capabilities only possible with digital manufacturing.
 - Designs should explore a visually consistent look between each other.
 - Designs should exploit unique qualities associated with 3D printing in order to diffuse light.
 - Designs will elicit intrigue as to how they have been constructed and function.

TERMINOLOGY

Traditional Craft

Traditional craft refers to the skill of doing or making something either completely by hand, or with the help of hand tools, as long as the direct manual contribution of the artisan remains the most substantial component of the finished product (“Crafts and Design”, 2017). The craftsman relates to a person or artisan who practices a particular craft at the highest level and develops their skills in workmanship. David Pye interprets “craftsmanship as a workman using any kind of technique and apparatus, in which the quality is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works.” (Pye, 1968, p.20). The idea being that the quality of the result is constantly at risk during the making process.

Digital Manufacturing

Digital manufacturing can be defined as an integrated approach to manufacturing that is centered around a computer system. This system comprises of three-dimensional (3D) visualisation, analytics and various collaboration tools to create product and manufacturing process definitions simultaneously ("Digital Manufacturing", 2017).

A machine is able to read a computer aided design (CAD) file in order to produce it as a physical object through either an additive or subtractive process (Sculpteo, 2017).

This method is able to rapidly deliver a prototype in just a few hours, with this same process it is possible to design, produce and fabricate molds for production.

Computer numerical control (CNC) technology is crucial in digital manufacturing as it not only enables mass production and flexibility, but it also provides a link between a CAD model and physical production.

Digital Craft

The term 'Digital Craft' is commonly applied in the context of craft with the aid of digital technology and manufacturing processes. The digital comes from the use of computer aided Design (CAD) software which becomes the tool for producing a model in virtual space and also produces the tool path that the Computer Numeric Control (CNC) machine will follow to create the model. This form of craft differs from traditional craft in the notion that with the use of CNC machines the craftsman may not even touch the work piece until it is finished which makes the craft aspect more rooted in the relationship between materials, tools and techniques as an intricate workflow (Loh, Burry, & Wagenfeld, 2016).

An object produced by a machine using this method has a unique imprint left on it, unique to its form of production, tool and tool path. The ability to understand and control this process is a skill that comes from an understanding of the digital tool and using the machines vast array of possibilities.

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PRECED

ENT REVIEW

LITERATURE & DESIGN REVIEW

3D printing has been broadcasted as a manufacturing technique capable of achieving feats out of the reach of any other traditional manufacturing procedure such as molding or casting. Designing for LDM extrusion 3D printing of ceramics has been guided by the possibilities and limitations of the technology. 3D printing lets one manufacture many different forms, textures and colours that otherwise would not be possible through traditional manufacturing means. The limitations associated with the traditional production of ceramics restrict creators and designers as to what they can make. Particular skills can take many years to master and some things are just simply impossible without the assistance of digital technology. Users are now able to design with and manipulate materials like ceramics and composites to create beautiful objects that would otherwise have simply been impossible without the assistance of digital technology. Developing a 3D printing process for a wider range of materials like ceramics and clays allows artists and designers to explore with materials that previously would have only been utilised by expert crafts people with many years of experience. Now with this technology artists and designers have access to produce fine and fragile ceramic objects as well as working in clay to present practical possibilities for ceramic artists.

Several projects have formulated ways to produce ceramic objects from a digital manufacturing process. The most common ways are extrusion-based 3D printing due to the accessibility to the technology, parts and open source platforms they run off. This Type of printing is fused deposition modelling (FDM), it works in an “additive” process by laying down material in layers, building a three-dimensional object incrementally. Extruded ceramics were first seen through the project L’artisan Electronique by Unfold (2010). This project involved participants by having them directly interact with the exhibition. The device creates pots from rolls of clay in response to movements of visitors hands through a sensor, almost mimicking the movement of a potters hands as they are shaping a piece on a pottery wheel as seen in figure 2.1. The digital potter’s wheel is connected to a FDM based 3D ceramic printer. As the virtual cylinder form spins on a monitor on front of the participant, they are able to make cuts away at the shape by passing his or her hand through a laser. When the user is finished sculpting away at their final form they can submit the customised model to a digital archive, which then supplies the 3D printer with instructions to physically produce the form. Finally, the printer traces the desired shape, layer by layer, in a process similar to coiling.

Other forms of printers have been used to tackle the challenge of 3D printing with ceramics, other technologies that have been used are selective laser sintering (SLS) of ceramic powder (Bertrand, Bayle, Combe, Gœuriot, & Smurov, 2007) and stereolithography apparatus (SLA). These techniques differs from FDM printing in the way that is does not deposit material but instead uses a laser to sinter powder material (liquid material in the case of SLA) in incremental layers, producing a three-dimensional object. This form of printing technology is the oldest, It's a technique that uses a laser as the power source to sinter powdered material, aiming the laser automatically at points in space defined by a digital 3D model, binding the material together to create a solid structure. This technology is typically used with metals and plastic powder, however Z Corp was one of the pioneers of Ceramic SLS 3D printing (Eden, 2013). 3D Printed parts made using SLS can achieve so called impossible geometric shapes and patterns due to the way they are supported in powder during their production. Nonetheless powder printing has a fragile green state before firing and coarse texture that prevents working with intricacy and detail. These objects also face the issue of tending to shirk inside the kiln during firing. An example of a company utilising this type of technology is the Belgium-based online service i.materialise (2017). It 3D prints ceramics models from an alumina-silica ceramic powder sealed with porcelain and silica as seen in figure 2.3 and 2.4. A lead-free, non-toxic glaze is applied for extra shine and durability and can give models a wide variety of vibrant colours.

fig. 2.2

fig. 2.3

fig. 2.4

Designers have recently been able to utilise for the production of 3D printed ceramics is SLA printing. However similar to SLS printing these machines are high end and are far outside the grasps of consumers (Bak, 2003). This method has only recently gained traction with the introduction of the Kickstarter project Porcelite by Tethon3D (2016). The product they released in early 2016 is a ceramic-based photo resin for use in SLA or DLP 3D printers. Objects produced from the printer are a solid ceramic composite. It is not until the object is fired in a kiln that Porcelite transforms to a 100% porcelain object suitable for glazing or other post processing treatment. Shortly after the release of this product the design studio Nervous systems (2016) began working with the resin on one of their form 2 DLP/SLS printers. The first set of designs for the material was a series of cups surrounded by intricate cellular networks on their outer surface as seen in figure 2.5. Due to the nature of porcelain in a lattice structure the cup remains cool to the touch when hot liquid is contained within. SLA is one of the smoothest and most detailed 3D printing methods (Bak, 2003), allowing nervous systems to freely explore a wide range of generative cell structures similar to other designs they are known for, complex parts that cannot be produced by traditional methods. This project was very successful in exploring designs that really required the use of 3D printing and would be nearly impossible to make any other way, even by hand. These shapes are not only beautiful and functional, but are also self-supporting for both the printing and firing processes. Nervous systems even explained how they had attempted to design a series of cups previously playing with a similar idea of using texture and patterning to create a heat sink for insulation properties. However they were very limited in their exploration due to the constraints of casting. The main constraints of printing ceramics with this process is the relatively low print volume, being that it is not very large and must accommodate supports and material shrinkage, leaving you with a low maximum build height. There are other high-end SLA printers capable for producing ceramics, but nothing accessible at a consumer level (Dehurtevent, Robberecht, Hornez, Thuault, Deveau, & Béhin, 2017) (Chia & Wu, 2015).

fig. 2.5

fig. 2.6

Another early adopter of ceramic FDM printing is Olivier Van Herpt, his work on projects such as “solid vibrations” (2015) and “functional 3D printed ceramics” (2012) explore a number of different methods for printing as well as different types of clays and colour combinations. Olivier’s interest in ceramics stemmed from the limitations of regular 3D printers not being able to handle heat resistant or food safe materials, and also their ability to print medium and large human scale objects. To produce his collection Olivier had to design and build his own extruder capable of working with unmodified hard clay. Olivier’s first ceramic project in 2012-2013 simply explored the possibilities and limitations of the technology with this material, with the aim to be able to produce a range of fine and fragile objects. On the project “solid vibrations” Olivier worked with sound designer Ricky van Broekhoven his projects often revolve around landscapes of noise that live briefly in the mind. The project aimed to combine the temporary nature of sound in his work with 3D Printing so that the noisescapes could become things. A song or a sound that would previously be a moment in time could be encapsulated in a tangible, physical object through its vibrations being turned into shapes and patterns by the 3D Printer. Olivier achieved this unique effect by mounting a specially constructed speaker rig below the build platform of the 3D printer that would produce very low sound throughout the printing process, the sound would amplify and create Moiré patterns on the object as it was being printed. Olivier’s project has proven to be a successful example of an innovative approach to 3D printing ceramics due to the way he exploited digital technology to produce unique patterning on his object that would be impossible to achieve through any other means of production. Previously Olivier had noted that the printer produced Moiré patterns naturally due to the vibrations in the printer while the build platform is moving. Rather than modifying the printer to try and mitigate this error he exploited it to create a compelling effect.

fig. 2.7

fig. 2.8

fig. 2.9

fig. 2.10

fig. 2.11

Digital technology and 3D printing also allow for objects to be produced with multiple materials with different properties in a single print job. However the multi material process being an emergent field within 3D printing should not be misconstrued as a generic process that can amalgamate any two materials in any combination. The current state the process is in is very restrictive with the number and types of materials that can be used. Currently very few of the 3D printing processes are capable of multi material printing, jetting processes and filament deposition processes are suited to using multiple materials in a single job. The simplest and by far the most common way to utilise multi-material 3D printing is by fitting additional extruders to a desktop filament 3D printer. This is a simple yet effective way of combining different materials within a single print, however it does not mix the materials. Mixing the material in different ratios and combinations is an important differentiator, which is only achievable through a multi cartridge jetting process. The jetting process mixes liquid resins during the printing process to produce multiple materials within the spectrum of the base materials. Designing for multi-material printing requires an in depth knowledge of the materials at your disposal, as well as an understanding of how different combinations of distinct materials will interact with one another (Chua & Leong, 2015). While there is a great deal of research underway that points to future developments, in order to expand 3D printing and making it more versatile. New processes are needed that are able to deposit a broader range of materials such as ceramics and composites but these options are still far from commercialisation (Ready, Whiting, & Ng, 2014).

fig. 2.12

fig. 2.13

While all these previous projects use vastly different technologies and influences one thing they all have in common is the object produced are all vessels. While this does pay homage to the historic use of the material it is interesting as 3D printing in theory is not limited to one type of object in the same way the traditional manufacturing processes were. All of these projects certainly add elements only possible with the aid of digital technology, however they do not explore new possibilities for the material. The lack of exploration in this area is likely due to the technology of ceramic printers being in their infancy and many designers and artists have not yet had an opportunity to work with them. However as ceramic printers share a lot of similarities and limitations with regular thermal plastic extruding 3D printers such as the types of geometries they can produce and as they have been available and extremely accessible for many years now there has been far more exploration carried out in this area. These projects can be used as a precedent for what can be achieved with some development. One avenue that designers have explored with regular 3D printing is into lighting design, focusing on the generation of new patterns and forms that are too difficult or even impossible for traditional manufacturing techniques to achieve. This direction has not yet been explored with any form of ceramic printing. For example a lighting project that utilises the unique nature and properties of 3D printing is Alex Buckman's "canopy" light diffuses (2014). This series that Buckman developed are low power LED bulbs that are housed by 3D printed diffusers, which take on organic forms made up of fractal patterns. The unique fractal geometries are found throughout nature such as splitting crystals, veins in leaves, branches and snowflakes. These decorations have been proven to have positive psychological effects on people, as they are ingrained in the evolution of the human race. The diffuses are made possible not only through the use of lightweight and low-voltage electronics but also through the use of SLS 3D printing enabling Buckman to produce thin wireframe structures with internal supporting structures, this would not be possible to produce through any other means. The use of printing as a means of production rather than a tool for prototyping is still a relatively new concept, this explains the lack of exploration into of this in the field of lighting design. This provides an opportunity to develop with in this specific area of design.

fig. 2.14

fig. 2.15

More and more artists are interested in producing work that is not only beautifully designed and produced, but also environmentally friendly and socially responsible (Harrison, 2013). Developing a 3D printing process for a wider range of materials like ceramics and clays allows artists and designers to explore with materials that previously would have only been utilised by expert crafts people with many years of experience. The main case against ceramic production having a negative impact on the environment comes from the notion of how much energy is used by kilns to fire and harden the clay; temperatures often in the thousands of degrees are needed to completely vitrify clay. On top of this many types of glazes require being fired twice to finish and completely seal a piece. Considering more than 80% of global energy needs are fulfilled by burning fossil fuels (World Bank Group, 2014), then this can all add up to a heavy environmental footprint for an object as mundane as a cup. However even with considering this environmental footprint, ceramics are far more durable and longer lasting than other materials, which could be used to produce the same type of objects. For example people do not generally consider throwing out ceramic cups or plates after a single use, although this is almost always the case with paper or plastic. While there are always other options such as wood like bamboo plates and cups which may last much longer, they are still far more prone to water damage and wear than ceramic is. Furthermore adding to the environmental impact harmful chemicals are often added to the clay throughout the process, the most notable of which is lead found in many types of glazes. There are many non-toxic alternatives for glazes and finishes so if these are considered it is hard to find a more durable and sustainable material than clay.

Additive manufacturing has become an increasingly more prevalent form of production in recent years through 3D printing technology, allowing material to be deposited layer by layer in order to construct an object (Kruth, Leu, & Nakagawa, 1998). Compatibility of materials has long been identified as one of the fundamental limitations surrounding additive manufacturing. Even since the first development of 3D printers when only very specific photopolymers could be printed, right up to present technology, this criticism still holds (Wohlers & Gornet, 2011). Nowadays the spectrum of materials and processes that additive manufacturing encompasses provide far more options than could have been imagined at the first introduction of the technology. Yet compared to the material selection that can be used with more conventional manufacturing techniques such as injection molding, it still seems very limited. However unlike traditional mass manufacturing, digital manufacturing allows for an unprecedented level of customisation due to the lack of tooling required which lends itself extremely well to form and material exploration for designers (Reeves, Tuck, & Hague, 2011). This research aims to focus on 3D printing materials which are not traditionally associated with digital manufacturing such as ceramics, the scope of the research will focus on the use of ceramics with artists and designers, even with many advancements in digital technology this area is still largely dominated by hand craft. This research will explore the ways a 3D printer can be optimised to use these materials and use this to challenge the way we understand common materials in digitally manufactured objects.

This thesis will explore how new digital technology can allow a dramatic change to the way we look at mass manufactured objects. The nature of current mass manufacturing technology is extremely restrictive and allows for no variation between objects it produces, this ensures consistent quality of a part or product but this uniformity impedes the unique nature of traditionally manufactured and hand crafted objects (Duray, 2002). In this case traditional mass manufactured products are defined as products that have been created in large numbers through a tooled process such as slip casting or press molding where every object produced is identical. Digital manufacturing processes such as 3D printing allows for a high level of flexibility in producing objects as it is not restricted by tooling equipment or the complexity of the form. Through experimenting with the machine on a range of forms and unique surface qualities to understand the influence a digitally controlled process can have in creating unique and individual results. The university has deeply invested in researching the limits of emerging manufacturing technologies and materials so applying these to a series of experiments addressing optimisation and limitations of the material, material flexibility, and material finishing on objects in a way that we were not able to explore before.

METHODS & E

EXPERIMENTS 3

PROCESSES

Complexity is Free

In traditional manufacturing such as metal casting or injection molding, a new product requires a new mold in which to cast the part. During a process such as machining several tool changes are needed to create the finished product. However, additive manufacturing is a “single tool” process regardless of the complexity of the desired geometry. This effect makes objects complexity free, there is no additional cost or time between making an object complex or simple. This phenomenon is what makes the additive manufacturing processes excellent for creating customised, complex geometries. Previous to this technology the more material removed from the stock material would add to the lead time of the part however with additive manufacturing the opposite occurs, as the machine is only depositing material where it needs to be and not producing any waste, there is more of an incentive to design objects in a way that uses as little material as possible. The additive manufacturing process is capable of building dozens of unique objects in a single batch, this type of customisation cannot be economically offered by any traditional manufacturing process (Campbell, Williams, Ivanova, & Garrett, 2011).

Waste reduction

Additive manufacturing processes are inherently “green” due to the way material is added layer by layer, only the material needed for the part is used in production, generally there will be zero waste. This is a severe contrast to traditional manufacturing processes, where a subtractive process such as machining produces the desired part by carving it out of a stock billet of material. The final product often resulting in much of the original stock billet being left behind as wasted material chips.

While Additive manufacturing technologies offer critical advantages over traditional manufacturing processes, there are inherent limitations in the processes that keep them from being a replacement for every manufacturing application. In their current forms additive manufacturing processes are limited for mass production purposes due to the time for production on a part. On average, in the time it takes an additive manufacturing processes to complete a part, an injection molding machine would be capable of creating many of the same part in just a fraction of the time. While processes are rapidly developing as technology advances and increasing the machines overall speed, it is unlikely they will ever be able create parts as fast as molding technologies. The limitation restricts most forms of additive manufacturing due to speed the print head is able to move as well as the rate of material deposition. However this limitation is only valid for the production of large quantities of a part and as tooling must be created for each unique part for injection mold, additive manufacturing is the preferred process when custom parts, or low-volume production runs. Furthermore due to the tool-less production of additive manufacturing it creates a manufacturing paradigm shift where production can be decentralised and rather than creating large quantities of parts in one location, many printers can use the same source data to produce smaller quantities of the part. Also a single printer can produce a large quantity of a single part and then be instantly reprogrammed to produce different products as demanded. (Campbell, Williams, Ivanova, & Garrett, 2011)

METHODOLOGY

Situating the Research

How can the unique qualities that digital technology & 3D printing offer generate unique and practical solutions in lighting design?

The purpose of this section is to refine and direct the process based on the knowledge gained through the exploration thus far, determining the criteria for the final design phase. This thesis reflects on the work by Nervous Systems & Olivier Van Hept, which explores the unique qualities that can be achieved in objects through the use of digital design paired with digital manufacturing technology. This thesis aims to address and further build upon areas of research prior explored in the field of digital ceramic production and digital design, as well as the information distilled from Duray's (2002) literature on digital technology. Reviewing literature on 3D printing and the distinctive changes it can bring in terms of manufacturing possibilities highlighted the importance of considering all the contributing factors to producing an object in this way. It was also crucial to consider all the possibilities that can be achieved through blending and modifying materials in order to be better suited for the digital process. Customisability, complexity and speed were identified in the literature review as key elements that set apart digital manufacturing processes from their traditional counterparts. In order to push the limits of digital manufacturing the final design phase will focus on lighting devices, focusing on the practical needs of a product and interaction design.

A design-led research process drives this thesis. Frayling (1993) identifies three types of design research: research into design, research through design, and research for design. Out of these three main forms of design research this thesis will follow only the Research through Design process (Zimmerman, Forlizzi, Evenson, 2007). Research through design is deeply embedded within the design process, as its main concern is to inform the overarching research question through an iterative process of design. Research through design also must be conscious of the end product of the design. (Godin & Zahedi, 2014)

"Research through design (RtD) is an approach to scientific inquiry that takes advantage of the unique insights gained through design practice to provide a better understanding of complex and future-oriented issues in the design field" (Godin & Zahedi, 2014, p. 1).

In Burdick's book *Design Research: Methods and Perspectives* (2003) the intention is to inform designers to the many research tools at their disposal and how they can be used to inform the design process as well as ideas about how and when to deploy these tools effectively. Burdick (2003) describes how research through design can take advantage of many of the skills gained through design practice including prototyping, analysis, testing and design thinking, which a term that is rarely defined but is often used to describe what designers bring to problem solving and to further rationalise designers input into a project or process (Zimmerman, Forlizzi, & Evenson, 2007). Aims and objectives further expand on how each stage uses each method and how they have been uniquely tailored to be best utilised.

EXPERIMENTATION

This chapter will follow all the various stages of the design process that lead to the final series of objects, analysing the results discovered at the end of each stage, this also relates to Nigel Cross's model of the design process (1984), exploration, generation and evaluation. The designer will repeat generation and evaluation over many times until there is a finalised design or series of designs.

The design research stage picked up right from the finding of the previous stage on ceramic printing and paste extrusion. Learning to design for this procedure involved a deep understanding of multiple factors, the first of which and possibly the more crucial is the material used in the process. In order for a successful final outcome to the project, the materials used need to be developed and iterated on alongside the development of the printing process itself. These two factors are deeply interconnected and as many design precedents do not disclose the exact composition of the materials they utilised in their research or how they go about developing the material it's very important to conduct research into this area and explore what role it will play in the project.

The knowledge gained through this process informed all the various qualities of the materials and how to control them. A range of materials used were used to present many different properties, ranging from varying grades of clay, to different binders, each one revealed a different expressive quality as well as shifting abilities to be extruded.

Material Preparation

The first series of testing began with the investigation of materials that are currently used in the production of ceramics. This involved a range of solid clays with properties varying depending on their intended use.

- Stoneware clay is the most commonly used material by hobbyists and professionals working within the field of ceramics currently, this type of clay is cheap, easily accessible and very easy to work with. The shortcomings to using this material however is that in order for it to be used as an object it must be fired in a kiln at very high temperatures, this hardens the clay but it will still be very porous. For the object to hold water it must undergo a second firing process once it has been covered in glaze. These final steps of requiring firing and glazing create a huge barrier for designers and artists the work with the material, requiring extremely specialised equipment to process parts for use.
- Higher end homeware clays such as porcelain have very different properties to some of the more commonly used clays in the industry, they only require being fired once and hold liquid without the need for glaze, however they require far higher temperatures in the kiln and are much more difficult to work with while crafting the object making them less suited for processes such as pottery throwing.
- In order to have a baseline to work from the material must first be thoroughly dried out and ground down to a constant size so that it can be measured and mixed into specific ratios for testing. This was achieved by rolling each of the clays into flat sheets, drying them in an oven set at 50 degrees and then finally grinding down the dried clay onto a fine powder. Portions of clay were then mixed with varying ratios of water to achieve a wide range of consistencies.

fig. 3.1.1

Unprocessed Porcelain.

fig. 3.1.2

Porcelain, Macs White, Earthenware Clay and Terracotta. Unprocessed as they would be used by a potter.

fig. 3.1.3

fig. 3.1.4

fig. 3.1.5

Rolling out material until it is 1-2mm thick so it can be thoroughly dried and broken up.

fig. 3.1.6

fig. 3.1.7

Setting the oven at 50 °C and leaving material to dry for 30 minutes. The sheet of clay needed to be flipped once during the drying process.

fig. 3.1.8

fig. 3.1.9

fig. 3.1.10

Once the material came out of the oven it was extremely brittle, after cooling it was broken up into smaller pieces and put into a mechanical grinder to turned into a contestant dust like fine powder.

fig. 3.1.11

fig. 3.1.12

fig. 3.1.13

Scales were used to measure out 20 grams of clay powder into each container, to which varying ratios of water were added. At least 5 different ratios of water were mixed with every different type of clay, spanning from 1:0.25 being an extremely thick and dry mix all the way to 1:1 being a very watery mix.

fig. 3.1.14

fig. 3.1.15

Samples were left to sit for multiple days so the mixture was consistent and homogeneous throughout.

Extrusion Testing

From the literature and precedent analysis FDM printing was identified as the most accessible process and usable to conduct the tests for this thesis, along with it being the only process that allows for multi-material printing. Many FDM based 3D printer work of open source electronics and components so the user has complete control if they wish to upgrade or modify parts. For testing purposes this is very convenient as it means a regular 3D printer can be used with minor hardware and software modifications.

- With the use of a scaled down paste extruder material testing can be conducted with minimal set up, rather than using the printer's extruders. Moreover in order to more efficiently and consistently test each material's ability to be extruded from a syringe it required the use of automated paste extruder. This allowed each material to be tested under the same conditions with the capacity to interchange syringe tips.
- Richard Horne (RichRap) provides downloadable design files to build a mechanical paste extruder, the designs are intended for use with an open source 3D printer however for the purpose of this research the design can be adapted for use as a stand alone unit.

fig. 3.2.1

fig. 3.2.2

fig. 3.2.3

The downloaded extruder file was printed in ABS plastic at 0.2 mm layer heights and infill to ensure a strong reliable part.

fig. 3.2.4

fig. 3.2.5

fig. 3.2.6

All the components were assembled based of the instructions provided on the download link. The extruder was then wired to an arduino micro controller to operate the stepper motor. The motor was programmed to move at a constant rate so that each material that is loaded into the extruded can be compared to one another.

fig. 3.2.7

fig. 3.2.8

fig. 3.2.9

The material had to be loaded into the syringe from the back taking great care not to create any air bubbles. Multiple lure lock nozzles were also tried ranging from 6-25 gauge. The smaller nozzle diameters struggled to extrude material consistently and also created a lot of back pressure. The ideal nozzle size trialled was 0.8 mm.

fig. 3.2.10

fig. 3.2.11

Extruder operating with the largest diameter nozzle, 25 gauge. This nozzle produced minimal back pressure with all the materials it was tested with however due to the large extrusion bead size it produces it is not optimal for fine detail printing.

Material Binder Development

This stage involved taking the material exploration phase of the project much further, with the overall goal of this to better align the material used with the printing process. Based off the insight gathered in the previous stage it is evident that with some level of processing and optimisation the traditional materials that are used the production of ceramics can also be used in a paste extruder 3D printer setup. However as these materials have properties that make them satisfactory for pottery throwing or sculpting, it is unclear if these will lend themselves to the printing process.

- As the digital process is vastly different from traditional methods due to the extrusion and layering process, it is necessary to explore a range of materials and binders that can be used in a paste extruder 3D printer setup in order to generate the best-suited material.
- The range of material that were tried in this study involved many combinations of binders both related to the clay and ceramics industry as well as many that did not at all but could have possibly lead to desirable properties.
- As the literature review identified lighting design as a potential application for the output of this research the material experiments had a clear focus on facilitating this function. This included developing material to provide some level of transparency/translucency as well as electrical conductivity. This has been identified as strong area, which has not been explored through traditional manufacturing techniques due to the inherent limitations of the process. The features that were identified that could led to the ability to product lighting design objects are the ability to produce complex internal geometries, print with multiple materials in a single print and also create thin wall structures. Creating internal geometries is an important step in achieving the overall goal of creating a lighting device as it allows for components to be housed within the object.
- Materials that were selected include commonly used materials with ceramics such as stoneware clay, macs white clay, porcelain, glaze, sculpy and gloss top coat. Other material used as transparent binders included glues, silicone, acrylic clear coat and bio based materials such as starch, P.V.A. and cellulose. Finally conductive materials were tested such as metal powders including zinc, nickel, graphite and graphene.

fig. 3.3.1

fig. 3.3.2

Clear gel binding medium was mixed with clay powder in varying ratios similar to the previous tests. The goal of these tests was to achieve some level of translucency.

fig. 3.3.3

fig. 3.3.4

The mixture was then loaded into a mould with incremental steps ranging from 0.5 mm to 4.0 mm to analysis translucency at each thickness. Light can be seen through the material until a thickness of 2.0 mm.

fig. 3.3.4

fig. 3.3.5

fig. 3.3.6

Glaze was mixed with porcelain again to try and achieve some level of translucency. These samples were then heated to solidify the porcelain and glaze. No translucency was observed in these tests however.

fig. 3.3.7

fig. 3.3.8

fig. 3.3.9

Zinc powder was mixed with clay in varying ratios in order to achieve some level of conductivity in the material.

fig. 3.3.10

fig. 3.3.11

fig. 3.3.12

The paste was then extruded into lines to be tested with an LED light attached at one end. It was discovered that a ratio of 1:1 clay powder to zinc powder was optimal for conductivity. Lower ratios of zinc powder resulted in reduces performance in the LED and ratios higher than 1:1 produced an extremely brittle material when dried, to the point where it could not hold together when being tested.

fig. 3.3.13

Printer Trials and Calibration

Carrying on from the knowledge gained in the previous section this stage focused on specifically printing with the chosen materials. In order to produce designs at later stages of the research this section further tests the abilities and limitations of the chosen materials, testing's distinct layer high changes in the printing software, print speed, e-step rates of the paste extruder, extrusion rates at different consistencies, unsupported overhangs and internal infill's. If these settings were not calibrated correctly it would result in under extrusion causing failure in objects or over extrusion leading to inaccuracies in objects.

- In order to produce consistent, repeatable and comparable results in this section the object used for testing is a cube. This was chosen as it can show clear changes in surface quality on the faces depending on their orientation as well as overhangs, internal infill and scale.
- Testing technical details of printer settings such as print speed, nozzle diameter, extrusion rates etc. is normally not necessary with materials that are commonly used with 3D printers such as plastics in which plenty of pre-set values are provided within the printer's slicing software, as well as specifications provided by the manufacturer of the material. However as there have been so few projects using paste extruding 3D printers there is little to no information on there to start.
- For the testing in this section the slicing software that was used was Cura, an open source program available that is compatible with a wide range of 3D printers. This software was chosen due to its customisability and flexibility with over 200 adjustable settings, which is especially important as this setup uses an unusual extruder. Other software was trialed such as Slicer and Repetier but it was concluded that Cura allowed for the most flexibility and ease of use when it came to paste extrusion with the chosen hardware. While many 3D printing software's have fixed pre-set setting or compatibility with specific hardware configurations Cura allows users to modify settings such as precise print speeds, steps per mm of material in the extruder to control flow, percentage of infill density on a part and many more configurations that contribute the quality of a part. Through testing it was discovered that the optimum print speed was 1 mm-2 mm per second and 10000 e-steps per millimeter of material at the desired consistency.

- Other considerations had to be made at this stage that had not become relevant at previous stages, for example the way in which the syringes were loaded for the paste extruder was crucial to the quality of the part. Each had to be carefully primed from the open end with a focus of not allowing any air pockets to form while the material was filling the syringe. If any air bubbles were present in the mixture they could compress as the material was being extruded and create a sudden release in pressure as it worked its way to the nozzle damaging the print or forming a small void in the part. Another similar issue that would present itself at the beginning of this stage was printing errors or failures due to inconsistencies in the material, if there was any change in the flow rate of the material due to the liquid content of it this would lead to errors in the printed part. As well as nozzle blockages due to large particle build up or higher viscosity in the material.

For this series of tests a 30 mm x 30 mm x 30 mm cube was used for all the experiments to create a baseline to calibrate the printer. Figure 3.4.3 & 3.4.5 are trials with no nozzle on the syringe, the material extrudes at around 2 mm thick.

Again multiple sizes of syringes were trialled ranging from 6-25 gauge. The 0.8 mm stainless steel drawing nozzle was discovered to be the most effective. The nozzle was cut shorter to reduce back pressure on the syringe and improve the overall quality of the print. These initial cube tests are examples of the printer e-steps per mm of material extrusion settings being sets to high. The optimal setting for this was around 10000.

fig. 3.4.11

fig. 3.4.12

fig. 3.4.14

fig. 3.4.13

fig. 3.4.15

Different layer heights were tested ranging from 0.3 mm to 0.8 mm as seen in figure 3.4.11. The most successful tests were 0.3 mm & 0.4 mm, the printer starts to create dimensional errors when the layer height exceeds 80% of the nozzle diameter, which for these tests was 0.8 mm. Figure 3.4.14 shows the materials ability to create unsupported overhangs, there is noticeable sagging at it takes 3-4 layers before the printer can recover.

Structures with infill such as 3.4.19 were tested with some success, at around 15% infill the prints are successful but exceeding this results in artefacts where the nozzle comes in contact with the objects outer wall, 3.4.17 for example.

All the objects produced. The results for this series of tests showed that layer heights of 0.3-0.4 mm or optimal for clay printing. Infill above 15% results in reduced quality, and the highest quality parts having 0% infill. Also print speed had to be set at 1-2 mm per second to successful print, anything faster would not give the clay enough time to adhere to the layer below.

Thin wall/ Shell Structures

The next series of printed objects explores a specific feature within the slicing software, which is the shell function. This feature is achieved through importing a solid form into the slicing software, setting the models wall thickness equal to the nozzle diameter and having 0% infill. What this series of setting produces in the model is a single layer wall object that is printed by continuously coiling around the profile of the object, constantly extruding without the need to make rapid movements to anywhere else on the object. As the printer is constantly printing and does not need to retract material to move to its starting position each layer the object is left with less z-axis stepping artifacts, additionally smaller layer thickness increases the dimensional accuracy of the part since the step effect is again minimised. However the thickness is limited by the nozzle thickness of the extruder.

- This series of objects explores the qualities of this shell/coiling technique on both primitive 3D objects and more complicated forms.
- This technique is limited to the types of forms it can print due to the nature of the way it generates the object, it is unable to achieve most overhangs as it does not produce any infill or internal support structure. This means objects cannot have tops or large windows/ cutout structures.
- Due to the nature of the slicing process the 3D object file also needs to setup correctly, the file must be a solid object without any thin wall structures, as the slicing programs will just skip these.

It was discovered the best quality printed were produced when the object has 0% infill and no top or bottom, there is very little surface area touching the print bed which minimises warping from drying.

fig. 3.5.9

fig. 3.5.10

Complex prints using this shell method would often fail such as 3.5.9 and 3.5.10. For the best results the model must be set up so the printer constantly extrudes a single bean of material. Not having to stop and start the extruder as well as no rapid movement around the model result in a much more successful print.

fig. 3.5.11

fig. 3.5.12

Figure 3.5.11 shows the most successful prints where the printer was able to continuously draw a single line of material to build the model.

Light Diffusion

The next part in the design phase was beginning to apply the skills and techniques discovered in the previous stages to the application of lighting design. With the knowledge of material properties and printer settings this can now be applied to creating unique and individual geometries that each express features previously identified as being only possible through the use of 3D printing. These models are all based around a flat tile form so that the focus of each object is specifically on the way it diffuses light, free of any other distractions.

- Printing tiles presented challenges that meant they could not be sliced in the same way as the previous stage, these objects had to be created as solid forms with 100% infill. Building this way means the printer is constantly depositing on to a solid piece of material so it improves the success rate of the prints dramatically however it uses significantly more material per print than the previous method used and also limits the details that can be resolved in the model. These obstacles had to be considered carefully while producing the object files for this series of tiles.
- The light box ensures each tile test can be compared consistently against one another. This also explores the idea of how 3D printed forms can interact with a lighting device and how they can be integrated into each other.
- Tests focusing on hidden geometries yielded the most interesting results as the models appear to have some form of surface patterning but the complexity of this is largely hidden until the light shines through it. The hide and reveal technique is in a very primitive state in these tests however due to the thickness limitation of this series of models as well as them being completely solid. The underlying principles to this idea will be explored further as it is incorporated with the insight gained in previous testing.

As shown in 3.6.1 these objects were produced with 100% infill, this is a solid clay object with no internal structure. These objects were prone to over extrusion as well as warping due to the thickness of the objects and the speed at which they would dry on the print bed.

fig. 3.6.3

fig. 3.6.4

Figure 3.6.3 and 3.6.4 tested an interwoven patten, looking at the printers ability to produce overhangs. The print was successful but was dimensionally inaccurate due to over-extrusion in some places.

Figure 3.6.5 and 3.6.6 looked at creating a series of squares reducing in size to see how light is dispersed at each size.

fig. 3.6.7

fig. 3.6.8

Figure 3.6.7 and 3.6.8 look at cone shape cut outs, the top surface had only pinhole to diffuse the light however on the underside the are much wider to channel the light through the small 0.5 mm hole.

fig. 3.6.9

fig. 3.6.10

This test also looked at creating a wide opening on the underside leading to a thin slit on the upper side.

fig. 3.6.11

fig. 3.6.12

fig. 3.6.13

fig. 3.6.14

Figure 3.6.13 and 3.6.14 were the most successful tests in this series, they explored creating a louver pattern so from the upper side of the object the slits are hidden and it is not until the light is illuminated that the pattern is revealed.

Three Dimensional Light Diffusion

Approaching the final stages of testing different methods of manipulating light delusion and building 3D form, there was still need to develop previous experiment, revisit old ones and try to gain control over each technique. In order to produce something with truly unique qualities the process may be developed and pushed to its absolute limits.

- This series revisited the idea previously explored of inputting a solid model into the 3D printers slicing software and manipulating the printing parameters in such a way that it creates just a shell of the object. This method of printing can achieve structures with very few printing artifacts if each layer is deposited with a strong connection to the layer beneath it.
- By controlling the angle of the model and the distance between each step within the 3D modeling software, voids could be created within the printed model. The patterning these voids created conceived a unique aesthetic for defusing light. These voids are not part of the STL file that is input but with this method of printing any surface that is a 90-degree angle is ignored leaving a hole in the model.
- This series of models works as the culmination of the successes of the previous test, within one model it is able to show the ability of the material and printer to produce extremely thin walled structures, use a single line drawing method of printing (no infill) and incorporate a complex hidden geometry.
- Creating a completely hollow structure leaves the possibility open for adding internal components to make the object function as a fully enclosed lighting device.
- Investigating the distance of each step to maximise the quality of the final part by reducing overhangs/bridges while maintaining void pattern. Distances below 2.5mm resulted in layers overlapping completely and not leaving any voids for light to pass through. Distances of up to 5mm were tested, with the shorter distances yielding superior print quality and a more complex light diffusion pattern. Oppositely object with very steep angles exceeding 50 degrees such as the semi-sphere would not be able to make enough contact at all to build without collapsing at a certain point.

fig. 3.7.1

fig. 3.7.2

Figure 3.6.13 and 3.6.14 were the most successful tests in this series, they explored creating a louver pattern so from the upper side of the object the slits are hidden and it is not until the light is illuminated that the pattern is revealed.

fig. 3.7.3

fig. 3.7.4

1 mm steps results in no voids for light diffusion.

fig. 3.7.5

fig. 3.7.6

4.5 mm steps.

fig. 3.7.7

fig. 3.7.8

2.5 mm steps

fig. 3.7.9

fig. 3.7.10

2.4 mm steps.

fig. 3.7.11

fig. 3.7.12

2.5 mm steps.

fig. 3.7.13

fig. 3.7.14

3.7.13 & 3.7.14 was the largest object in the series produced at 85 mm high and wide. The step height was 2.4 mm, this is the smallest the steps can be and result in a successful print that is able to diffuse light.

fig. 3.7.14

This style printing proved to be the most successful method. Inputting a solid STL file into the slicing software Cura and then programming the printer to create the object from a single continuous bean of material produced the best results. As the open slits are a bi-product of the method of printing they come out far cleaner than if they were built into the STL file to begin with.

fig. 3.7.15

The STL file that is importing into Cura is a solid object, normally a printer would print this as a solid model that could not be used to diffuse light however due to the manipulation of the settings used all 90-degree angles are ignored by the printer leaving a series of voids where there should be caps on the STL model.

Final Series

The final output for this research needed to beautifully showcase the results of the experiments with most potential, expressing the visual, tactile and functional qualities. Using material variances in the material quality to indicate the objects intended movement and tension in the form of the object to encourage interaction; Revealing the depth and function of the patterning and surface texture through the use of illusion; and Using internal structures to create a fully enclosed light circuit to challenge the perception of the limitations and properties of the material. This phase employed all of the previous approaches as a base to begin designing the final series of objects from. Developing directly from the objects produced in the previous stage as the main housing and body of the light and the light diffuser. This technique used to build the final object is an amalgamation of many of the previous tests into light diffusion, using hidden geometries in the form of louvers as a way of scattering light in unexpected ways; exploit the 3D printers ability to continuously construct a object with a single bead of material in a coiling motion, void of any internal support structures of matrixes; utilise the ability of the material paired with the 3D printer to create thin single wall structures.

Building the circuit into the body of the object as it is printing is made possible only through the use of multi material 3D printing, there is no other manufacturing process that allows two distinct materials with unique properties to be deposited simultaneously in a job to produce an object in a single operation. Moreover there is not even a single other variety of 3D printing that allows for multi material printing of a hollow object with the ability to pause the job, add internal components and then resume the job encapsulating the components in permanently. This understanding is core to the value that the digital manufacturing process is adding to the material, having a deep understanding of the possibilities and limitations of the process allows a designer to intuitively identify and realise value in an opportunity and exploit it.

To push the limits of what the material and process is capable in the final series, it had to incorporate all of the knowledge gathered in the previous stages of research. This mean implementing the lighting function of the object in a meaningful way, exploiting both the unique properties of the building process and the inherent nature of the materials. With the ability to simultaneously build in multiple materials this allows an object to be printed with an internal embedded structure, this paired with the conductive material facilitate the implementation of a circuit directly into the print. For this to be a functioning lighting device however it does still require certain components such as a light source

and power supply that cannot be printed. These can be easily added to the printed circuit during the print by pausing the job at a specific height, adding the components and then resuming the print so that everything is then enclosed. Using low voltage LED lights will be very simple to implement into a printed circuit and will only require a very small power source such a button cell battery to run it.

Figures 3.8.1-3.8.5 are failed attempts to test print the base of the object with varying levels of infill.

fig. 3.8.6

fig. 3.8.7

Failed attempts to test print
the base of the object with
varying levels of infill.

fig. 3.8.8

fig. 3.8.9

fig. 3.8.10

fig. 3.8.12

fig. 3.8.11

fig. 3.8.13

Final object being printed. Once the base and conductive material have been deposited the printer can be paused and electrical components can be added. A single LED and button cell battery were inserted into the object, and then the print could continue around the components sealing them within.

fig. 3.8.14

fig. 3.8.15

3.8.14 & 3.8.15 show the top portion of the object being printed around the conductive component, battery and LED.

fig. 3.8.16

fig. 3.8.17

Completed print.

RESULTS

Results

Developing and exploring a printing method that can achieve extremely thin wall structures with no infill helped in the success of the final structure. It was discovered that designing solid objects with holes and patterns in its surface resulted in a poor quality print due to the inaccuracy of the printer and its tendency to over extrude material. This issue was overcome by exploring thin wall or shell structures and manipulating the printer settings in such a way that a 90-degree surface or top on an object would be ignored by the printer. This allowed a solid STL file to be imported into the slicing software so that the printer would not have any issues generating a single path around shell of the object but then also result in pattern of voids across the surface of the object.

To capitalise on the directional nature of the light diffusion due to the printing process, it was advantageous to incorporate an interactive element into the design so that the user has an opportunity to fully experience the object in both its illuminated state as well as its dormant state. Achieving user interaction in the objects was accomplished through the design of the base. Creating an object that communicates some level of tension to the users in its inactive state is able to promote an interaction, which can trigger the circuit and reveal its hidden geometries and lighting aspect. As all of the light is diffused upwards due to the form of the object it is important to have the unique pattern and shadow that is created facing a surface or wall so that it can be fully appreciated. To make this implicit in the design of the object it needed to be designed in such a way that in its activated position it can achieve this.

In order to create the design with a useable interaction the base of the model must house all of the components as well as create a stable mechanism to facilitate the interaction. This requires a far more robust part than the comparably fragile light diffusion portion of the object. To achieve this the base portion was printed with slightly different settings than the top, increasing the infill density and wall thickness. These changes were made to ensure there was sufficient weight in lower portion of the model, keeping the center of weight low enough that the model would not topple over in either of its positions. Having thicker walls in the base portion contrasted the upper section as it was deprived of voids, this also aided in the concealment of the electronics within. Having all the electrical components and circuitry concealed added to the mystery of how the light operates.

There was a lot of attention to detail given to the final object in order to meet all the criteria put in place to ensure that the approach taken and results reflected the dramatic change in manufacturing that can be achieved through the use of digital technology. The methodical approach to develop the final object was essential in engineering a pragmatic solution to a functioning interactive lighting device, while still allowing for a creativity novel approach the entire way.

- Incorporating internal structures printed inside of the enclosed object.
- Printing in a second conductive material to create a working circuit during a single operation.
- Utilising the printer's ability to print incredible thin unsupported microstructures (as thin as 0.8mm), allowing for complex geometries with the capacity to diffuse light in an original approach.
- Electing a design that embodies modern linear geometries while giving emphasis and attention to the digital tectonics displayed on each object. This aesthetic of a extremely geometric object contrasts forms produced through traditional means and strongly reflects the digital process that produces them.

fig. 3.8.18

fig. 3.8.19

3.8.18 & 3.8.19 show the interaction with the object, in both its inactive and active positions.

fig. 3.8.20

fig. 3.8.21

Unique digital tectonic aesthetic quality across the surface of the object.

fig. 3.8.22

fig. 3.8.23

fig. 3.8.24

DISCUSSION

5

How can the unique qualities that digital technology & 3D printing offer generate unique and practical solutions in lighting design?

This critical reflection will review the utilisation of the technology and process, the performance of the elected materials, and the design decisions. This reflection will also analyse further applications for this research, limitations and future recommendations. The scope of this study concentrates on integrating clay and ceramic material with an emerging digital manufacturing process, within the scope of lighting design. This idea of having the ability to 3D print with multi-property materials and produce a functioning lighting device in a single operation stems from the development of the technology itself. With the barrier to entry for these processes rapidly reducing it is quickly becoming a fertile area for design researchers to explore for new possibilities and opportunities. It is evident that the ceramics industry is well overdue for a major technological advancement and with the growth of digital technology in manufacturing and industry, understanding how to properly utilise these technologies will be essential in the future. Conducting this research helps develop a process and scenario that capitalised on all the benefits of the digital manufacturing process as well as expanding the current use cases of the material.

The challenges of expanding the use of digital technology and creating unique solutions for lighting design posed by the initial research question drove the development throughout this thesis towards a form of production for ceramics that would fall outside of what is considered a possibility within the realm of traditional manufacturing. This thesis progressed based on Frayling's (1993) research through design, allowing for constant exploration of objects and materials in order to derive the final design output. The success of this research's final output was heavily established on this ability to make changes based on knowledge gained through testing and to constantly iterate at every stage of the process. This methodology endorses an iterative process to establish a final design output, which is crucial for this category of research. Using this process allowed for an extensive investigation into design utilising techniques such as sketching, 3D CAD modeling, material testing and rapid prototyping.

Beginning the analysis into the advancements in digital technology and the radical changes it is making in manufacturing and design revealed why this area offers such potential for research. The

first sets of experiments explored the possibility for the LDM paste extruder method of deposition to be paired with a regular FDM 3D printer. After identifying specific desirable material properties that could add functionality and further align the material with the digital process and context, 3D printing tests were conducted to establish optimal printing parameters and guidelines. These tests defined criteria and limitations of the process such as the minimum size nozzle that can be used, print speed, extrusion rate, wall thickness, build angle and the printer's ability to free form unsupported structures. After these guidelines were established they were then applied to all subsequent tests. These included series exploring single wall structures, 2D tile experiments into how structures affect light diffusion and then finally applying all the knowledge gathered into the final series of 3D forms focusing on light diffusion. Building upon the knowledge gained at each stage ensured the final outcome was directly derived from the most successful prototypes and delivered a novel approach to the research question with physical qualities that can only be accomplished through the utilisation of digital technology.

Decisions made into the final form largely stemmed from the unique aesthetic that is attained through the digital process of depositing layer after layer of material to produce a physical object inherent to this method of printing. Due to the tool-less nature of 3D printing it theoretically allows for any form of structure to be created. However in practice master the ability to utilise the printing processes strengths and mitigate its shortcomings requires an in-depth knowledge for all the factors that are essential for a successful print as well the materials used. Design decision made when considering this type of manufacturing should always thoroughly acknowledge this process in order to effectively utilise the unique opportunities it offers. For example during this research it was discovered that the technique of "coiling" or extruding a single continuous bead of material to build an object proved to be the most advantageous as this by far provided the best quality prints as the machine was not creating rapid movements and vibrations laying infill. Expanding on this method also led to the discovery of being able to create objects with complex patterns of voids as the printer would ignore certain build angles and overhangs in a solid digital model due to the combination of settings in the slicing software. These types of discoveries are only made possible by the research through design

process as it allows for continuous evaluation and changes throughout the whole research process as knowledge is acquired.

Using the context of lighting as a use case scenario created a focus and direction for this research to be applied to, as the majority of the research was centered around developing a process and material it could easily have been tailored to fit in many different contexts. However, having a clear objective from the beginning helped drive the project forward and justified design decisions along the way. Furthermore this context was chosen as it is an area that would not typically be associated with clay or ceramic so it further emphasises the opportunities provided by the implementation of digital technology. Utilising multi material 3D printing allowed the final object to be constructed in a single operation. Through the use of the conductive material as one of the material selections it was made possible to embed a circuit within the enclosed structure. With any other form of manufacturing producing an object such as this would require multiple operation and many individual parts. Even within the field of 3D printing this type of procedure is only possible with multi material FDM printing as no other method can build an unsupported structure in multiple materials as well as being able to interact with the object during the printing process.

Limitations of this research largely span from the research through design process. As this is predominantly a qualitative procedure the decisions made at each stage have a heavy bias based on the approaches of the designer conducting them. As I was the only designer directing the research ultimately the progression of the design process was entirely linked to who I am as a designer. It is entirely possible that a different designer with a contrasting background and approaches could take the same inputs and process, and produce a vastly distinctive output. However the overall goal of this thesis was not to produce an absolutely quantitative solution to the research question but more to thoroughly explore one possible scenario and provoke future thought and development into the area. The other major limitation that was identified during the process was the separation between the small-scale material experiments and the comparably large-scale test prints. This occurred during the transition from the initial material tests where certain materials were chosen for desirable

properties and their ability to be extruded and built upon but when larger scale tests were conducted these effects did not translate. This issue could have been largely avoided if the material exploration from the beginning was more closely tied to the printing experiments. Having the separation in the earlier stages and testing with a manual extruder simply led to limitations not being discovered until later in the research process. However this fact did not have any real bearing on the final output of the research.

Certain aspects of material properties that were explored in the early stages of prototyping that did not make it into the final design phases, utilising materials with translucency/transparency would offer some interesting and unique opportunities that have also not been widely explored in previous literature. Creating materials that vary in translucency would allow for a range of applications when paired with multi material 3D printing and opaque material. These possibilities would range from their use in lighting design as explored in this research but also further afield into other areas of product design. The ability to create objects with various levels of transparent material built into it is something not outside of the scope of high-end 3D printers such as PolyJet type printers using UV curable resins. However this has not been explored in the context of paste or ceramic printing, which could open up a whole new range of possibilities. Secondly an aspect of this research that could be expanded on is the introduction of internal support structures with the second printing material and producing complex 3D circuits within an object. This research was focused on the application of lighting design so the circuits created did not require any complex 3D structure. Finally further recommendations to follow up on this research in the future would mainly involve taking the process outlined in this thesis and applying it to a different scenario. This research focused solely on how material properties can be modified and optimised for digital technology and then how this process can be applied to lighting design, other scenarios could result in equally valid research.

CONCLUSION

As the constraints surrounding emerging digital technology diminish, designers are presented with a novel opportunity to revisit materials and the processes that surround them for a chance to produce something truly innovative. This research explored the possibilities that could be achieved through creatively exploiting features of the 3D printing process paired with a material with a rich history encompassed in handcraft. Bringing the machine and the unique way it interacts with materials to the forefront of the research allows the designer to focus on singular details and moments rather than just considering it another means of production. This type of research proposes a new role of the designer as the gap between designers deeply rooted in CAD technology/software and craftspeople grow. This process suggests that designers need to become competent in the entire procedure so they have the ability to apply a richer layer of complexity and expression.

The final design output of this thesis aimed to be a collimation of all the research conducted previously. The form of the final object was derived from the process of coiling material in a single layer to create a thin wall structure that is able to diffuse light through a pattern of void across its surface. Creating thin fragile structures was identified through the literature review as an area that had not been previously explored in ceramic printing. Furthermore using this printing process also creates a series of holes and voids across the surface of the object is not an idea that has previously analysed in lighting design. The second important component to the final design output is the utilisation of multi-material and multi-property 3D printing. For this element an internal structure of conductive material was utilized in order to create an embedded circuit during the print. The embedded circuit also stemmed from the application of lighting design as the ability to produce an object with internal components in a single operation is something that has never before been possible in manufacturing. The use of 3D printing to produce this circuit also aids in the level of complexity it can provide, this was capitalized on in the final design output by creating a tilt switch printed inside of the object. Finally this circuit adds an interactive element to the final object, as a user will have to handle the object in order to activate the light within. This functionality of creating an interactive object through its internal conductive structure further reinforces its merit within the field for lighting design.

Emerging technology in 3D printing offers a range of possibilities that other manufacturing techniques are unable to achieve. These possibilities have already begun creating a huge shift in the way

designers look at manufacturing processes and their ability to expand the potential offerings of product design. The use of materials and process throughout this research draws a line between mass manufacturing and hand craft, where mass manufacturing processes create simplified surfaces set to tight specifications and strive for efficiency, and on the opposite side of the spectrum the master crafts person takes great risks as they push their abilities in order to produce a masterpiece. This research draws from both epistemologies, pushing the machine itself to the limits creating objects with a high risk of failure. Opportunities where products with complex internal structures or circuits that can be produced in a single operation dramatically widen the scope of possibilities for product design using digital technology. This type of process could further impact traditional manufacturing techniques if implemented at prototyping stages of product design as it allows for the production of a working object in a single operation streamlining the entire process.

Expanding the capabilities of multi material 3D printing introduces new methods for constructing objects and products, and with the development of 3D printing increasing rapidly the potential and accessibility to this technology will only expand in the future. Moreover introducing new possibilities to a material that has yet to experience a major technological advancement opens up opportunities for it to be utilised in fields for which historically it would have never been considered.

LIST

OF FIGURES

All images that are not listed are made by the author.

Figure 2.1) Knapen, T. (2011). Virtual Pottery Wheel [Image]. Retrieved from <http://unfold.be/pages/l-artisan-electronique>

Figure 2.2) Cass, R. (2014). Z-Corp 510 3D Printer [Image]. Retrieved from http://digital_hand.cias.rit.edu/wordpress/the-fabulous-brinkman-lab/

Figure 2.3) Brooke, R. (2014). Polybrick [Image]. Retrieved from <http://www.tctmagazine.com/3D-printing-news/polybricks-puts-spin-on-ceramic-3d-printing/>

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Figure 2.5) Nervous Systems. (2016). Finished cup design 3D in porcelite [Image]. Retrieved from <http://n-e-r-v-o-u-s.com/blog/?p=7341>

Figure 2.6) Nervous Systems. (2016). Printing porcelite on form2 [Image]. Retrieved from <http://n-e-r-v-o-u-s.com/blog/?p=7341>

Figure 2.7) Roelse, R. (2015). Solid Vibrations [Image]. Retrieved from <http://oliviervanherpt.com/solid-vibrations/>

Figure 2.8) Hept, O. (2012). Functional 3D Printed Ceramics [Image]. Retrieved from <http://oliviervanherpt.com/functional-3d-printed-ceramics/>

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Figure 2.10) Hept, O. (2012). 3D Printed Ceramics [Image]. Retrieved from <http://oliviervanherpt.com/3d-printing-ceramics/>

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