COLOUR 3D/4D PRINTING FOR FILM

by
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ABSTRACT

The value of materiality and tactility is vital to enriching our experience of the world. We understand these interactions implicitly, and can see when they are portrayed incorrectly in film. CGI (Computer Generated Imagery) can seem disconnected from the actor, yet practical special effects are constrained by reality. Recently, the 3D printing company Stratasys released a colour, multi-material printer called the J750, which has the capacity to create full colour, flexible articulating prints. This technology gives us the opportunity to find a balance between CGI and practical effects, harnessing the freedom of digital making together with the tactility of physical interaction. Building on the conclusions generated by Ross Stevens' and Bernard Guy's work "Lissom", this study explores how CGO (Computer Generated Objects) can be used by physical prop-makers to enhance the perception of reality in the increasingly digital film industry.

Textual analysis of special effects films shows that CGI and practical effects influence films through Narrative, Audience Experience, Spectacle, Visual Branding and Believability. Through material testing and critical iterative creation, this research defines the skills and knowledge required to effectively design special effects using the J750. Liaising with overseas print bureaus, I also use my knowledge to facilitate other students' use of the J750, allowing me to analyse the strengths and weaknesses of this technology from a thematic perspective. In addition to this, I also conduct my own prototyping tests to understand how to exploit the technology at a more advanced level. This range of technical and contextual knowledge ultimately result in the production of two final prototypes, which reflect different aspects of my research. These final prototypes will be presented in short films, which will be reflected upon to suggest conclusions on the future 3D printing may have in the film industry.

PREFACE

Acknowledgements

The prototypes generated as part of this thesis would not be possible without the funding support from MADE, the NZ Product Accelerator and Stratasys.

Furthermore, I would like to thank Ross Stevens and Bernard Guy for supervising and guiding me throughout my research.

I am also grateful to many of the faculty from the School of Design, and also Darlene Farris-Labar and Susanna Leung.

Finally, to my family, friends, and loved ones - thank you for your support and encouragement.

Author's Note

This thesis is a theoretical and practical exploration into a specialised manufacturing process and its relevance to an industry.

The research specifically focuses on the J750 3D printer, which unlike other 3D printers available, can simultaneously generate full colour, transparency, and flexible material in a single print.

To effectively communicate my ideas and the relationship of 3D/4D printing to the context of cinema and filmmaking, I have elected to use first person tense throughout this document. My writing style is partially targeted at the non-academic audience I am hoping to inform and influence with this research, which are practitioners in the film industry.

I also use MLA7, as this referencing style best suits the cross-disciplinary nature of this research.

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INTRODUCTION

As computer technology has developed over the years, the use of Computer Generated Effects (CGI) has become a dominant tool in the filmmaking industry. While this has expanded the potential for more fantastical and impossible stories to be told, the audience can also feel a disconnect between the digitally created illusions and their own experience of the real world. Speculation at Victoria University of Wellington had already begun concerning how filmmakers may be able to use multi-material 3D printing technology to produce Computer Generated Objects (CGO) to bridge this divide. The production of the short film "Lissom" by Ross Stevens and Bernard Guy demonstrates this potential using a combination of three and two-material Stratasys Connex technology.

The use of flexible materials in conjunction with hard materials gives prints the opportunity to articulate and move over time. This added dimension turns 3D printing into 4D printing, where the prints may change in appearance, form or position. This gives 4D printing the opportunity to create once-impossible illusions, similarly to CGI. This research does not intend to replace CGI, which can achieve much larger scale illusions, such as the creation of entire alien planets and other impossible phenomena. There is the potential for 4D printing to create smaller-scale effects, which may particularly be of use with regard to character enhancement and augmentation.

The recent release of Stratasys' new six material and colour 3D printer, the J750, turns the speculative idea proposed by "Lissom" into a reality. With the addition of colour to multi-material printing, there is the potential for filmmakers to create believable object effects that are inseparable from the natural organic world.

This research will explore the potential this new technology has in the filmmaking industry. Technologies are often forgotten if they do not have a realistic application, and the J750 could create an impact on the way filmmakers use special effects to tell stories. This research will also explore the place 4D printing can have in filmmaking, by analysing the current position special effects have in this industry. The thematic analysis of successful special effects will inform my design research, which will also be supplemented by the technical exploration of the procedures needed to exploit the J750 to its potential.

The outcome of this thesis is the production of two prototypes, which have been filmed to demonstrate the effectiveness CGO has in creating a special effect in the real world.

DEFINITIONS

3D Printing:	The manufacturing process which constructs a digital file, layer by layer, into a physical object.
CGI:	Computer Generated Imagery. Special effects constructed by a computer for use in filmmaking
CGO:	Computer Generated Objects. Proposed by Stevens and Guy, this is the term for digitally created 3D prints which have the capacity to create filmic illusions similar to CGI.
J750:	A six cartridge 3D printer manufactured by Stratasys, which has the capacity to print in soft and hard materials, and full colour.
JPEG:	An image file format.
STL:	The file format used by 3D printers which contains 3D mesh/form data.
Tango:	The name designated by Stratasys for their soft and flexible material. Comes in TangoBlack or transparent TangoPlus.
Vero:	The name designated by Stratasys for their hard rigid material. Comes in a range of colours, including transparent VeroClear.
VRML:	The file format used by colour 3D printers which contains 3D mesh/form data, and the information needed to map a coloured texture to the mesh surface.

RESEARCH OVERVIEW

Aims and Objectives

1) Investigate the current state of character enhancement and augmentation in the special effects industry:

    a) Analyse the use of practical and visual effects surrounding character creation in film through literature, film and conversational texts.

    b) Create a taxonomy of film scenarios for the future design experimentation of character-driven special effects.

2) Develop techniques that will effectively utilise current colour 3D/4D manufacturing technologies, and create and test examples of colour 3D/4D printing that can be used as special effects in film.

    a) Conduct material testing through continuous iteration and critical assessment and articulate a workflow to support 3D/4D printing techniques for practical character effects.

    b) Create prototypes in response to the developed film taxonomy and developed practical techniques.

    c) Film prototypes and compare and contrast in relation to digital effects in order to determine the strengths and limitations of 3D/4D printing special effects.

METHODOLOGY

Introduction

In order to understand how the new and emerging technology of the J750 may be placed in a certain industry, I required an understanding of the needs of this industry, as well as the technical capabilities of the J750 itself. This led to me developing two methods of research, the first based on qualitative analysis, the second focused on research through design. As I progressed throughout the research, aspects from the two sides fed into each other, influencing my understanding of both areas. Aim 1 illustrates the process needed to gain a theoretical understanding of the place special effects have in the film industry, particularly in regards to character enhancement and augmentation. Aim 2 shows how I will gain expert knowledge of the J750, and learn the best way to apply that knowledge to the relevant area of the film industry.

Aim 1 - Methodology

The first aim required the use of textual analysis, a research method which systematically studies and reflects on relevant texts. As well as academic texts, this also included films which demonstrate relevant special effects.

Initially, textual analysis assisted me in identifying themes in my literature review which would justify further research (Hammersley 578). This background research helped me explore my field of study, giving me an understanding of special effects, and how 3D printing has the potential to influence them.

In addition to my background research and literature review, I also used textual analysis in order to fulfil Objective 1a. I intended to create a taxonomy by analysing 10 films, selecting those that have received awards for practical or digital special effects. This taxonomy was a system of classification, making sense of the various elements that are instrumental in the creation of a successful film effects sequence (Bloor & Wood 164). After some evaluation, this analysis was relaxed to a thematic analysis of academic literature which discusses special effects, in relation to the 10 films. This was accompanied by small case studies of certain character augmenting effects. While less strict than my original intentions, this method of textual analysis allowed me to identify the range of elements that contribute towards successful character-augmenting special effects.

In reversal, I also gained an understanding of the impact special effects have on a film. This is also demonstrated through texts secondary to the film itself, such as interviews, documentaries and books often used for promotional purposes. Textual analysis allowed me to acknowledge the bias apparent in such texts, and to find information relevant to my overall thematic analysis (McKee 64).

Aim 1 - Research Methods

To perform this methodology, a variety of methods are required. Textual analysis is used while performing these methods, to critically find themes relevant to my aim.

Reading Academic Texts - Gather and read a range of academic texts to discern their significance.

Watching Visual Texts - Watch films which exhibit successful uses of special effects. These texts can be selected based on: my past knowledge, the awards they have received, and the academic regard in which they are held.

Watching Secondary Visual Texts - Instead of written documentation, films also have accompanying secondary visual texts that are often created by the studios and filmmakers to explain or exhibit important elements of their work. By watching texts such as behind-the-scenes documentaries, I am able to gain an understanding of how certain special effects were made, and what the filmmakers' intentions were.

Reading Published Film Reviews - Slightly different to more objective academic writing, film critics can describe their personal response to a film. This may be subject to a range of bias, such as emotional or sociological, however these responses are important to assess whether certain effects appear successful to the general public audience.

Note-taking, Recording and Organising - The above methods require effective note-taking to record anything that may be useful in the future. By organising these notes, I can begin to identify relevant themes for analysis.

Writing Reflective Thought - As well as taking note of relevant pieces of information from the studied texts, it is also important to combine this with unstructured reflective thought. By writing down any thoughts I have while reading and watching, I can then refer back to these later to assist when writing my thematic and close analysis.

Presentation of Themes and Analysis in Written Form - Finally, for this methodology and methods to be of future use, I must present and articulate my themes and analysis in a clear and coherent way. This writing links my notes on academic, visual texts (and so on), with my own independent, critical thought and analysis.

Aim 2 - Methodology

Aim 2 outlines the process required for my main body of research, which mostly consists of practical experimentation, observation, and design. A "research through design" methodology is used when a researcher desires to gain new knowledge through practical exploration of design methods.

Objective 2a required material testing, as the J750 was such a new and relatively untrialled form of rapid prototyping (Martin & Hanington 82). My material testing involved the evaluation of a wide range of prints, which included J750 prints produced by Ross Steven's INDN Future Under Negotiation (FUN) class. By analysing the two different input formats the J750 takes, I was able to pull themes from my written analysis, and compare the attributes the two different input types produce.

My main body of research was formed through the generation of my own work. By iteratively creating material outputs, I was able to critically reflect on and improve my prototypes (Burdick 82). As Pieter Van Stappers explains, "through realizing 'products' designers absorb knowledge from different directions and confront, integrate and contextualize this knowledge" (84). Furthermore, prototyping was used to complete Objective 2b (Martin & Hanington 138). As a consequence of the limited availability of the J750, many of my early prototypes in response to Objective 2b also doubled as material tests for Objective 2a. Ultimately, I created two final prototypes using the two J750 input methods. As the main physical output of my thesis, these prototypes were a result of my thorough prior research and greatly influenced the final conclusions of my research.

It is important to note the iterative nature of my research. It is common for the design process to take a cyclical route, looping back on itself as the designer evaluates the work they have done so far (Milton & Rodgers 15). Lawson notes the complex and unpredictable route a design process often takes, as a designer cannot completely direct themselves through a completely linear process as there will naturally be unforeseen opportunities and issues which arise (39).

As the designer continues through this progressively looping process, each loop contains several important processes that enables them to gain new knowledge and move forward. Milton and Rodgers details four steps in each loop: understanding, observing, visualising and reviewing (15). I would also insert "implementing" after visualising, as an idea will evolve as it goes from a 2D sketch to a 3D printed object. There is even some difference between a 3D model that is generated purely to demonstrate concept, and a 3D model that has the technical capacity to be printed successfully within the printer's requirements.

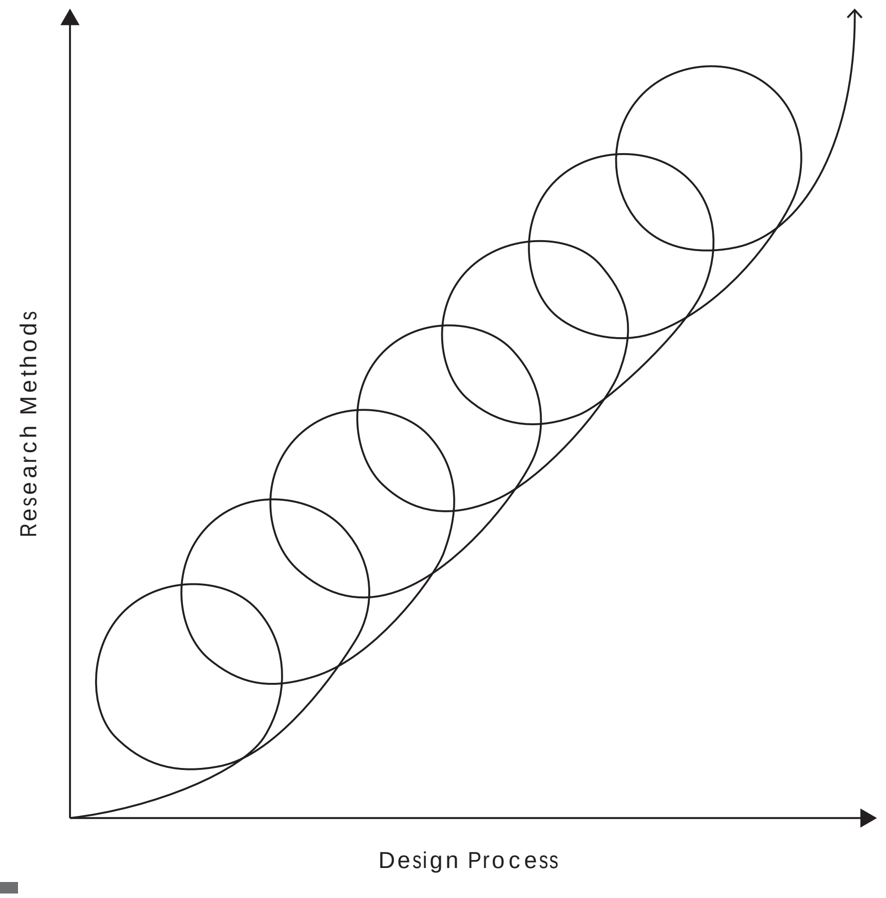


Fig. 0.01. Iterative Design Process. Diagram adapted from Bloor, M., & Wood, F. *Keywords in Qualitative Methods*, (London, United Kingdom: SAGE Publications, 2006), 15. Print.

Aim 2 - Research Methods

To fulfil this iterative, practical methodology, my research methods included:

Concept Visualisation - The most obvious example of this is loose, expressive sketches which visualise my ideas and intentions. This also included the collaging of inspiring textures into existing sketches. I also did 3D sketches - CAD of my ideas, in order to inspect them in three-dimensional space. These 3D models did not have to be constrained by the techniques needed to create a well-modelled file for 3D printing. Through these methods, I was able to systematically narrow down what the visual and physical aspects of my project would be.

Making - This involves the process needed to make a 3D print. I take the final idea created through concept visualisation, and transform it into a printable file. Through Autodesk Maya, I use mesh-sculpting techniques such as box modelling. This involves the creation of a form from the general to the specific. This way, I am able to determine the overall silhouette and function of my print before modelling in constricting details. After this, I put the models through a mesh repair program, before printing them. Some prints were first manufactured on a lower-quality, 2-material Connex printer before finalising their forms to be printed overseas in full colour.

Observation - The critical observation of any printed part allows me to identify and record qualities for further assessment. In the early stages of my research, I had the opportunity to facilitate and study the J750 outputs of a class of third year undergraduates. I observed how they worked with the J750, and conducted analyses of each of the 45 objects, which I then evaluated in detail. In regard to my own printed work, I practised stepping back from my work to take critical note of what needed to be improved for the next printed iteration. This review process often starts as I clean the support material off the object. Support material must be meticulously cleaned off layer by layer, which allows the scrutiny of every aspect of the print in detail.

Looking and Play - While the method of Observation is critical and intentional, it is also valuable to acknowledge the importance of more abductive ways of thinking. Crouch explains that "Abductive thinking often takes place unconsciously and decisions are arrived at quickly, hence its colloquial name 'intuition'" (Crouch 22). By sitting back and simply playing with my 3D prints, I was able to intuitively identify what makes the most satisfying designs from an interactive standpoint. Play can also identify more serendipitous qualities that a stricter form of observation would have passed over.

Evaluation - Through the various stages of this thesis, I gathered my observations into written form and evaluated the success of each print. When studying the undergraduates' prints, I also conducted a rigorous thematic evaluation of their work, taking themes from my written observations, and using them to compare and contrast the two manufacturing methods the J750 could produce. When evaluating my work, I used a more reflective, loose form of evaluation. I wrote notes and ideas about what did and did not succeed, then articulated them into a piece of writing explaining my thoughts and what information I would carry into the production of the next print.

Photography / Filming - I regularly filmed and photographed my printed prototypes in order to check whether they were effective once placed in front of a camera. While part of my intentions are to create meaningful interactions with actors, these interactions do still have to be successful and compelling in front of the camera. I would then evaluate these short videos, in the same way I evaluated the physical objects, to obtain new understanding about the best way to film my final work.

Conclusion

Design research uniquely relies on a mix of analytical and creative thinking. In order to provide structure to such an individual process, the definition of methods and process is vital in order to express the validity of the knowledge acquired. Through the methods outlined here, I have been able to create a solid body of research, and express this practically through final, informed prototypes.

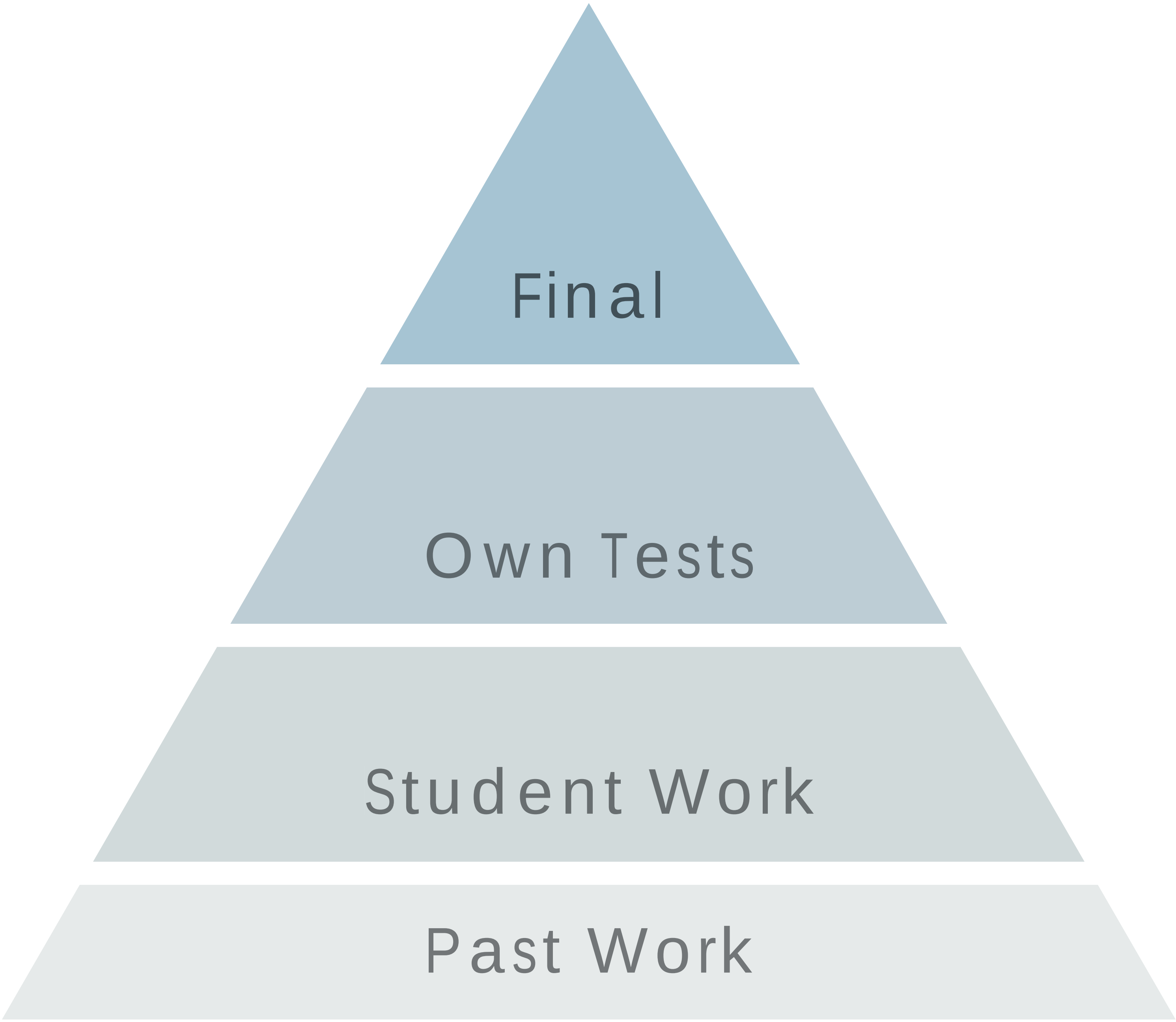


Fig. 0.02. "Structure of J750 Investigative Work". *Author's Own Diagram*. Oct. 2016. Diagram.

Fig. 1.01. "Final Fruit before Support Removal" *Author's Own Image*. May. 2017. Photograph.

PART 1:

BACKGROUND RESEARCH

How could 3D/4D printing impact the way special effects are used in the film industry?

LITERATURE REVIEW

Introduction

As the nature of special effects in film has evolved, there has been a shift from physical to digital, resulting in a predominantly CGI heavy climate in the world of cinema. As an admirer of both practical and visual effects, it seems that filmmakers are lacking a balance between the two approaches. 3D printing could solve this, yet there is little research done to address this.

My attention was drawn to this issue through my experience of the latest resurgence of superhero films, mostly from Marvel. These films are some of the most apt to bend reality, creating hyper-realistic sequences of events that could not actually happen in real life. This is fine in moderation, yet I am finding the formulaic use of CGI draining. I am beginning to be nostalgic for a time when the film aesthetic was more natural, when effects were often created practically.

In this review, "special effects" is an umbrella term for all illusive devices created for film, often to fabricate scenarios in fictional worlds. Within this lie two sub-categories, "visual effects" and "practical effects". It is possible for the film industry to blend these two fields together, through 3D printing. By using effects that are both practical and digital, filmmakers would not need to rely so strongly on CGI, thereby giving them a more rewarding filmmaking experience and genuine end product. This literature review identifies the need for an alternative that will bridge the gap between CGI and practical effects. 3D printing can achieve this, as new technologies like the J750 are developed. The incorporation of movement and colour into 3D printing poses new opportunities, but to execute these successfully, research must consider the filmic context in which this technology will be used.

History of Practical Special Effects in Film

To discover how 3D printing can be used for practical special effects in filmmaking, there needs to be an understanding of the evolution of special effects throughout filmic history, especially in the field of practical effects. "Practical effect" includes elements that are physically present when filming, such as props, prosthetics, and miniatures. The design and execution of props and other special effects have a huge role in defining the genre and aesthetic of a film (Smuszkiewicz 223).

One way of analysing the evolution of special effects throughout history is through the analysis of films noted for their advances in special effects. For example, the comparison of Méliès' 1902 silent film *Le Voyage Dans la Lun* and Kubrick's 1968 film *2001 A Space Odyssey* highlights the huge developments in film techniques in just over half a century. These films both heavily rely on practical effects. In Méliès' film, these effects are highly stylised, while Kubrik's film utilises these effects to create a more realistic aesthetic (Boron 18, Hall & Neale 218).

In terms of literature, Norman M. Klein goes far beyond the use of special effects in film, identifying unlikely precedents such as Leonardo da Vinci and Baroque architecture (7). The most relevant information can be found in the third part of the book, which specifically discusses the use of special effects in film, using examples such as Kubrick to examine the thematic implications special effect tools provide (Klein 233).

While Klein examines the wider social consequences of special effects, Hall and Neale take a technical and economic perspective (1).

The authors explain how the presentation of special effects in one successful film sets a standard for following films, such as production of *Jurassic Park* and the subsequent aesthetic of the *Star Wars* prequel films (Hall & Neale 218; Spielberg; Lucas).

Behind-the-scenes documentaries provide specific examples of the use of practical effects in films. Notable examples include the making-of documentaries for the *Alien* films, *The Lord of the Rings* trilogy, and *Blade Runner* (Fincher, Cameron, Jeunet, & Scott; Jackson; Scott). These kinds of sources will typically have a bias toward the promotion of their respective films, so must be treated critically through textual analysis.

Of significance is a practical effects manual by Bernard Wilkie, an industry professional. Written when special effects were largely practical with few computer-generated effects, it explains the techniques used at the time (Wilkie).

Meanwhile some case studies of the use of practical effects are offered by Robley and Merrill's respective magazine articles. While less reliable, they provide helpful information on the process of making practical effects, and the advantages and disadvantages of such techniques (Merrill; Robley). They note that the use of these techniques is becoming rarer, due to the rise in popularity of CGI and visual effects.

The Perception of CGI

Visual effects are virtual or optical tricks, most often created today through CGI in post-production. The rise of CGI is detailed in a number of articles. Similarly to Hall and Neale, Pierson details the early years of this form of special effects. (159). Before landmark films like *Star Wars*, visual effects were mostly performed by independents and small commercial effects houses (Turnock, "Before Industrial Light and Magic.." 134). Pierson also explains the past history that informed the aesthetic of CGI today, noting the effects in James Cameron's 1989 *The Abyss* which strived to be hyper-realistic, yet were held back by the technical capabilities of computer simulation (172).

The aesthetic of CGI is mentioned in most articles, with a few discussing the impact this presentation has on an audience's perception of a film.

Singh identifies "a parallel development of dominant ideas of what CGI represents and how it should be read", noting that CGI is used to make a film realistic and believable, but also to create spectacle (543). These contrasting features of CGI have intermingled, making the images "more-than-real", bringing "the constitution of reality into question" (546).

Blackmore takes a more critical approach to this marriage of spectacle and realism. He proposes that CGI has caused us to move "the eye-camera through space and around objects more quickly than the eye can comprehend" (370). Audiences are becoming used to this overstimulation, Blackmore noting sequences "that made the eye wince in 1982… is now a laughable dribble of action" (370).

Singh also notes that nowadays the audience is more aware of the presence of CGI, viewing with a more critical perspective (555). This critical perspective means studios push themselves to create increasingly exciting and spectacular CGI effects in order to attract an audience (549).

To highlight the consequences of this change, a comparison can be made between Peter Jackson's *The Lord of the Rings* and *The Hobbit* trilogies, created over 10 years apart. Critics note that Jackson chose to use far more CGI in *The Hobbit* than in the original *LOTR* films. These new effects lacked the natural realism that were so successful originally, instead presenting a hyperrealistic aesthetic which distracted the audience (Renee; Turnock, "Removing the Pane of Glass..." 31). Viggo Mortenson, a star of the first trilogy, shared the opinion that Jackson had begun to overuse special effects (Robey).

Mortenson's comment introduces another group affected by the evolution of CGI: the creators of films. Motion capture, a digital process that captures the movement of actors for the use in visual

effects, was originally greeted with fear by film industry professionals. Animators shunned it as a way to cheat the creation of animated movement, while actors rejected it as a form of true performance (Freedman 38).

Directors and actors simply prefer to work with practical effects, with director Christopher Nolan electing to film as much practical footage as possible in his latest film *Interstellar* (Ashley; Nolan). He explains that filming practically allows him to make more informed creative choices, and is more enjoyable than shooting in front of a green screen (Actionzone; Ashley).

Merrill explains that films like *The Lord of the Rings* and *Star Wars* had such successful effects because they used an effective balance of both practical and visual special effects (2003, p. 164). He cites Animation Director Rob Coleman, who explains: *"For many directors, production designers and prop masters, there is nothing quite like being able to hold a prop-prototype or model in their hands. Viewing a model or prop on a computer screen only tells you part of the story."* (qtd. In Merrill 164)

This fact identifies a need for an alternative that will bridge the gap between CGI and traditional practical effects. As CGI does not interact with the flaws and complexities of the real world, its hyperrealism can sometimes appear distracting and inauthentic.

3D Printing Practical Effects in Film

This need for an alternative that will bridge the gap between CGI and traditional practical effects is beginning to be answered by 3D printing, a tool that shares aspects of both digital and physical creation. "3D printing" is defined as the process used to manufacture a physical object digitally modelled on a computer. Typically, this is done by building up layers of material with a machine called a "3D printer".

This technology of printing static forms through digital means is growing more popular, especially in the creation of props. 3D printing allows for high customisation and rapid production which is perfect for use in the fast-paced film industry (Khan & Mohr 26). There are already many examples of different 3D companies working in collaboration with the film industry in order to manufacture props (Changing Technologies, Inc.; Geller; Stratasys).

As these innovations are so new, there is a lack of academic documentation on the application of this technology, so detailed magazines such as *Empire* begin to show more relevance, communicating up-to-date information. In an interview with Helen O'Hara from the magazine *Empire,* the creators of the recent science-fiction film *Guardians of the Galaxy* explain in detail how they used 3D printing to manufacture props. O'Hara also explains that in addition to *Guardians of the Galaxy*, 3D printing was used in *Thor* and *Maleficent* (O'Hara; Stromberg).

The most documented use of 3D printing in film interestingly comes from the realms of stop-motion. Debruge explains that Laika, a studio specialising in this practical form of animation, has developed this technology in *Coraline*, *Paranorman* and *The Boxtrolls* (Debruge, "Models of Innovation" 79). Most recently this was used to great effect in *Kubo and the Two Strings*. These films can be used as precedents when considering the potential possibilities of future work. In a series of articles, the trade magazine *Variety* goes into detail about the technology used, and the advantages 3D printing provided them (Cohen; Debruge, "Building a Better Puppet"). For example, since *Paranorman* in 2012, Laika animators have used 3D printing to create millions of faces with slight variations in facial expressions to give the animation fluid, natural movement. This degree of customisation would have previously only been available through hand sculpting, yet this process eliminates human error (Roper).

Currently, 3D printing can only create animation-level movement through stop motion. Research into 4D printing may change this, as the use of soft articulating materials can create movement in a single print. The static use of 3D printing in stop motion is vastly different to the use of 4D prints as actor responsive props.

Multi-material 3D/4D Printing

The term "4D printing" is used when a 3D print includes the fourth dimension of movement or change over time. This is usually done through multi-material printing, where a combination of materials allow a print to flex or articulate when influenced by some kind of force. Research by various institutions demonstrates that the film industry may benefit from this new technology.

A leader in multi-material printing research is Neri Oxman, from MIT. Her article "Variable Property Rapid Prototyping" explores how nature can inspire the design of multi-material printing to create efficient structures and forms (3). Her research develops the gradient mixing of materials that contain different properties, such as flexibility and colour (Oxman 5). Her paper goes into great detail on the topic of multi-material printing and her pioneering examples of design work set a precedent for future work.

This form of manufacture is possible through the use of Stratasy's Connex technology, which uses PolyJet technology to deposit various blends of materials throughout the creation of one print. Near the beginning of this research on April 4, 2016, Stratasys released their latest printer, the J750. At the time, no specifics were known about this printer, particularly about how to prepare files for printing. We did know that it has the capacity for six cartridges, and can therefore print in blends of soft and hard, and full colour at the same time (Stratasys, "J750 Brings One-Stop…").

One precedent specifically exploring moving 4D printing has been created by the Self Assembly Lab, who have designed Connex prints that will self-assemble when placed in water ("Self-Assembly Lab"). This movement is due to the different materials expanding from water absorption at varying rates, causing them to articulate.

Notably, the only work done in the area of film is Victoria University's "Lissom" project (Stevens & Guy) . Using the unique qualities created by Connex materials, the researchers created a video of 3D printed squid-like creatures that upon first glance, seem to be generated through CGI. This concept of 3D printing moving special effects could have huge significance in how the film special effects industry operates. Special effects have constantly evolved throughout history, and this new technology now augurs the genesis of a new aesthetic generated by the rapid technological development in physical manufacturing of digital special effects.

Conclusion

The above consideration of research performed in relation to the history and perception of CGI, the 3D printing of practical effects in film, and recent developments in 4D printing has identified new scope for future academic research. In addition, this review indicates opportunities for considerable future innovation in the film industry. A review of academic literature on both practical and visual effects reveals a divide between the two. It has been demonstrated that practical effects can be limiting, but draw-backs are also surfacing concerning the overuse of CGI. The rapidly developing field of 3D/4D printing has the ability to bridge this divide with great scope for further development.

INFLUENCE OF SPECIAL EFFECTS IN FILM

Introduction

To gain a comprehensive understanding of the function and purpose of special effects in film, thematic considerations were gathered through the textual analysis of academic, visual, and supplementary texts. Close analyses of specific character effects are also included here, to explore how the special effects most relevant to 3D/4D printing are deployed. The combination of the general with the specific allows a multi-faceted, practical understanding of the place 3D/4D printing can take in film. Overall, I find that special effects influence films through the distinct themes of Narrative, Audience Experience, Spectacle, Visual Branding and Believability. Based on textual analysis, these themes are included in the main body of the following chapter, while the close analyses of specific character effects are inserted throughout. In order to narrow the wide scope of material available, recent films are prioritised over historical examples. While historical examples are nonetheless important, it is more relevant to the analysis of the potential future effects of current developments in 3D/4D printing to understand the context of contemporary films, rather than the context of films in the past.

Narrative Demands

Nowadays, many films across all genres use special effects to assist filmmakers in transforming their raw footage to meet the expectations modern audiences have surrounding believability.

There are some specific genres that rely on special effects to achieve the narrative demands of the genres. In her essay "The Fantastic", Vivian Sobchack broadly separates films into those "which operate generally within the confines of verisimilitude— events which happen according to natural possibilities— and those which defy or extend verisimilitude by portraying events which fall outside natural confines" (312). This latter category can also be described as the "fantastic" or "impossible" films, which basically consist of those in the fantasy, sci-fi and horror genres. Without special effects, many filmmakers that create within these genres would not have the opportunity to tell these stories. These genres, while portraying imaginary phenomena, are rooted in realism. They reference human experience, desires and fears through the presentation of magic, futuristic speculation and the machine, and psychological and bodily horrors (Sobchack 315-316).

Imagine what it would be like to experience films like *Harry Potter, Star Trek* and *Jaws* without their special effects, both digital and practical. Each of these films relies entirely on special effects to enhance their characters' interactions with otherworldly elements that could not be replicated in the real world. Relating the genres to realism, Sobchack says "the horror film contests and complements what is taken to be 'natural' law; the SF film extends it; and the fantasy film suspends it" (315). This will influence the type of special effects needed for each genre, dictating how they will 'fit' into the filmed diegetic world. Special effects need to convincingly contest, complement, extend and suspend 'natural' law to effectively support the narrative demands of the genres. As Barnwell comments, "the visual dominance of special effects is often criticised for detracting from the story in some way, when they are there primarily to support those elements" (116). Thus, special effects must support the demands of the narrative to contribute to the success of a film.

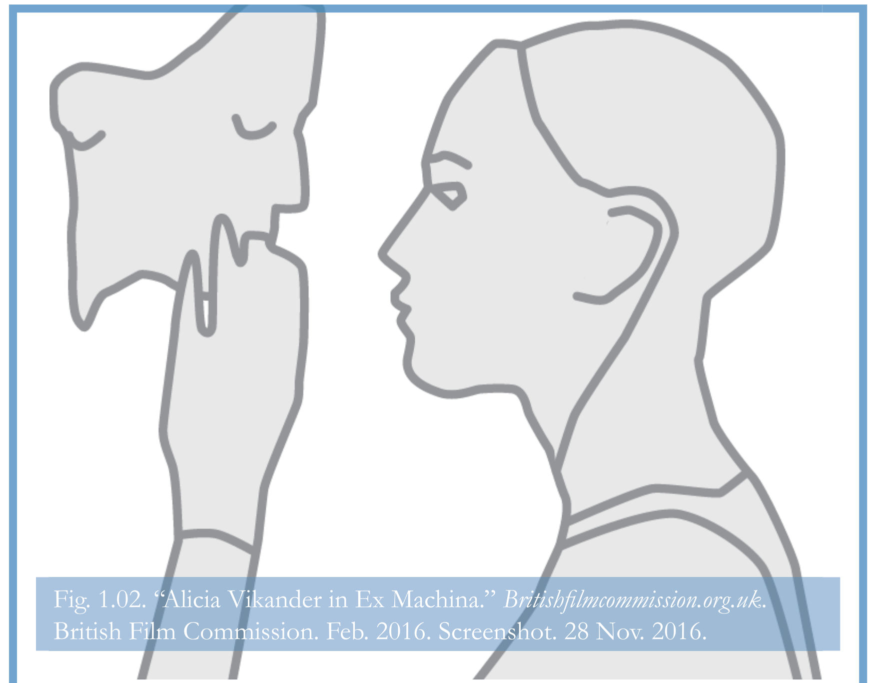


Fig. 1.02. "Alicia Vikander in Ex Machina." *Britishfilmcommission.org.uk*. British Film Commission. Feb. 2016. Screenshot. 28 Nov. 2016.

Ava, Ex Machina

Ava, the pivotal character in *Ex Machina*, relies on special effects to reinforce her unnatural presence. As an advanced artificially intelligent android, much of her character design takes advantage of the lingering artificial qualities of CGI. She is not expected to behave in a completely real and organic manner. Her transparent, reflective form emphasises her questionable humanity, as director Alex Garland describes "You get a sense of a girl flickering in your periphery vision as you look at a machine" ("Making Ex Machina"). As we learn in the final act of the film, she is able to wear skin over her robotic form, making her identical to a human. However, the filmmakers chose not to do this till the end, as a visual symbol showing her development as a character.

Gollum, The Lord of the Rings Trilogy

As a film that put the New Zealand company Weta Workshop's effects onto the world stage, *The Lord of the Rings* trilogy relies on extensive amounts of practical and digital effects to realise the world of Middle-Earth. The most impressive effect, however, is the work done to create the character Gollum. As the character representation of the effects of the One Ring, Gollum has significant narrative purpose, serving as an antithesis to the main character, Frodo. As Gunning asserts, Gollum's physical form "recalls simultaneously an infant, an aged person, a foetus, and a corpse". While physical prosthetics successfully achieved the creation of many other characters in the film, monstrous or otherwise, Gollum's reductive form and bulbous eyes were so different to the human frame that motion capture CGI suited the character's production.

Visual Branding

Filmmakers also utilise special effects to help them achieve the unique aesthetic that will market their film effectively and maximise audience numbers. In fantasy, sci-fi and horror films especially, a production designer relies on special effects to build their imagined fictional world.

M. John Harrison, a fantasy/sci-fi author, comments that the art of building a world is similar to the creation of a brand. He comments, "JK Rowling & JRR Tolkien have done well for themselves, but –be honest!– neither of them is anywhere near as successful at worldbuilding as the geniuses who devised 'Coke', or 'The Catholic Church'" (Harrison). If we consider the fact that a film is a product which is marketed and sold for economic benefit, then it makes sense that the aesthetic construction of a film is vital to a film's success. Based off a long-running TV series, J.J. Abrams' 2009 reboot of *Star Trek* mines a rich history of jewel-bright uniforms and sleek spaceship interiors. Alien characters and creatures are scattered amongst humans, and the alien worlds explored by the Enterprise crew each have a unique flavour that are nonetheless connected to the *Star Trek* universe. By using the design language of a much loved TV series, Abrams convinces his audience that this new film is also worth seeing.

Even with films that exist in the "real" world, special effects can often be used by filmmakers to subtly change characters or the environment to influence the aesthetic and context of the film. As Stephen Prince observes, many of the 1968 San Francisco scenes in David Fincher's *Zodiac* had to be created through CGI to accurately depict a certain historical period (Prince 33). CGI and other special effects are dependent on budget, and filmmakers may have to think creatively about how "genuine" they want their film to look if they are short of funds (Barnwell 11; Beard qtd. in Ettedgui 170).

Believability

This use of special effects to achieve realism ties into the next theme, believability. As well as contributing to unique world building, the creation of digital and practical special effects are used to immerse the audience in a believable world. If something seems "fake" a viewer is distracted by this, and pulled out of the story. Audience reaction to special effects is nuanced according to the genre and context in which the special effect is presented. In the fantasy, sci-fi and horror genres, the scenes presented are often so outlandish that the viewer will assume this was achieved through special effects, usually CGI (McClean 55). This makes them noticeable to the audience as they are so impossible. As stated above, filmmakers like David Fincher often use subtle special effects to change the environment or characters in more "realistic" genres. As McClean explains, "for the fantastical setting, the intention most likely would be to create a spectacular delight. For the contemporary setting, the intention might be to describe the diegetic world in a convincing manner" (56). We can then assume that an audience will be more critical of special effects presented in the fantastical, verisimilitude-defying genres of fantasy, sci-fi and horror than those in a diegetic setting.

James Cameron, director of hugely successful films including *Titanic*, *The Terminator*, *Aliens*, and *Avatar* actually started in the film industry as a special effects technician (Cameron qtd. In Lussier). In his work as a director, he has been at the forefront of pursuing new innovations in special effects, which culminated in the production of the entirely digital, motion-captured film *Avatar*. Cameron postulates that "the lines will just continue to blur between CG and photography until it becomes meaningless" (Cameron, "Conversations…" 188). While Cameron's filmmaking indeed created an immersive and believable world in *Avatar*, the use of CGI, like any other tool, is not always so

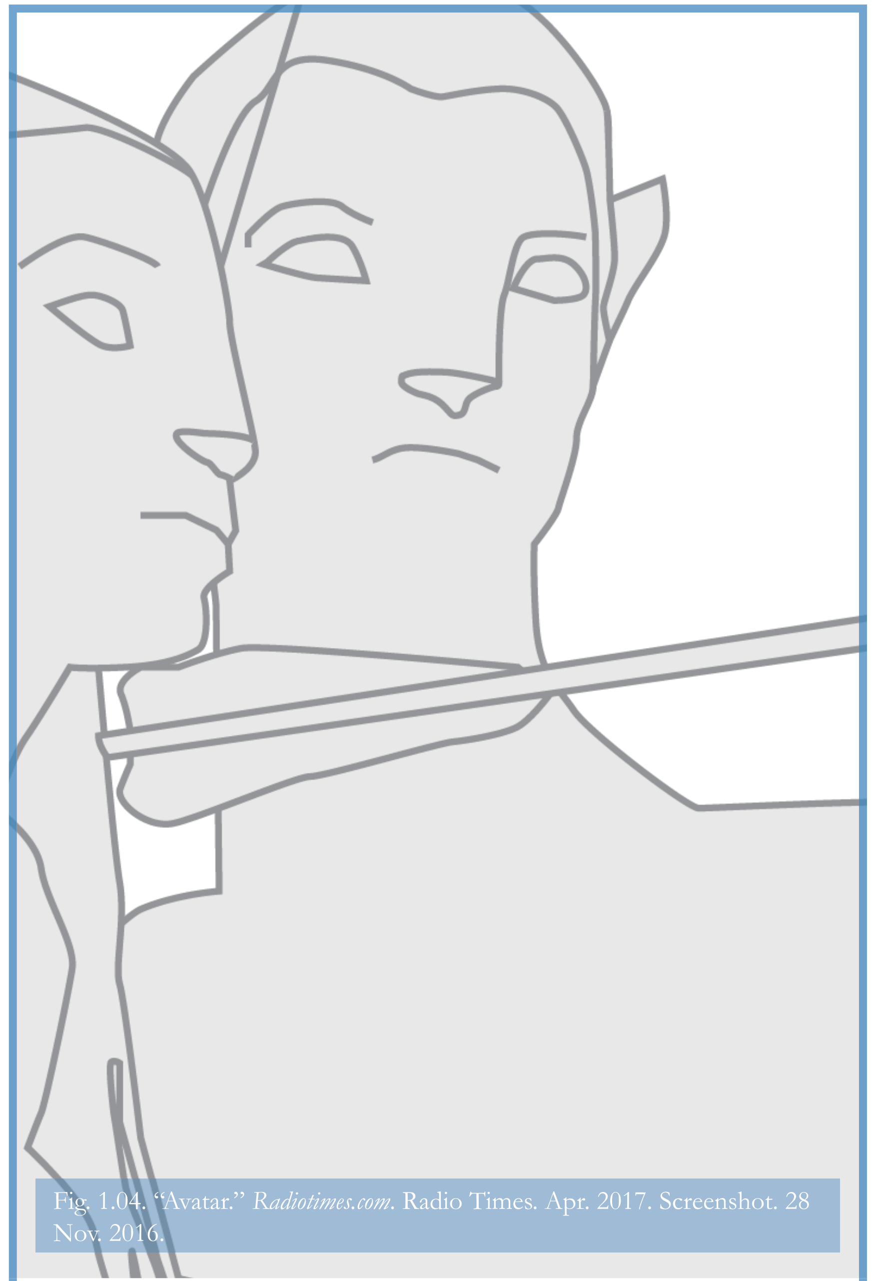


Fig. 1.04. "Avatar." *Radiotimes.com*. Radio Times. Apr. 2017. Screenshot. 28 Nov. 2016.

Na'Vi, Avatar

James Cameron took the motion capture technology used for Gollum in LOTR to the next level, using this digital effects technique to create alien characters that the audience empathise with. However, it is not just the Na'Vi alone that make this planet so compelling. Rather, it is the entire design of the planet and the flora and fauna it contains that makes such a rich and believable world. The motion-capture performances of the Na'Vi supplements this in such a way that the audience forgets that what they are watching on the screen is entirely digitally fabricated.

successful. Cameron’s opinion contradicts frustrations expressed by actors when asked to act with green screens and little reference (Bode 155, McKellen). While actors can imagine what it would be like to be in this imagined environment, it seems that it would still be quite difficult to do all of this and still give a believable performance.

Can the audience still believe these hyper-realistic special effects if there is a disconnection between the actor and CGI? Some recent big-budget films like *Mad Max: Fury Road* and *Star Wars: The Force Awakens* have made a concentrated effort to push back against this culture. *Fury Road*’s director George Miller used real-world stunts and effects, while *The Force Awakens*’ director J.J. Abrams referenced back to the practical nature of past *Star Wars* films, utilising animatronics and prosthetics (Redding). These effects demonstrate natural flaws, and other slight sensory feedbacks which are often missed in hyper realistic CGI. The critical success of these recent films indicate that audience preference is shifting back to practical effects.

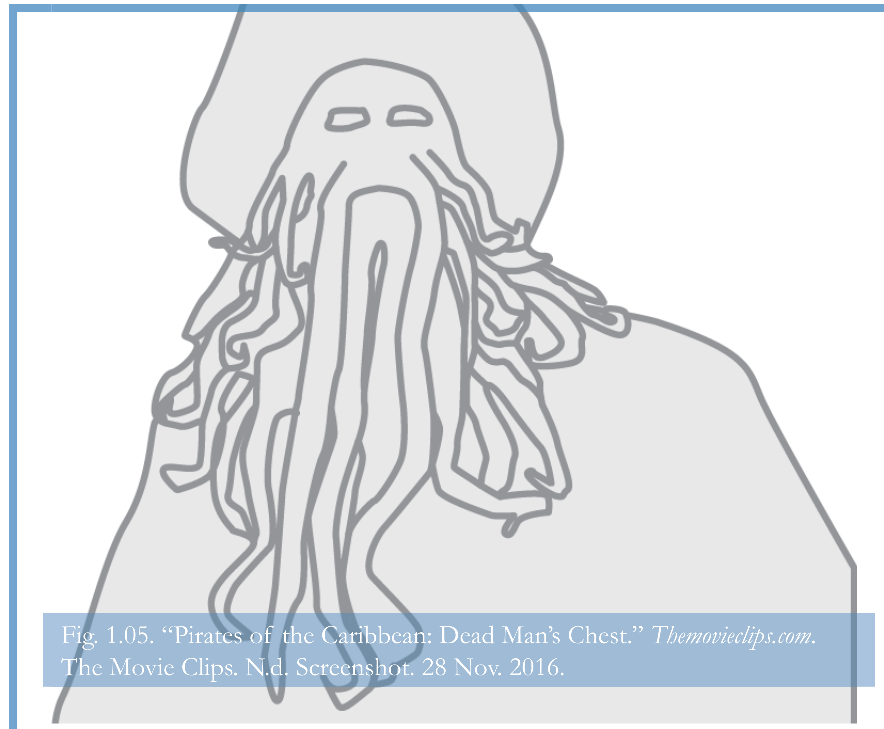


Fig. 1.05. “Pirates of the Caribbean: Dead Man’s Chest.” *Themovieclips.com.* The Movie Clips. N.d. Screenshot. 28 Nov. 2016.

Davy Jones, Pirates of the Caribbean

CGI and motion capture were also used to create the tentacled antagonist of the Pirates of the Caribbean films, Davy Jones. As his form is not necessarily a reduction of the human form, rather containing the addition of suckers and tentacles, he may have been made using prosthetics in the past. However, CGI can be used to create a more nuanced, expressive version of Davy Jones than the acted performance alone - the tentacles move according to his moods, and the breathing holes flare in the place of regular nostrils. The addition of CGI to his face and corrupted body expresses his connection to the sea in accordance with the larger-than-life style of Disney films.

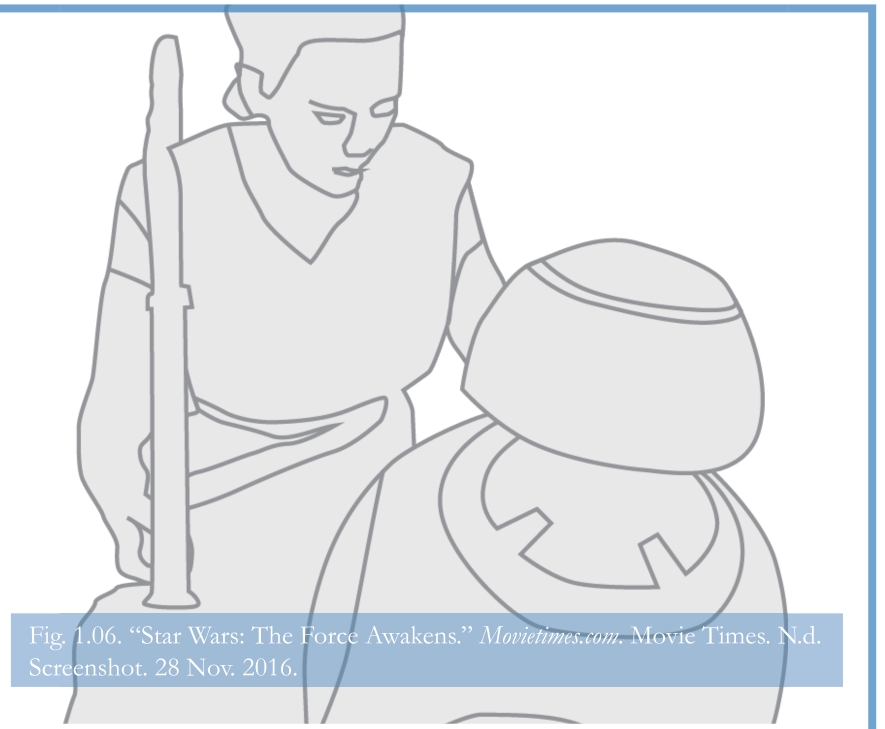


Fig. 1.06. “Star Wars: The Force Awakens.” *Movietimes.com.* Movie Times. N.d. Screenshot. 28 Nov. 2016.

BB-8, Star Wars: The Force Awakens

The reboot of a much loved series that relied heavily on practical effects to build a believable world (or galaxy), The Force Awakens acknowledges the merits of its past by continuing to use practical effects in combination with CGI. This is the most evident in the droid BB-8, which was realised using a series of different animatronics or puppets for different types of scenes (Brooks). The droid’s practical production was first revealed at Star Wars Celebration Anaheim. The revelation that the companion droid had been made as a physical effect was greeted positively by the audience (Brooks). The puppet had a significant presence throughout the film as a supporting character central to the plot, and the actors easily interact with it in any scene, whether action or character centred.

Spectacle

In her book “Plastic Reality”, Julie Turnock explains that blockbusters possess such an attraction to audiences because they provide “sensation, kineticism, and spectacle” (106). As many blockbusters happen to fall under the genres of fantasy, sci-fi or horror, their extension of verisimilitude is a perfect place for filmmakers to use special effects to create spectacle. Mulvey notes that spectacle is “stopping of narrative in order to gaze at a woman” (662). While many critics tend to use spectacle to disparage a film, Turnock cites academics such as Kirsten Thompson and David Bordwell to point out that this does not always sacrifice narrative integrity (Turnock 106). McClean builds on Mulvey’s point, saying “specularity can also be used to slow or stop the narrative, not to provide a substitutional element in place of story but a beat of pacing” so we can take a moment to experience a prior emotional or intellectual moment (71). This means that spectacular special effects can provide value if utilised in conjunction with narrative, instead of completely separately. This links back into the main question of this thesis - can we manufacture 3D printed special effects that will *augment* the portrayal of a character or character’s experience? Special effects that draw the eye do not necessarily distract an audience, in fact, the effect may prompt the audience to respond in an emotional or physical way that will impact the narrative itself.

As previously stated, James Cameron used technological innovations in CGI to create the effects needed for *Avatar*. As well as exhibiting a detailed, rich alien world full of colour and beauty, Cameron used the film to discuss world issues with his audience, particularly the impacts of colonialism and environmentalism (Cameron 192). The spectacle and emotional narrative of the film allows Cameron to communicate a strong message about the negative impact the human arrivals have on the native Na’vi without the film seeming like a lecture. The audience is so caught up in the spectacular, magical world of Pandora that it seems natural to want to protect it from violence. Without the extensive use of special effects, the film would have been quite different, providing a far less nuanced and less entertaining perspective on something the audience is already familiar with. In addition to this, without the pull of spectacle, it is likely that the film would have attracted a much smaller audience, limiting the spread of Cameron’s message.

After all, as Walter Benjamin explains, spectacle is a form of art worthy of seeing, stating “the shooting of a film, especially of a sound film affords a spectacle unimaginable at any time before this” (677). The act of going to a cinema was originally an act of seeking out spectacle.

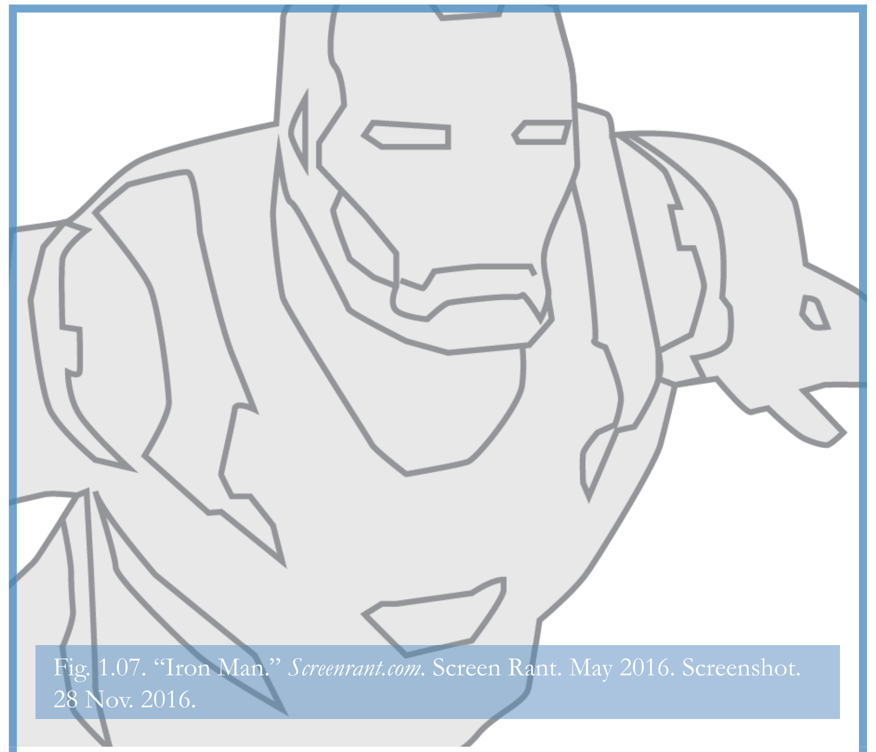


Fig. 1.07. “Iron Man.” *Screenrant.com.* Screen Rant. May 2016. Screenshot. 28 Nov. 2016.

Iron Man, Iron Man

As the first successful movie which launched the Marvel film franchise, the design of Iron Man’s suit was heavily influential on the critical reception of the film. It had to reference the designs found in the comic books, but appear modern and functional. Legacy Effects used both physical prop-making and CGI to realise the suit in different situations of the film. The physical suit was produced using 3D printing. Scans of actor Robert Downey Jr’s body enabled the making of a suit that fit perfectly, allowing him to perform unhindered (MacOwan). While the filmmakers are secretive about the particular moments where CGI or physical effects are used, it is safe to assume that the physical suit was used for close-up, drama scenes, while CGI was used for the more “impossible” action scenes.

In fact, the earliest films had no plot or narrative - for example, the 1896 film depicting a train arriving at a station (Lumiére and Lumiére). The simple display of illusion was enough to draw a large audience. Sobchack explains “the common ground that links audience desire (to see the unseeable) with studio concerns (to sell movies) is their general dependence upon special effects” (317). That is to say, special effects fulfil an audience desire to see the unseeable. As the film audience becomes more saturated by these special effects, filmmakers strive to maximise impact by creating newer, bigger and more unseen spectacles than ever before.

Audience Experience

Another aspect that influences the role of special effects in film is how much audience knowledge there is regarding their creation. Peter Jackson's *The Lord of the Rings* film trilogy is well known for the large amount of practical and digital effects used to make the world of Middle Earth as realistic as possible. Illustrated in detail through DVD documentaries, the filmmakers show how practical effects such as detailed props, prosthetics, animatronics and miniatures are used to give as much depth as possible to this fantasy world. They also show how CGI supplements this heavily, especially in creating fantasy landscapes, large scale battles, and creatures such as the Balrog, the troll, and of course, Gollum. Gollum is introduced in the middle film, *The Two Towers*, as a character that is of vital importance to the overall narrative due to his history with the Ring. Created using a mix of key frame animation and motion capture (Robertson 16) Gollum started a conversation in Hollywood about the line between animated character special effects and acting (Freedman 43).

The importance of Andy Serkis's performance to the final computer generated character seen on screen was heavily emphasised in the publicity surrounding the film, while the extended edition DVDs are transparent about the efforts Weta Digital went through to achieve this. This transparency Weta has around their effects differs to many other effects houses, which may be the reason for "Weta Effect" discourse (StoryBrain, Amidi, Anderton). In 2015, a video titled "The WETA Effect, or, Why Special Effects Peaked in the 90's" was published, which has now received over one million views on YouTube. The video criticises how CGI has developed to a point that studios "make everything in the scene look as glossy and as polished as possible, and the result is that these fully CGI scenes become more and more beautiful, and more and more impressive, and more and more phony" (StoryBrain). While this may be the case, it is interesting to note that this development has coincided with a huge explosion of available information due to the influence of the internet. As Singh explains, "the spectator's eye is trained to 'spot the CGI' due to increased exposure to technology" (Singh 543). Audiences now know how special effects are made, and are therefore more aware when they come across something "phony".

In contrast to Weta Digital, some filmmakers and effects companies deliberately choose not to disclose how they make their films. When asked how the 2014 film *Birdman* was able to seem like one continuous shot, director Edward Norton "didn't want to speak much about the making of the film… wanting the film to instead speak for itself" and maintain the "magic" (Acuna). It was only after the film received four Oscars that the Rodeo FX team disclosed the amount of CGI needed to transform the raw footage into the final, award winning film (FXGuide). Weta seems to be blamed for CGI saturation as it is a company known for being open about its creative process, which has

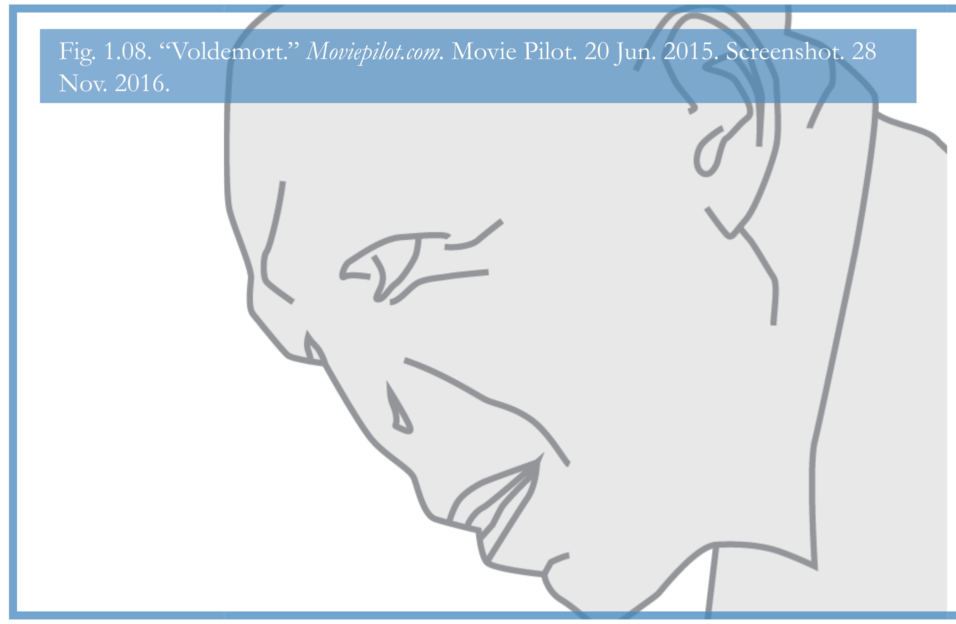


Fig. 1.08. "Voldemort." *Moviepilot.com.* Movie Pilot. 20 Jun. 2015. Screenshot. 28 Nov. 2016.

Multiple Characters - Harry Potter series

It is difficult to single out one character that truly embodies the amount of character-augmenting effects in the Harry Potter series of films. Of course, there are the most memorable, but there were also countless small effects which work together to make the world rich and magical.

One of the most famous antagonists in popular culture, Voldemort, had his face changed through a combination of CGI and makeup so that he resembled something inhuman with pale white skin and no nose. Dobby, another iconic character encountered throughout the films, was created entirely through CGI to achieve the impossible, tiny and skeletal proportions of the bug-eyed, charismatic house-elf.

Fig. 1.09. "The mystic Faun 'El Fauno.'" *Pans-labyrinth.wikia.com.* Pan's Labyrinth Wiki. n.d. Screenshot. 23 Jun. 2017.

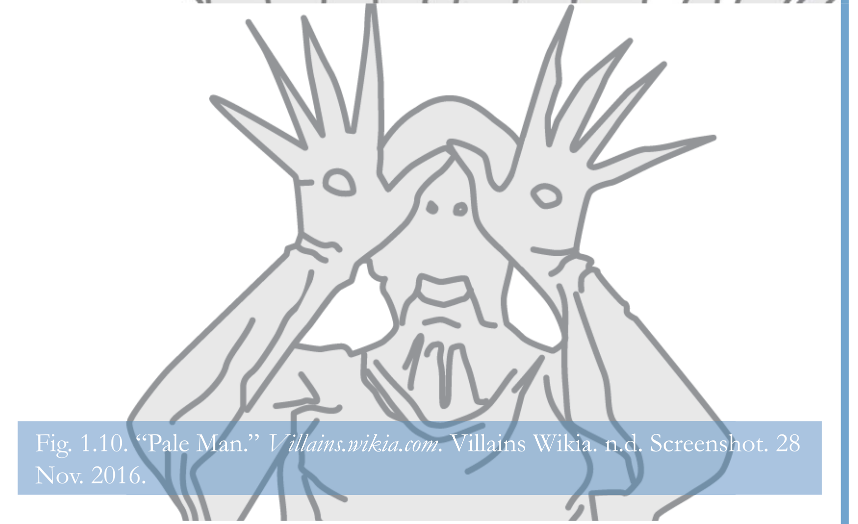


Fig. 1.10. "Pale Man." *Villains.wikia.com.* Villains Wikia. n.d. Screenshot. 28 Nov. 2016.

The Faun and The Pale Man, Pan's Labyrinth

Set in 1944 Post-Civil War Spain, *Pan's Labyrinth* follows the story of a girl who, when coming to live with her Falangist step-father, becomes entangled in a dark fairy tale. Two of the characters she encounters are the Faun and the Pale Man, both played by actor Doug Jones. The two characters embody entirely different roles in the story. The Faun is a sinister but friendly guardian, while the Pale Man inhabits the most frightening scene of the film, threatening the protagonist with cannibalism. The design of the Faun is ornate, with swirling circle motifs, the designers conceiving a character that could "disappear into the wooded environments and looked like something that had existed in nature for hundreds of years". Meanwhile the Pale Man is shrunken and menacing, recalling the facial features of a shark, and surprises the audience with the iconic yet gruesome eyes worn in the palms of his hands. Both effects were created using makeup and prosthetics, with Jones' legs erased using CGI to give the characters more impossible proportions (Wixson).

also given it a certain level of fame in comparison with other effects companies (Giardina). This does not completely invalidate the overall message of the "Weta Effect" video - audiences will indeed react negatively when they can see through an illusion. But to contradict the video's title, the "uncanny valley" phenomenon of special effects has been apparent throughout film history, and not just in post-90s films.

Conclusion

The close and broad analysis of existing special effects in film enables me to design my own work within a rigorous context. I can conclude from this research that I should design my work to support a narrative, to give the video itself meaning, and to support the spectacle of the special effect in an emotional way. As my printed special effect will naturally be a physical object, it is easy for the actors to interact with it, and respond to it, giving it believability. As this is so easy, I want to really push this, to emphasise the interactive nature of it. In regards to special effects that augment the character themselves, as listed throughout this analysis, the design of the effect needs to support the characteristics of the character, while not restricting the abilities of the actor themselves. Additive special effects make sense for some actors, but this study explains why I absolutely still support the use of CGI in some instances – characters like Gollum, Davy Jones and Voldemort could not exist without the reductive and expressive use of digital effects. Pan's Labyrinth is an excellent example of how practical effects and digital effects can exist in unison – the Faun and the Pale Man use a majority of worn prosthetics, but the final touch is the digital removal of the actor's legs to give a more inhuman silhouette. Finally, while I do want to demonstrate how I created my own physical special effect, I need to maintain the illusion throughout the video so the audience can remain totally absorbed. The audience should be invested in the spectacle and narrative that the video creates, rather than the contemplation of the technical achievement of the printed object. This analysis of recent special effects gives me a strong understanding of the contemporary context for which I will design my printed CGO effect.

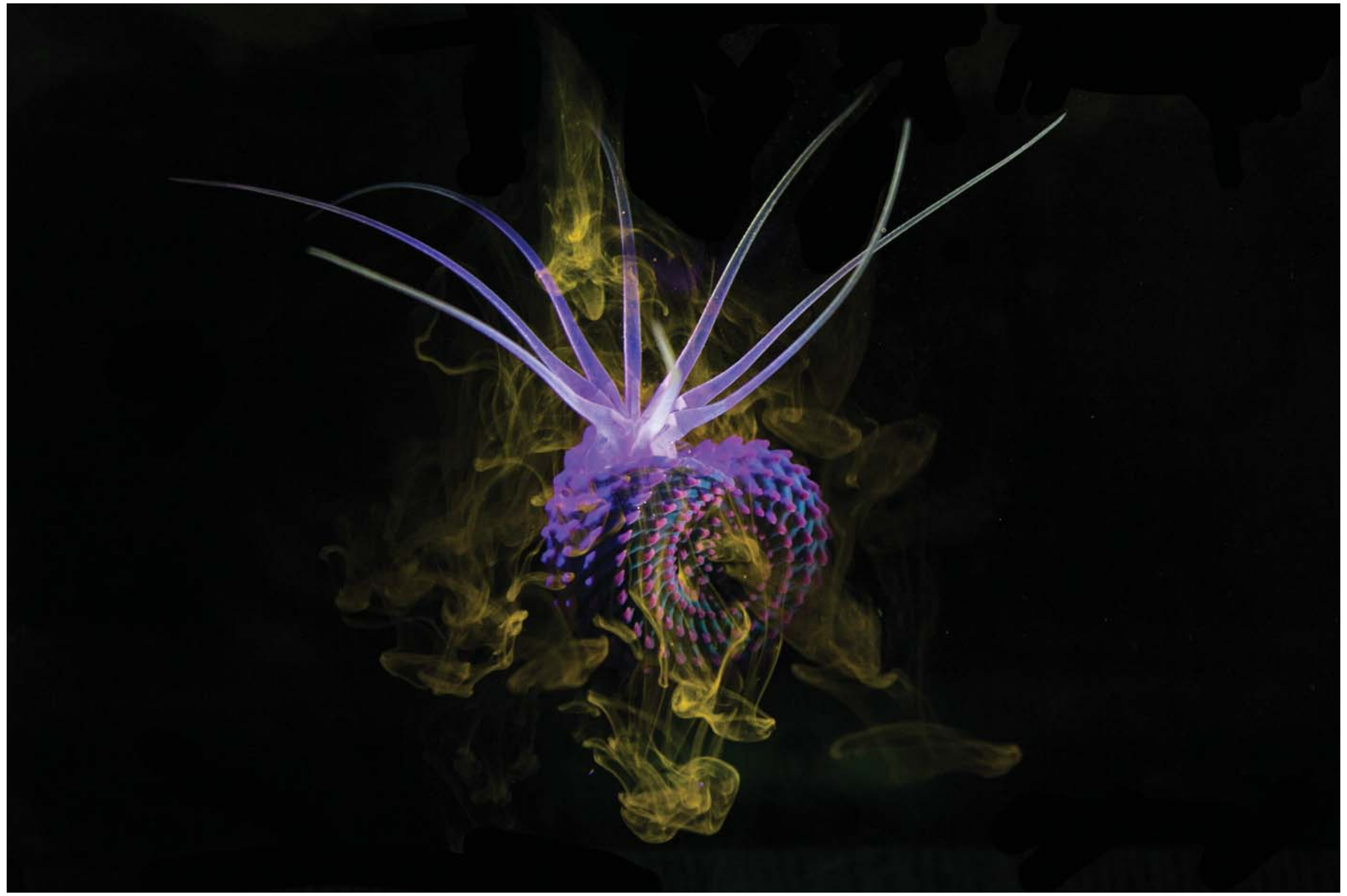


Fig. 1.11. Stevens, Ross & Guy, Bernard. “Lissom 1.” 23 Feb. 2015. Photograph. 21 Jun. 2016.

DESIGN PRECEDENTS

Introduction

While the following design precedents have been previously listed in the Literature Review, it is useful to further analyse and explore their relevance in relation to my own work. “Lissom” is the main reason I felt it possible to explore the relevance of multi-material printing in film. Meanwhile, Neri Oxman, who wrote the seminal paper “Variable Property Rapid Prototyping”, has created a huge, widely published body of work that demonstrates the technical potential voxel coding has for multi-material printing. A sample of her work is discussed here, which is unique due to its focus on physiological design.

Lissom

Lissom is a research project created by Ross Stevens, Bernard Guy, and a group of summer research students and other lecturers at Victoria University. It cherry-picks the most useful attributes discovered about multi-material printing, and combines them to make a compelling and believable 4D object. This is the first instance of the concept of CGO (Computer Generated Objects), and upon first glance, it is difficult to tell whether it is created digitally or physically. The answer of course, is both. The object is digitally modelled with great precision on the computer, then output as a physical form. This physical object can then naturally interact with the world surrounding it.

The unique physical aspects of multi-material printing help its manufactured nature seem more impossible. The audience assumes the creature is CGI, as they have never encountered a material that moves like that. The soft Tango material has an interesting material memory. When flexed, it will move lazily back to its original position, before falling further down due to gravity. This was discovered by accident, when Guy and Stevens were playing with a student’s print of a single tendril. They found this movement so interesting that they put

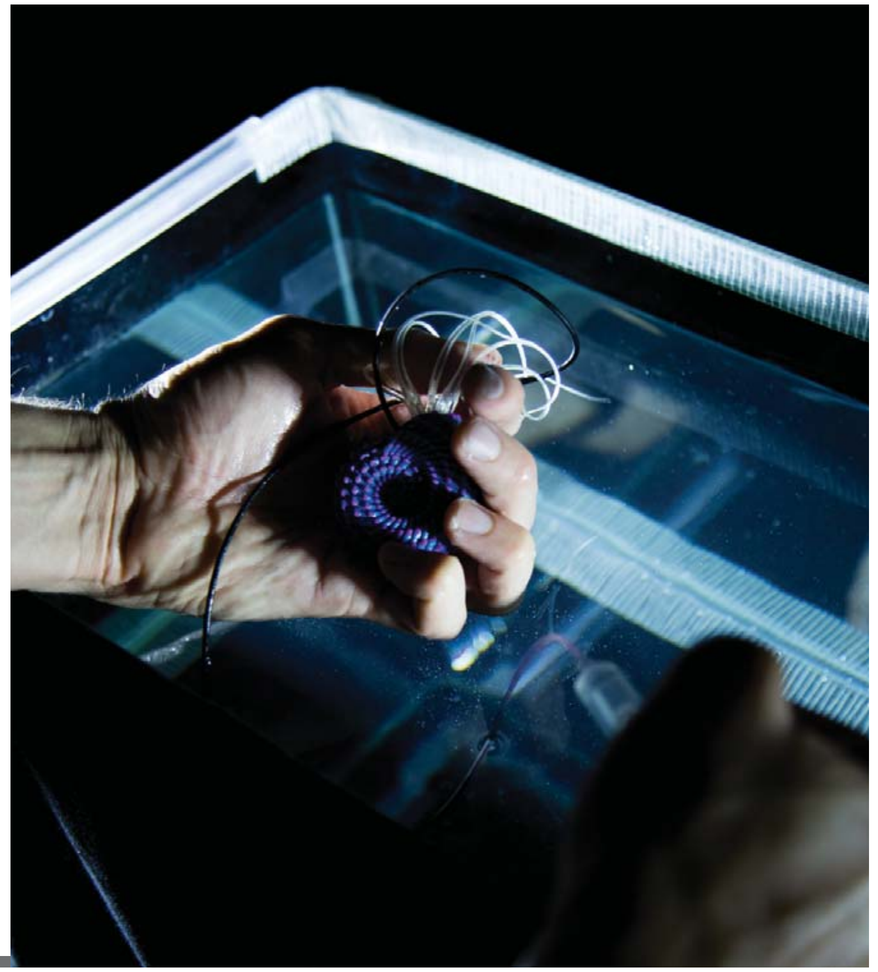


Fig. 1.12. Stevens, Ross & Guy, Bernard.
“Lissom Process.” 23 Feb. 2015. Photograph. 21 Jun. 2016.

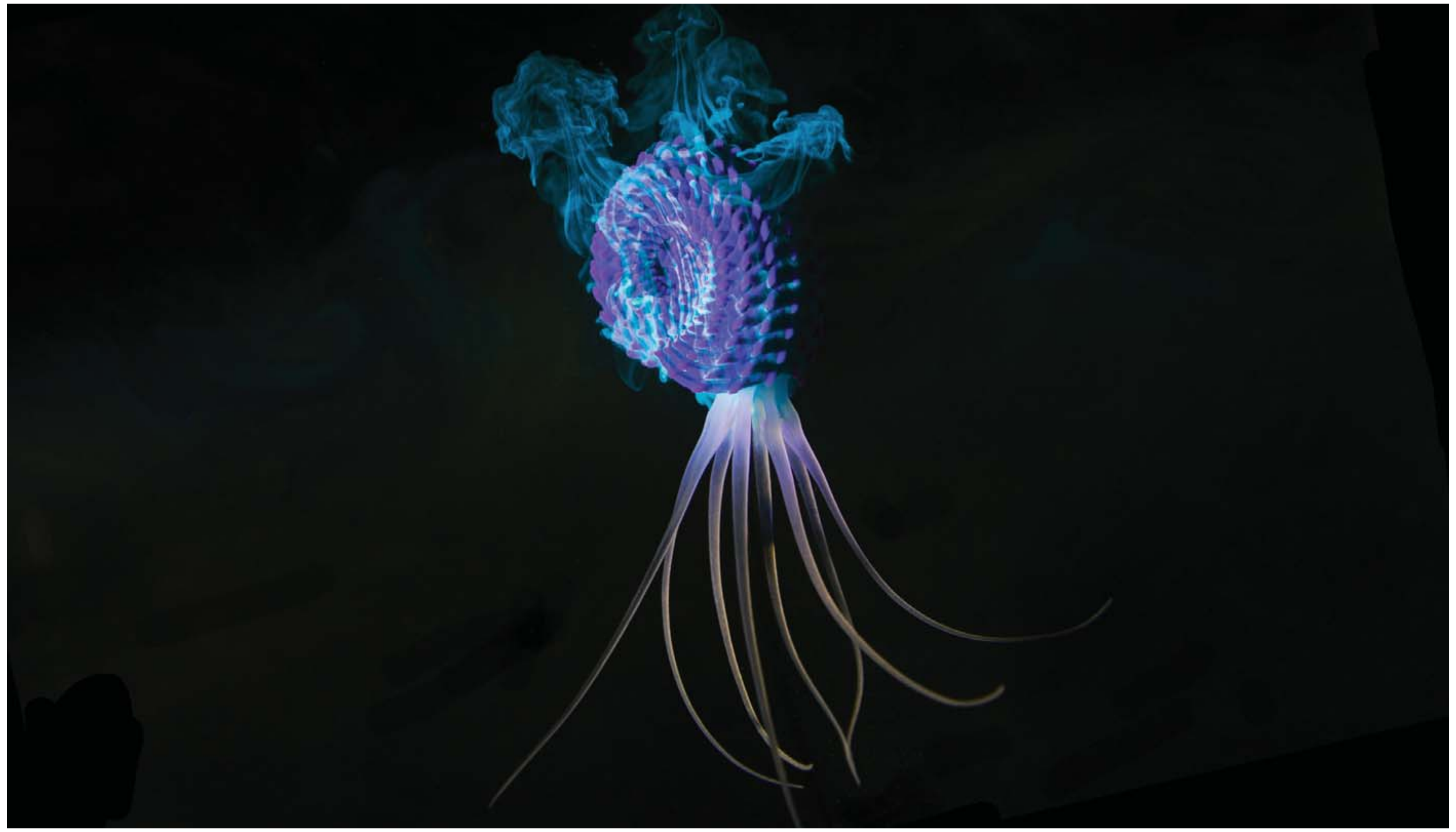


Fig. 1.13. Stevens, Ross & Guy, Bernard. "Lissom 2." 23 Feb. 2015. Photograph. 21 Jun. 2016.

it into *Lissom*. Another important element was the previous research conducted into hydraulic multi-material printing. This allowed the researchers to insert a liquid powered mechanism inside the final print which would cause the tentacles to push out, just like a squid.

The success of *Lissom* is due to a number of factors. Firstly, the overall form is relatively simplistic. The most compelling part of the print is the way the thin tentacle/tendrils move, which are quite basic shapes. Secondly, the print is filmed in water, which makes the materials move in a slower, more realistic way. By adding fluorescent gel from light sticks to this, the liquid easily interacts with the tentacles, making a simple, yet beautiful video. Finally, the video is dark, with glowing forms. This hides the flaws of the prints and makes the forms more ethereal, closer to CGI than a brightly lit scene could achieve. While *Lissom* is a simple enough work, with no narrative or purpose behind it, it exhibits the compelling spectacle 3D/4D printing can elicit.

Fig. 1.14. Oxman, Neri. "Mushtari." Nov. 2014. Photograph. 24 Jun. 2017.

Neri Oxman

Neri Oxman's work explores the "intersection of computational design, digital fabrication, materials, and synthetic biology" and how that can be output into new technologies (Oxman, *Emerging Voices*). I am particularly interested in her prints which interact with the human body, although she and other researchers at MIT have also applied their research to other areas such as architecture. Much of her work appears to be produced through the use of voxels, rather than other traditional outputs. A voxel is a three dimensional pixel which allows for the particle-by-particle assignment of materials.

Until the middle of 2016, Oxman's work mostly focused on hard and transparent materials. This makes her piece *Mushtari* seem quite disconnected from the models body, due to the hard material's inability to conform organically to the skin. While the forms are organic, the material is rigid and shiny, and sit slightly offset from the model's body. If a designer were to critique it, they might say it looks like an uncomfortable, yet ornate, diaper. While this is indeed a successful and compelling work of art, it does not sit well in the world of design as an interactable object.

Meanwhile, the mask *Rottlace*, created by Oxman in collaboration with MIT's Mediated Matter Group, seems to solve some of these issues. Created for a Björk performance, the mask was modelled based on scans of the musician's face, and utilises both soft and hard materials. The form of the mask mirrors the shape of the muscles of the face, and from the few pictures available, appears to integrate well with the form of the face and style of Björk. This seems to be the closest of Oxman's work to my own ideas. The one aspect that makes it seem a little too artificial is that there are no colours. But the choice of black and white is still effective as it isn't entirely unnatural, and the extremely detailed organic form compensates for this.

The most important aspects to note as a design precedent is the production of physical, digital biology which augment the human form using body scans. As wearable objects, these pieces of work augment the human body by taking the visual language of organs and muscular tissue, and extending that into something fantastical. This is taken even further with Rottlace, which interacts physically with the human body by responding to the movement of the face to make it seem natural and believable as a prosthetic form.

Fig. 1.15. Oxman, Neri. "Rottlace." 3 Jul. 2016. *Thephotophore.com*. The Photophore. 24 Jun. 2017.

PERSONAL MULTI-MATERIAL PRINTING HISTORY

Introduction

Throughout my previous experience at Victoria University of Wellington, I have had several opportunities to utilise Connex multi-material 3D printing in my coursework. The following are the most pivotal projects in this area. While this work is obviously not produced here as part of my thesis research, it is important to include it to communicate the extent of my prior knowledge and experience, as these projects have influenced my current work in a variety of ways.

Fruit-Maker

Fruit-Maker is a conceptual piece of work that explores how 3D printing may be used by the food industry in the future. Prompted by a brief from Frucor Beverages to revitalise their Fresh-Up brand, I designed a promotional event that would allow customers to design their own fantasy fruit, and see it printed out by a rather unconventional vending machine (Oct. 2015).

Real fruit contain a variety of textures and flavours that make eating a fruit appealing. Real fruit generally contains materials of different consistencies, and this complex variation of textures greatly influences the experience of eating. Current 3D printed foods are generally created through the layering of a consistently textured paste, making the idea of eating such foods a little unattractive. I speculated that we could use multi-material printing technologies to solve this problem. I also researched molecular gastronomy techniques such as spherification, which makes little bubbles of liquid that burst in the mouth.

As I was fairly new to 3D Modelling at this time, I generated a lot of my forms using an online Autodesk application called Shapeshifter. This allowed me to use sliders to generate complex, lattice-like looping structures. I then supplemented this with additional work in Autodesk Maya. From a technical standpoint, I was relatively inexperienced with

Fig. 1.16. "Fruit-Maker Outputs 1." *Author's Own Image*. 20 June 2016. Photograph.

Fig. 1.17. “Fruit-Maker Style Guide.” *Author’s Own Image*. 26 Oct. 2015. Digital Image.

Fig. 1.18. “Generated Fruit” *Author’s Own Image*. 26 Oct. 2015. Digital Image.

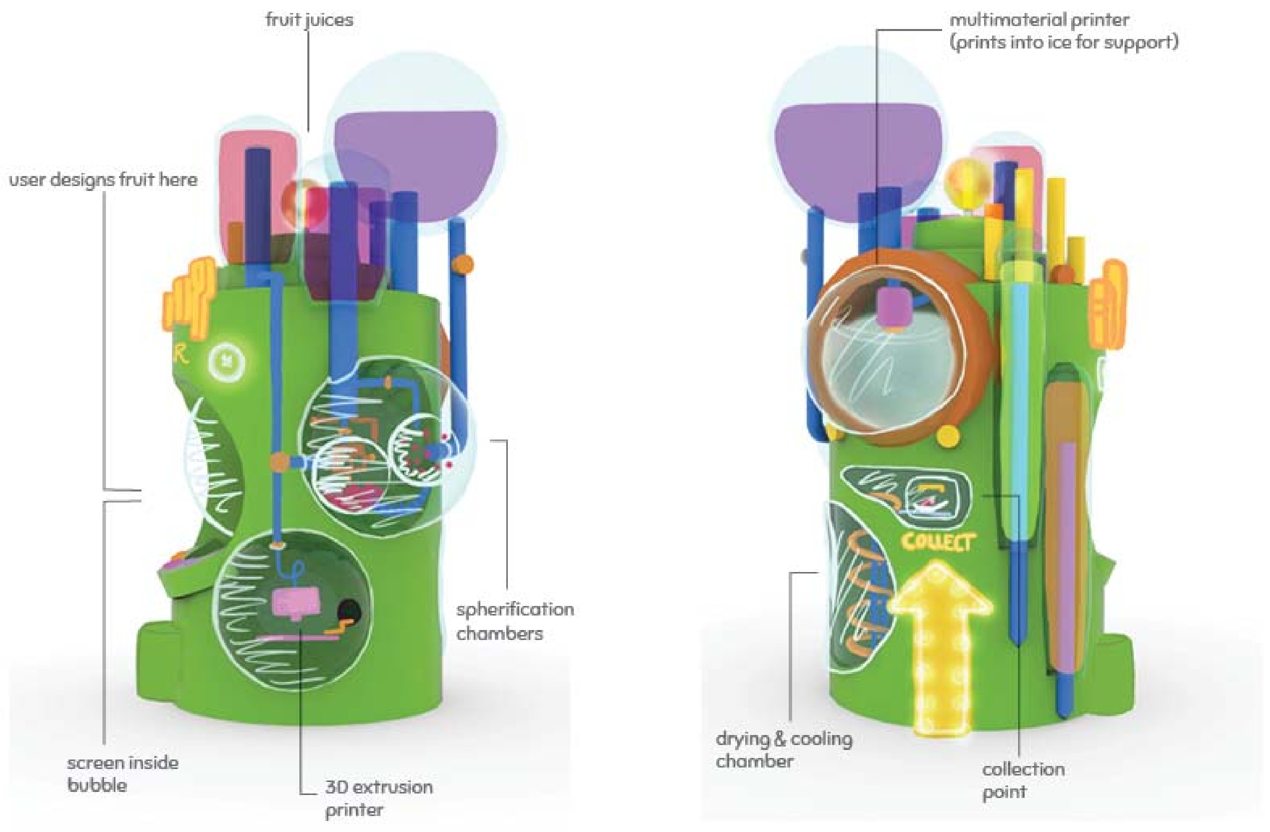


Fig. 1.19. “Fruit-Maker Machine.” *Author’s Own Image*. 26 Oct. 2015. Digital Image.

Fig. 1.20. “Fruit-Maker Outputs 2.” *Author’s Own Image*. 20 June 2016. Photograph.

Fig. 1.21. “Fruit-Maker Outputs 3.” *Author’s Own Image*. 20 June 2016. Photograph.

using Maya to create files for 3D printing, as it requires a different workflow than programs like Solidworks. Identifying errors and issues with my prints helped me discover better techniques for the optimisation of future prints.

I printed these prototypes using Victoria University’s two-material Connex printer, using hard VeroWhite, and soft clear TangoPlus. I found this quite limiting as while I wanted to distinguish with colour between different flavours and textures, I had to do this by making some things very hard, and some things very soft. This contrast was effective, but deviated from my original design intentions.

I then dyed the white rigid and clear soft materials by soaking them in food colouring. This process was additionally restrictive, as it was almost impossible to assign two different colours to the same print. A colour printer could create much more detailed variations of colour, so I speculated that in the future we may not be able to distinguish between digitally manufactured and natural fruit.

As part of this system design, I also created a style guide for each kind of fruit. Users would be able to use this machine to select a few of their preferred fruits, and the machine would generate a final fruit based on these combinations.

Summer Creatures

I was introduced to my thesis topic when I worked for Ross Stevens and Bernard Guy on a Summer Research Scholarship (Nov. 2015 - Feb 2016) after graduating from my Bachelor degree. With three other students, we investigated the potential for the Connex 3 printer to create a follow-up to *Lissom*. The Connex 3 printer could blend 3 materials together, meaning we could blend two colours and still have cartridge left over to also blend with soft material. The constraints I identified when printing the Fruit Maker prototypes were already beginning to disappear.

We aimed to create believable fantasy creatures that naturally interact with their environment. Each of our creatures would be the subject of a short film, showing them each interact with a different element. I chose to melt my creature from ice, first testing the process with small prints. Time lapses made the slow movement of a soft print moving over time compelling. When I conducted time lapses of the final, larger colour creature, I found it difficult as the print took more than 12 hours to melt. This meant I had huge difficulty lighting the print, and had trouble sustaining the battery and keeping the lighting constant over such a long period of time.

We also concluded that while our prints looked beautiful, we had not considered how to design for filming early enough in the design process. They were too static, and did not seem like believable creatures in front of the camera. *Lissom* was able to succeed because it depicted a simple, jelly-like creature - perfect for Connex printing. With more complex creatures, we needed to look more into puppetry and animatronics to investigate how they could articulate independently.

While I was unable to make a video that was successful enough to follow *Lissom*, I was able to progress my skills in 3D modelling for colour 4D printing, and progressed my understanding of how to design for film.

Fig. 1.23. "Multi-material printed creatures melting from ice 2." *Author's Own Screenshot*. Jul. 2015. Screenshot.

Fig. 1.22. "Multi-material printed creatures melting from ice 1." *Author's Own Screenshot*. Jul. 2015. Screenshot.

Tops (*Orbit*)

Before I began my thesis research, I worked on a project which aimed to showcase the unique qualities of the Connex 3 printer through the design of spinning tops. While this did not have any direct relation to film, it did create a compelling interactive experience for the user. The flexible connections in these tops mean that the tops will open out when spun, creating shifts in colour through the changes in geometry and orientation. The tops were designed for an exhibition, where visitors would implicitly learn about the power of centrifugal force which affects these tiny surprising objects, creating unique moments through the mesmerising power of movement, design and colour.

This project was inspired by kinetic art, which celebrates the joy in motion, engaging viewers with moving works of art. This pleasing user interaction emphasises the positive physical qualities that a digital object can create when it is 3D printed.

Fig. 1.24. "Orbit 1." *Author's Own Image*. May 2016. Photograph.

Fig. 1.25. "Orbit Video Still." *Author's Own Screenshot*. May 2016. Screenshot.

Fig. 1.26. "Orbit 2." *Author's Own Image*. May 2016. Photograph.

Fig. 2.01. "Test Fruit Detail." *Author's Own Image*. Nov. 2016. Photograph.

PART 2:
MATERIAL RESEARCH

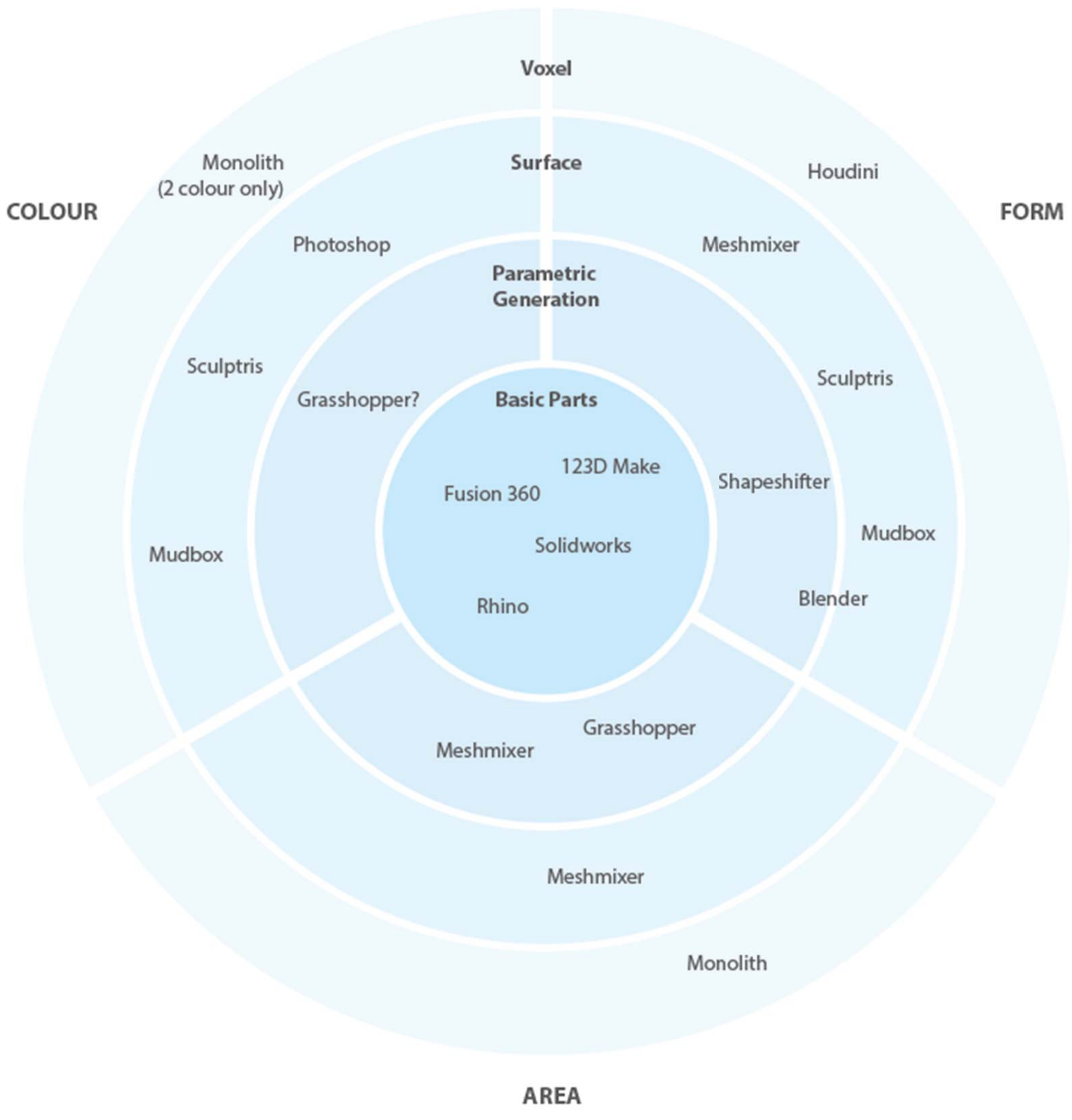


Fig. 2.02. "Software Diagram." *Author's Own Diagram.* Oct. 2016. Diagram.

SOFTWARE REVIEW

As the files needed for 3D Printing can be generated in various ways, it is important to clearly understand the different tools that can be used to achieve various goals. This becomes even more complicated when dealing with multi-material printing.

Core, traditional CAD tools such as Solidworks and Fusion 360 can be used to create basic parts, such as components for a machine or small organic forms. This is similar to other types of printing, and it is easy to dimension parts and design to scale. Most of these programs also allow for the creation of assemblies or groups of separate meshes. These programs are used throughout Victoria University School of Design when printing with the in-house two material Connex printer. Different materials are exported as individual STL files, which are labelled with a shore-hardness, and printed.

The outer circles can also contribute to this STL printing method, but the way the designer approaches the programs is different in terms of thinking and desired outcome. These outer circle categories are Parametric Generation, Surface, and Voxel. These three categories are also divided into three different aspects that the programs can affect - Colour, Form and Area.

"Parametric Generation" is when a designer can create or influence code to change the output of their print. Many programs exist which can change or generate the form of an object through changing the values of predetermined operations. Autodesk's Shapeshifter, and other smaller programs such as the ones that can be found online through Shapeways, are easy for designers and casual creators to use, even if they have little to no CAD experience.

Meanwhile, more skill is needed for programs like Grasshopper, a plug-in for Rhino (Rhinoceros 3D). Grasshopper is a "graphical algorithm editor", which facilitates visual coding by stringing different operations together on screen, allowing designers to parametrically construct three dimensional forms directly into Rhino (Loomis). Due to the freedom and scope Grasshopper provides, it can also fit into the Area and Colour categories, but the program is most optimal for working with Form, more specifically Surface.

Blender is an open source program which has the capacity to do a great many things, mostly targeted at animators. It also has functions surrounding 3D printing which may be useful. Unfortunately, it doesn't seem to have anything that particularly assists with multi-material printing. Blender also has a reputation as a hard program to learn, and I have never found the need to use it. Nevertheless, a designer with coding experience may find that Blender could give them the freedom to achieve greater complexity than other programs, due to its particle simulator and other facilities.

One program that is easier to grasp than Grasshopper or Blender is Meshmixer, which is a program which edits existing, imported meshes. While it is useful for preparing and fixing files for 3D printing, it also has other useful operations which can more fundamentally change the file. The "Make Pattern" command can distribute shapes throughout the interior or "area" of a mesh, making it easy for a designer to make simple forms more complicated by generating lattices and other structures.

Following Parametric Generation are programs which can edit a form's "Surface", through processes like digital sculpting or painting.

Meshmixer also falls into the Surface section, as it also offers a rudimentary sculpt tool. While less refined than other sculpting programs, it is useful for small edits and avoids having to jump to another piece of software. At the same time, I would not recommend using Meshmixer to sculpt something from scratch - programs like Mudbox and Z-Brush are better for this, as they allow the designer to sculpt from rough to much finer detail. It is a lot more difficult to separate the finished file into different materials using these programs, and it therefore may be better to construct a workflow to include other programs in the Basic Parts section. This will help to initially separate materials before the designer begins sculpting.

There are quite a few programs that deal with sculpting and the subsequent colouring of a digital model, but the ones that I know to be compatible with 3D printing are listed in the diagram. The most helpful program is, somewhat surprisingly, Photoshop CC, as

Adobe has introduced a 3D section into the image editing software. If a designer is used to doing digital painting on this platform, then the jump to painting on a 3D surface isn't that far. The controls for navigating the 3D space are cumbersome, and should definitely be improved to something more intuitive. Photoshop CC's 3D workspace also has strong support for optimising files to 3D print. This includes integration with 3D printing bureaus like Shapeways.

Finally in the outer circle is "Voxel". This involves programs which can define the different materials and structures distributed throughout the interior of a single form. As stated previously, a Voxel is a 3-dimensional pixel which consists of one drop of 3D printing material. Controlling individual voxels means the designer is able to achieve much more complex blends of materials, but the vast majority of programs are designed to model only the exterior of an object through meshes.

Described as "a hybrid between a 3d CAD and a 3d image editing application", the program Monolith was developed by two researchers from Harvard to make it easier for designers to control multi-material printing on the voxel level without the need for coding skills (Autodesk Inc 1).

As the program's form creation controls are a little limited compared to other dedicating form-creation programs, Monolith is mainly useful for controlling how material is distributed through an area. It differs from Meshmixer in that it exports printable objects in image slices rather than STLs, which means it can attain more complex combinations down to a single voxel. In regards to Colour, Monolith can blend two colours together, no matter the shore hardness. This summer, three summer research students also investigated how to get Monolith to control more than two colours, with positive results.

Houdini is included in the Form section as, while similar in some ways to Blender, it has more advanced simulation tools. It is likely that it could used by an experienced coder to create complex, organic forms that can be controlled on a voxel level.

Another interesting program to note is Foundry, which was developed by MIT to make it easier to model for multi-material printing. Unfortunately it has not been released to the public, hence its exclusion from the diagram. It may prove useful in the future, as it appears to use visual coding to create and separate models into files ready for 3D printing.

As this review of software demonstrates, designing for such a new technology like multi-material printing can present challenges as there is often not one clear-cut way to create a successful file to print. By being aware of the range of different tools out there, I am able to analyse and create a workflow tailored to the needs of each project.

Fig. 2.03. "Test Claw/Glove by Stevens & Challies." *Author's Own Image*. Jun. 2017. Photograph.

INITIAL TESTING

Introduction

Shortly after the J750 was released, Stratasys gave us the opportunity to produce some example prints using their facility in Hong Kong. Ross Stevens organised the printing of a claw-like glove to explore the material's potential for prosthetic film pieces. Meanwhile, I created some small swatches, and a 3D-printed fruit inspired by my undergraduate work.

Claw / Glove

To demonstrate the potential 3D printing had in making flexible prosthetics, Ross Stevens, the thesis supervisor, worked with a research assistant, Zach Challies, to create a claw-like glove to fit over Ross's forefinger and thumb. This was the beginning of this research's speculation that the J750 could be used to create prosthetics. This would ideally use complex blends of soft, hard and coloured materials which would be much more difficult and time consuming to replicate by hand. If the model was successful, I would develop the concept in a more informed and developed way. The 3D model had to be created in only a few days due to time constraints, but it was still sufficient to demonstrate the concept. Zach scanned Ross's hand, then used that to create a soft glove covering the thumb and forefinger. He then modelled slightly harder coloured claws over the top of this, hoping that they would blend into the soft Tango glove. I then organised the printing of this, along with other test prints.

When this was printed, we found a number of material issues which resulted in it being a mostly unsatisfactory print. Firstly, when Ross cleaned the support material off the print, the thin edges frayed. Secondly, the Tango material ripped around the joint between the thumb and finger, as it was not flexible or strong enough to withstand the amount of movement created in that area. The print could have been modelled better to compensate for this, but it still would have not withstood the amount of use needed for a film prosthetic.

This was troubling as I had been considering using a soft material to create some sort of prosthetic for my final thesis project. This experiment demonstrated that the Tango material wasn't strong enough to make this a reality, for that project or for use in the film industry in general.

Fig. 2.04. "Close up of material weakness" *Author's Own Image*. Jun. 2017. Photograph.

Disk Swatches

One unique aspect of the capabilities of the J750 was that it now offered the capacity to print with full colour. This colour could be defined by painting it onto the 3D mesh. This used a file type called a VRML, which maps an attached JPEG image onto a 3D mesh. This means that every pixel of the JPEG can contain a different colour, allowing for much greater variation than the STL method provides, as this requires the creation of a different 3D mesh per colour. To exhibit the strength of this quality, I modelled a few VRML swatches. These swatches were inspired by iridescent bug eyes, and I attempted to make them look as if they shifted in colour when viewed from different angles.

I also used the opportunity to test how digitally defined colour would change as it is output into a 3D printed object. Colour on a screen is output as RGB, but it is printed through CMYK. This means the colour may appear muddier than the bright colours seen on a screen. When I received the printed disks back, they did appear slightly duller, but this did not seem a significant issue as anything brighter would have been somewhat unnatural in the real world.

When interacted with, the raised bumps which facilitated the colour-shifting also enhanced the depth and texture that can be created when combined with colour. I later used this technique to develop on the claw concept, taking the interesting qualities found in the glove and disks to create something new.

Fig. 2.05. "Detail of Disk Swatch 1" *Author's Own Image*. Jun. 2016. Photograph.

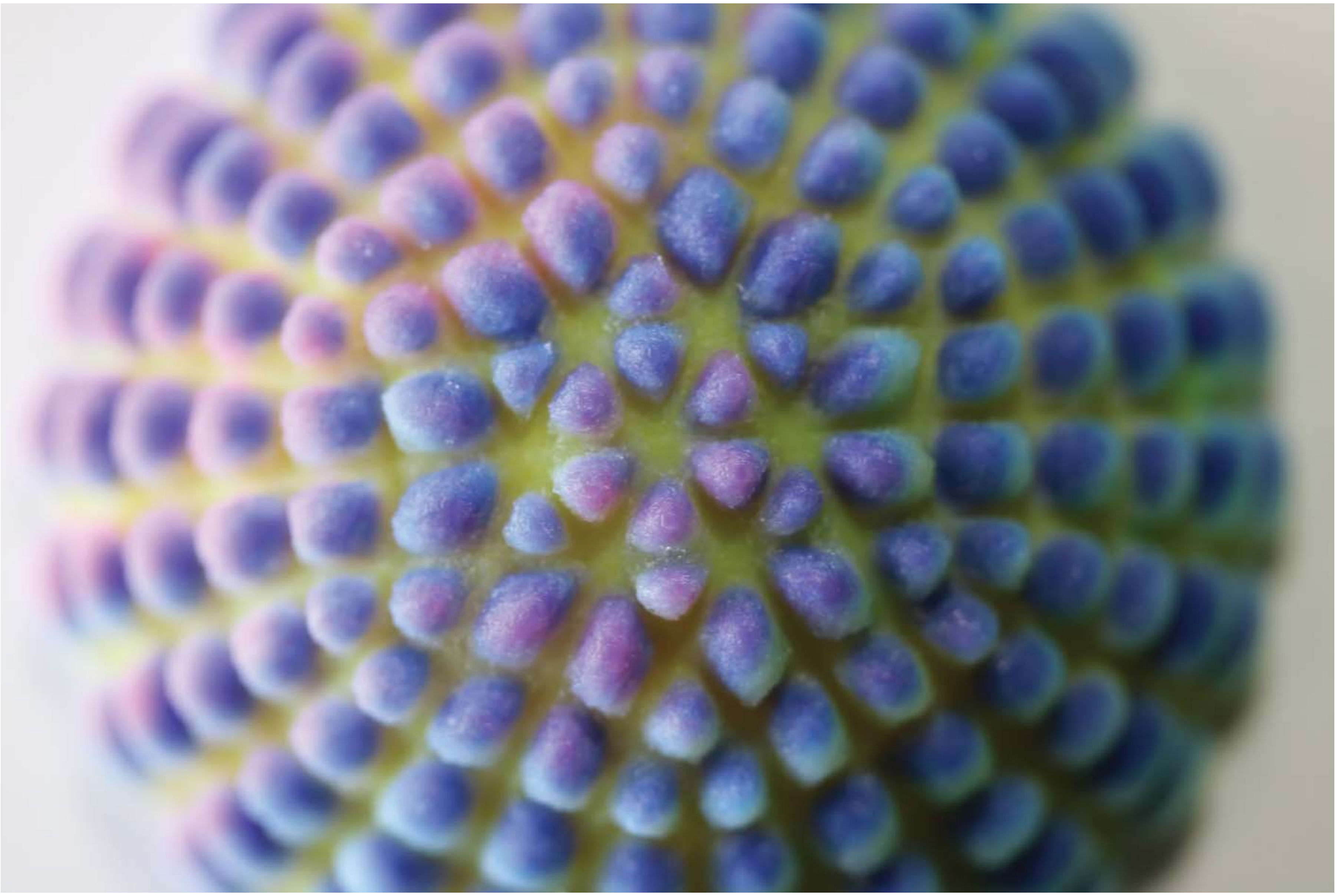


Fig. 2.06. "Detail of Disk Swatch 2" *Author's Own Image*. Jun. 2016. Photograph.

Test Fruit - Design & Making

Having previously explored the concept of 3D printed fruit, I felt that I could considerably expand on this idea given that I now had the opportunity to work with a much more complex 3D prototyping system. My skill with CAD had also improved, meaning I was able to design and control more purposeful, refined forms. Taking inspiration from mandarins, lychee, and dragon fruit, I designed a fantasy fruit that would fully take advantage of what I believed the J750 would be able to do.

After some sketching and research on existing real fruit, I decided to create a fruit that could be peeled apart, revealing interior layers and structures, similar to a mandarin or a pomegranate. In the past, I had been constricted by the presence of support material in a print. It was necessary to the printing process, but the need to clean it away in post-production prevented me from creating more complex forms. This time, I decided to integrate the support material into the design, speculating that it could behave like the "pith" of the fruit. I had always found support material compelling - it has a strange consistency that is quite unique, almost like a fibrous, oily jelly.

Fig. 2.07. "Initial Test Fruit Sketches" *Author's Own Image.* Aug. 2016. Sketch.

Even before I printed the fruit, I had to adapt my fruit to suit the technology's specifications. After making some assumptions based on the publicity material supplied to us, I made an assembly of coloured VRMLs which each had a different shore hardness. However, through communicating with Stratasys technicians via email, I learned that we could only either make hard, detailed prints using VRMLs, or use assemblies of solid-colour STLs to make prints with variations in shore hardness. These two methods are explored in detail in a later chapter.

As the 4D, moving aspect of my fantasy fruit was more important than having organic texture, I elected to use the STL Assembly method. I took techniques developed in my Summer Scholarship work with Creatures, and added interior meshes in certain areas to create more variation in colour. Another interesting aspect to note is that the thickness of softer prints will vary the intensity of colour, which does help to make the prints more visually interesting.

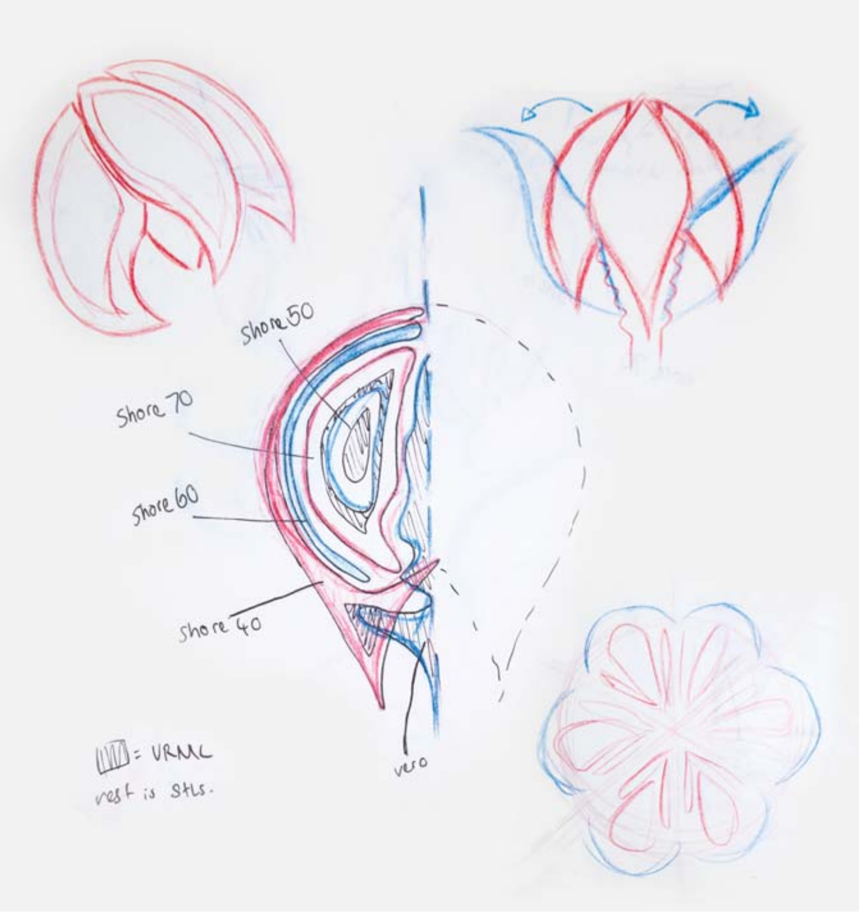


Fig. 2.08. "Further Test Fruit Sketches" *Author's Own Image.* Aug. 2016. Sketch.

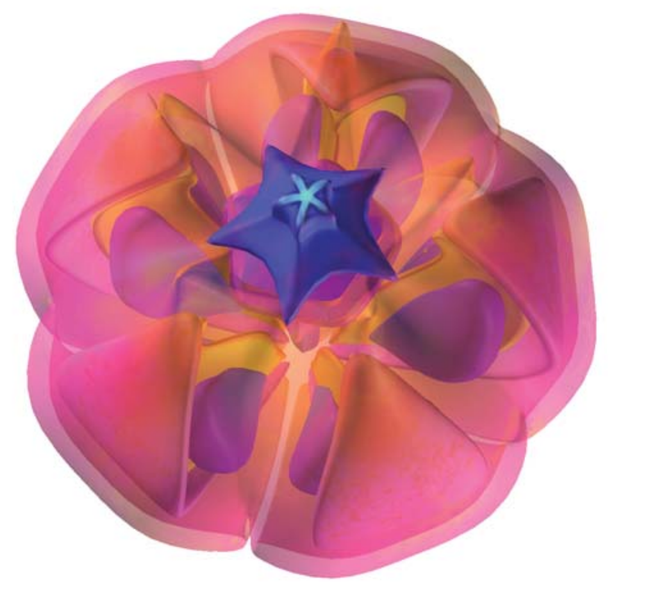


Fig. 2.09. "Layering Soft VRMLs" *Author's Own Image.* Aug. 2016. Screenshot.

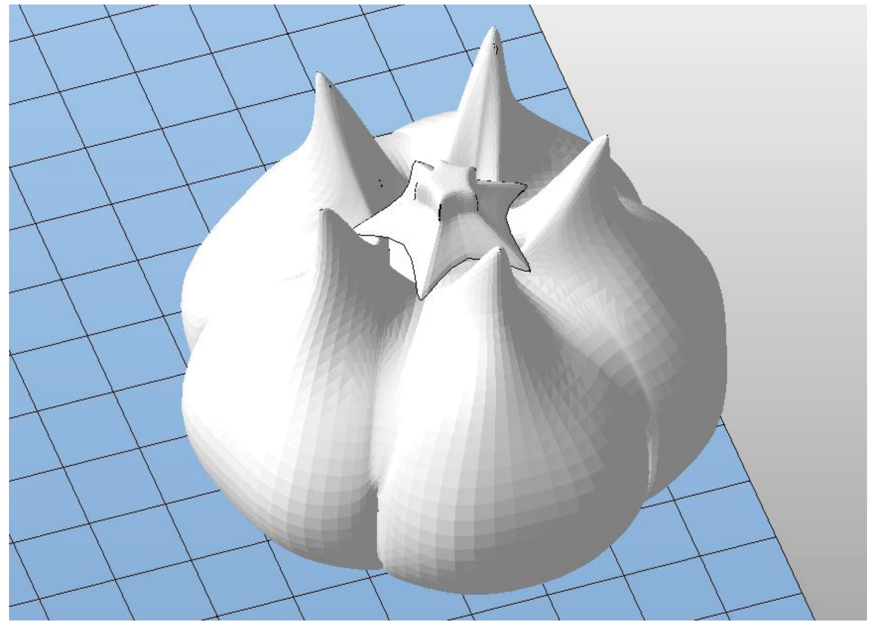


Fig. 2.10. "Switch to only STLs" *Author's Own Image.* Aug. 2016. Screenshot.

Test Fruit - Filming

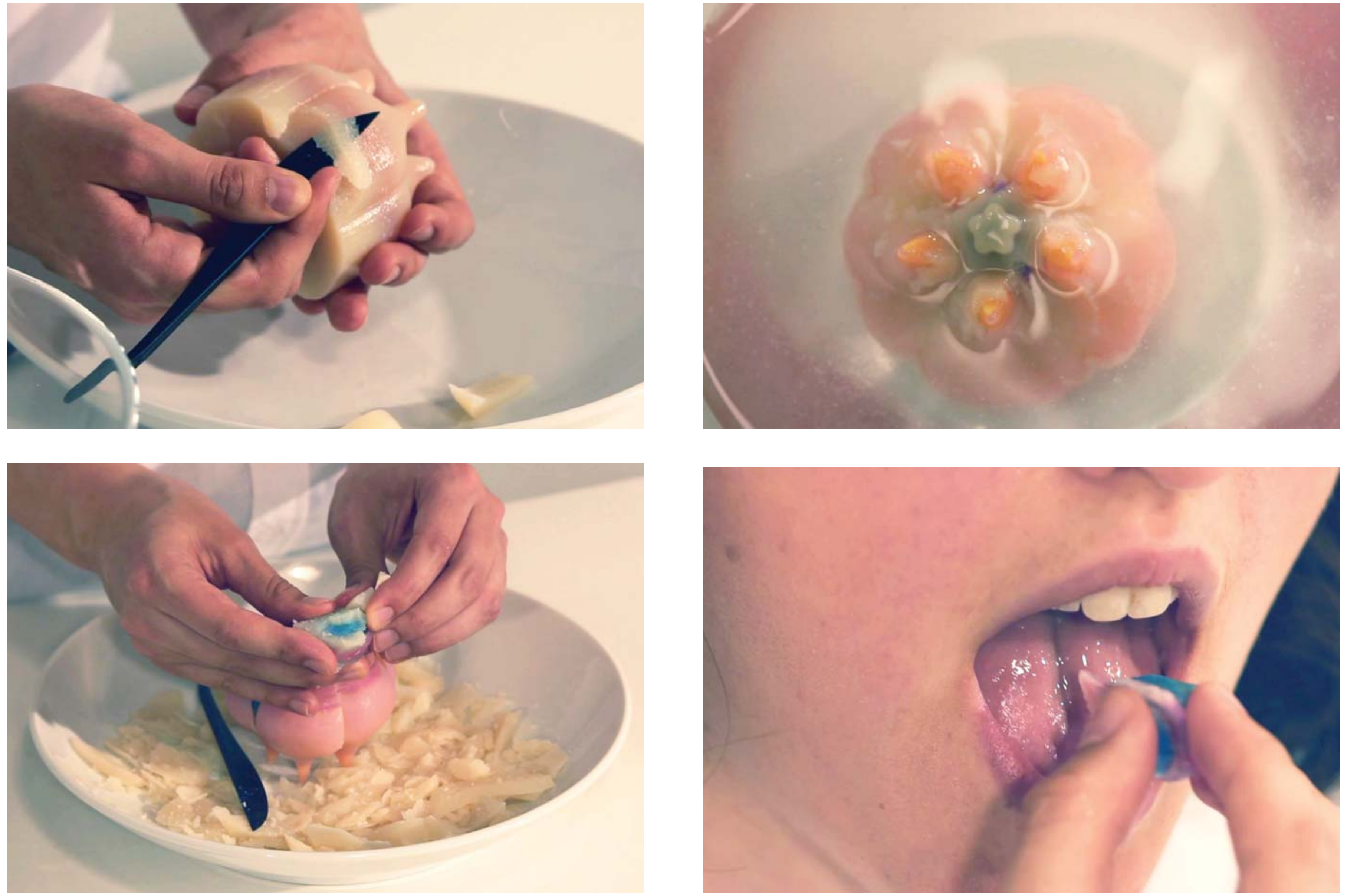
My intention for the video of this fruit was to film myself pretending to peel and eat the fruit, with the help of a friend. Unfortunately due to a communication error, Stratasys sent us the fruit already cleaned, and unfortunately there were some rips in the outer skin where they had attempted to remove the inner support. The second print that we received had an error line in it, where it had not been properly cured at some particular layers. I decided to film this print anyway, as I felt that the error line may not be too consequential, and I would nevertheless learn from the filming experience.

I had intended to document the process of dissecting the fruit itself. I had designed it to have two layers of skin, plus pods on the inside that could be pulled out. However, when filming this video, I unintentionally focused it on the removal of support from the exterior of the fruit . My perspective on this evolved as we played with the camera, trying to visually express the most compelling parts of the print.

As mentioned previously, post-processing Connex prints can be a process of analysis in itself. While it is certainly a time consuming and laborious part of the design and making process, the slow, careful removal of the support material forces the designer to scrutinise and assess every single element of the printed object.

Given that the exterior support had to be cleaned off in any case, I decided to take advantage of the opportunity to film that process before going on to the main focus of the film. As I watched the

Fig. 2.11. "Test Fruit Film" *Author's Own Screenshot.* Nov. 2016. Screenshot.



Figs. 2.12 - 2.15. "Test Fruit Film" *Author's Own Screenshots.* Nov. 2016. Multiple Screenshots.

playback through the camera, I saw that the slow carving of support material was compelling in itself. It actually turned out to be more interesting than the dissection of the interior, which unfortunately was quite clumsy. I found that extreme close-up shots tended to be the most interesting, especially when focusing on how the knife cut up the material.

Upon review, it was evident that while the support was interesting, it did not express my intentions. The fruit itself was unsuccessful in demonstrating how colour 4D/3D printing could be used for special effects. I decided that it would be impossible to work with the support material as originally hypothesized, and any future print would have to be designed to have the support material completely removed before filming .

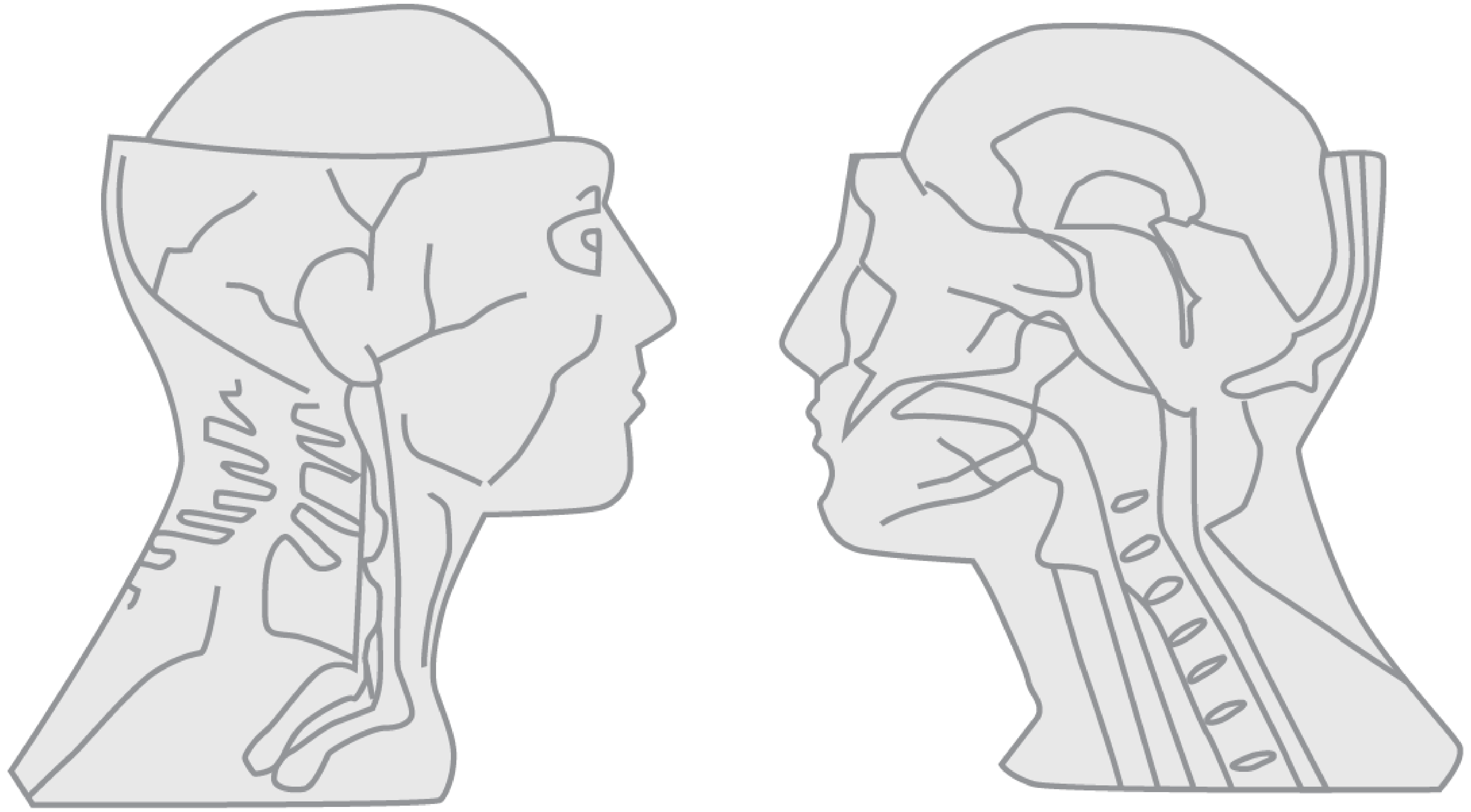


Fig. 2.16. "Head Anatomy Print." N.d. *Cimetrixsolutions.com*. Cimetrix. 24 Jun. 2017.

OVERVIEW OF J750 PRINTING CAPABILITIES

Introduction

The release of the Stratasys J750 caused many people involved with Connex printing at Victoria University School of Design to speculate how we could create files to take advantage of this seemingly limitless system. After Stratasys agreed to let us do some test prints with their Hong Kong branch, it was time to see if these theories would work. Unfortunately I discovered that the methods required were a lot more restrictive than the described potential of the printer would seem to suggest.

While this was limiting, and caused me to rethink some ideas I had for future projects, having this information allowed me to start thinking creatively about how to push these methods and take advantage of them in the best way possible.

Initial Assumptions

After looking at the example prints from Stratasys, I assumed that we would be able to paint onto hard *and soft* materials in Photoshop CC's 3D workspace, then export them as VRMLs in an assembly.

Before being given the opportunity to print with Stratasys, I had done as much research as possible into how they printed their showpiece prints. As a company that needs to conceal trade secrets to retain an advantage in their business, this was quite hard to do. I was able to make educated guesses, based on press releases and other images and information available on their website. Stratasys had recently announced a partnership with Adobe, which led me to think that their showpiece prints had been made possible through a merging of Adobe Photoshop technology with their Polyjet software. Upon viewing the hand piece in person (right), I concluded that some of the parts looked like they appeared to have been assigned different gradient blends through painting them on VRMLs. I also studied

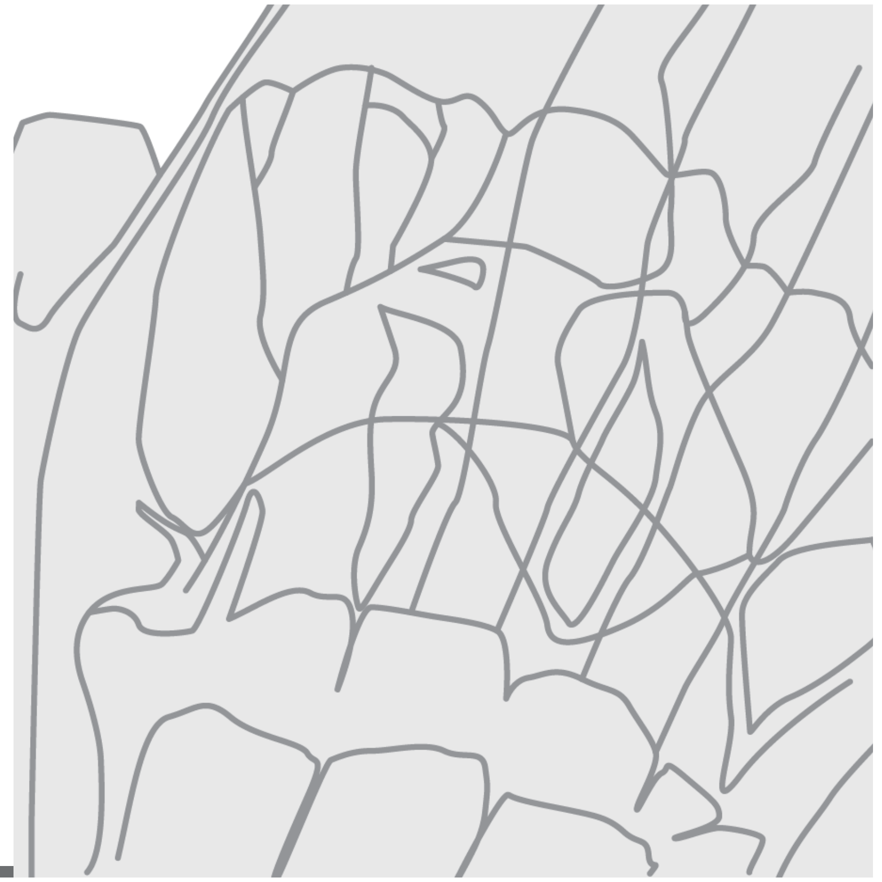


Fig. 2.17. "Hand Anatomy Print" 6 Apr. 2016. *Linkedin.com*. Linkedin. 24 Jun. 2017.

photos of other showpieces. The liquidy transitioning of a gradient in a print by Nick Ervinck also suggested that a VRML had been used to achieve such natural shifts in colour.

After assessing the techniques at my disposal, I decided on a method to use detailed colour and shorehardness blends. I had experimented with Photoshop CC's 3D workspace in the past, after seeing a video demonstration of a Stratasys print being coloured by a technician at a conference. Photoshop can export files ready to print in a file format called VRML (.wrl) which is a file format that supports 3-dimensional meshes. It was originally created for use in the 90s for 3D interactive vector graphics, although this format was superseded by more effective formats. It is now used by many 3D printing companies for colour 3D printing (eg. Shapeways and Stratasys).

I had assumed that this would be the simplest way to make the most of the wide range of materials available, but the software was not advanced enough for that. Upon sending my files to the Stratasys technicians in Hong Kong, I discovered that the technical scope of the J750 was a lot more limited than hoped. After some communication, I learned that the VRML method would only create hard Vero prints, while the STLs still had to be used for prints that contained soft materials.

An assembly of VRMLs was not possible, and nor was it possible to "dilute" the coloured VRMLs with a specified shore hardness. In addition it was not possible to combine textured VRMLs and filled STLs into one assembly. The prints that we had seen online turned out to actually use the old STL assembly technique, and were just complex combinations of meshes to give the appearance of a fluid gradient. It originally appeared to be a relatively simple leap in logic to change the STL assembly method to a VRML assembly, but unfortunately this was not the case.

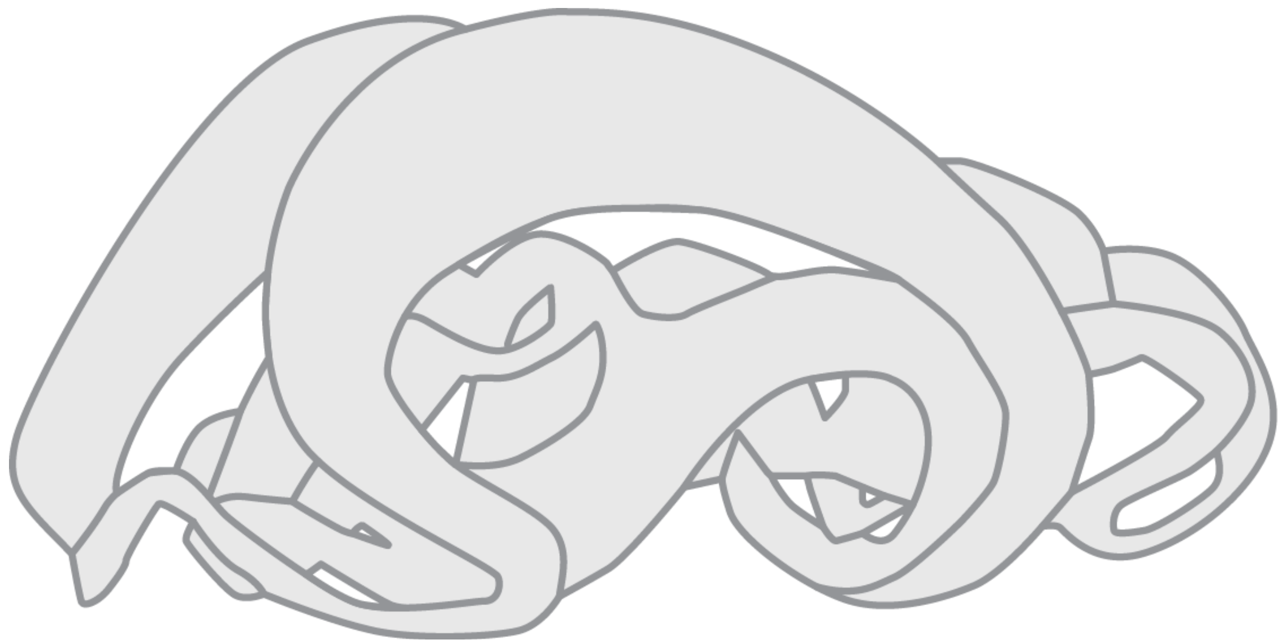


Fig. 2.18. Ervinck, Nick. "Bretomer." 2014. *Nickervinck.com*. Studio Nick Ervinck. 24 Jun. 2017.

Two Available Methods

After reading the manual Stratasys shared with us in response to queries, I clarified that there were only two distinct and separate methods that could be used for printing through the J750. An STL Assembly print, which can use blends of soft and hard materials, and a VRML print, which is a hard Vero print which can achieve complex blends of colour.

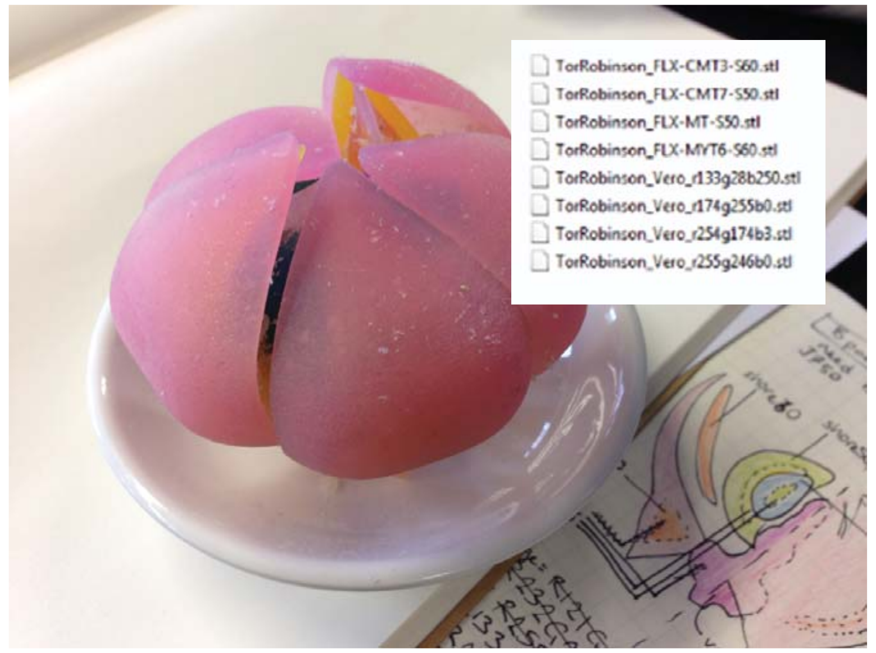


Fig. 2.19. "STL Assembly" *Author's Own Image*. Sep. 2016. Photograph.

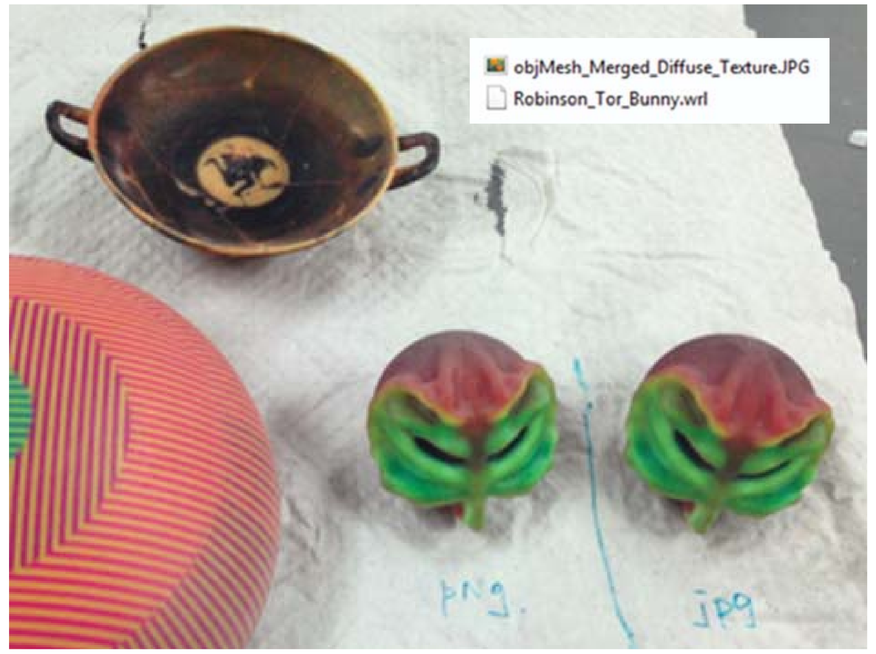


Fig. 2.20. "VRML Hard Print." *Author's Own Image*. Sep. 2016. Photograph.

STL Assembly Method	VRML Method
Multi-material print (blends of soft and hard).	Only Vero (hard) material.
Each material / colour blend is assigned to one 3D file (STL).	Single 3D file (VRML) that is attached to a texture file (JPEG).
Creates a coloured 4D print (movement over time).	Can easily achieve complex blends of colour, creating organic gradients and patterns.

I found that the separation of these two methods and their qualities limited the true potential of the multi-colour, multi-material J750.

The STL method has been used for Connex printing in the past, and is restrictive due to the need to separate a file into many parts to create a refined, complex variation in colour. The VRML method is new to Polyjet printing and it is possible to print in full solid colour on other machines. This means the method is less unique, but provides a higher resolution print.

It is important to note that these methods cannot be mixed together to create one print. As explained earlier, if the designer wants to achieve the qualities found in both methods, they will need to do two prints that can be combined together post-printing.

Colour / Material Limitations in 2016

In addition to the restriction on methods, there are other limitations that have held back the potential of the J750. As of the end of 2016, some of these limitations have recently changed, however they were influential on many of the initial test prints examined in this thesis.

Most of these limitations related to the colours and material blends available for printing as an STL assembly.

Firstly, I found it frustrating that colour palettes to make the most of the colours available in a 6 cartridge CMYK system were still under development. At the time of design of my objects, soft materials could only be specified using the limited palette left over from the Connex 3 system. The limitation to two separate methods meant that I could essentially only use the traditional STL method for 4D printing.

As detailed before, the STL method sacrifices the subtle, natural texturing and colouring that is available with the VRML method. At the time, the colour choice was also quite restrictive, giving bright transparent candy colours, or dark muddy colours that are mixed with a black Tango. The J750 allows the combination of all 6 cartridges of material, making more nuanced colour combinations. This was simply not available at the time of test printing. The material palettes only permitted three cartridges in one material.

This was partially solved for Vero materials, the designation of specific colours using an RGB code is permitted. I found this strange as the printer obviously prints in CMYK. RGB is designed for defining colours made with light - essentially, colours on a computer screen. CMYK is for printing with ink. This means that it is a little inaccurate to translate RGB to CMYK, as CMYK cannot achieve such bright colours as RGB. This means the RGB colour codes are translated by the computer into a muddier CMYK colour. I would have preferred to directly define as CMYK, so I could have more control over the final printed colour.

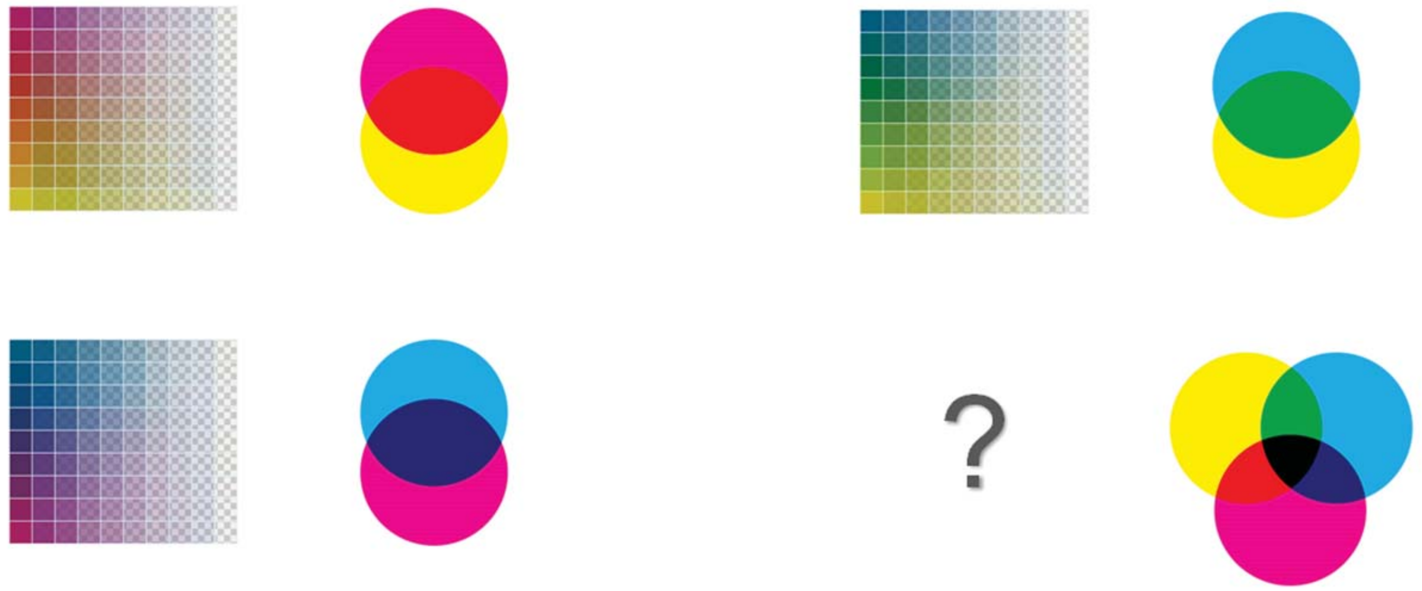


Fig. 2.21. "Legacy palette restrictions." Diagram adapted by Author from Stratasys, *Polyjet™ Colour Materials. N.d.* PDF File. Nov. 2016. Diagram.

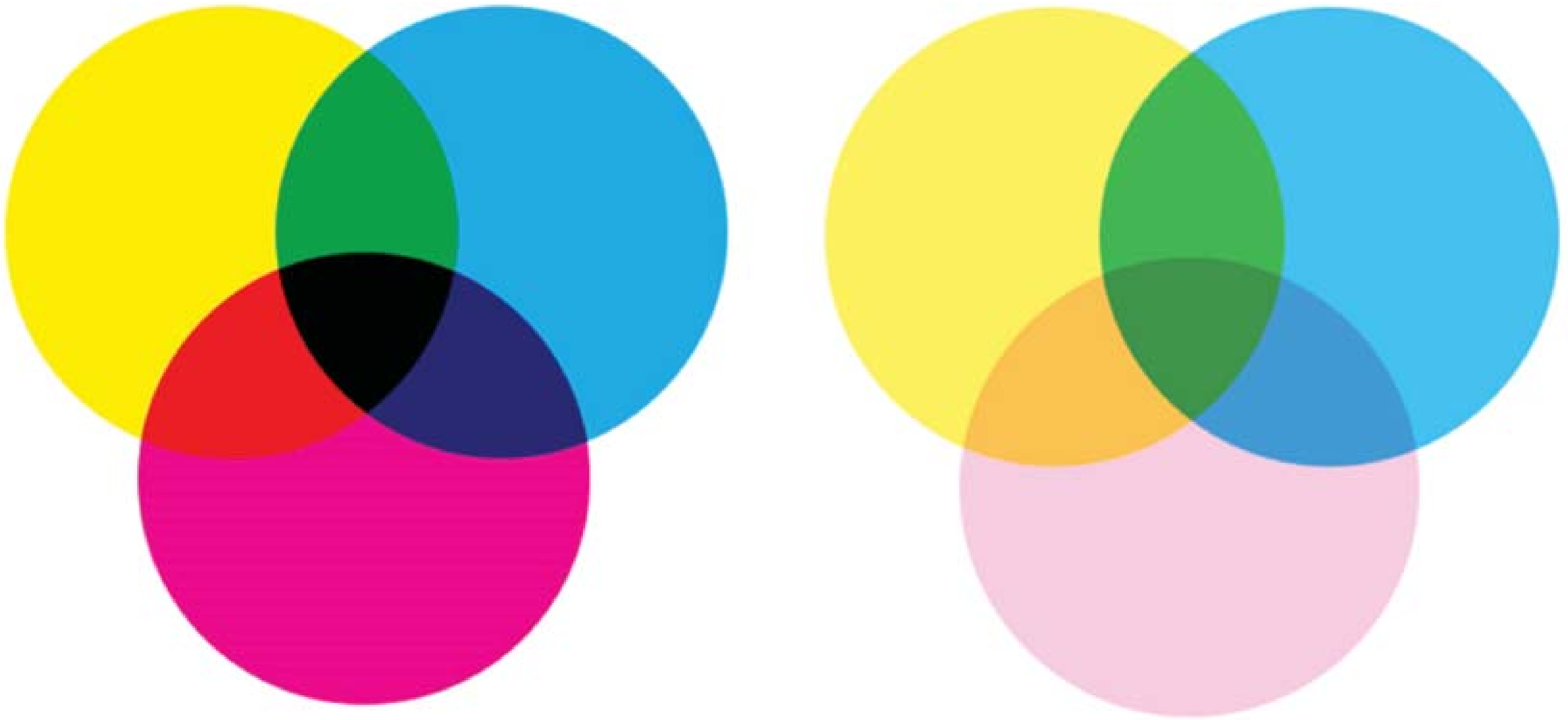


Fig. 2.22. "Demonstration of more nuanced colour potential". *Author's Own Diagram.* Nov. 2016. Diagram.

Fig. 2.23. "Selection of INDN332 Student Prints". *Author's Own Image.* Nov. 2016. Photograph.

INDN332 PRINT EVALUATION

Introduction

After receiving the first batch of test prints, I studied the two printing methods and explained them to Ross Stevens' Future Under Negotiation class. These students had the opportunity to print with the J750 to make a toy for their future grandchildren. Some students had not printed before, so it was critical that I understood and expressed the methods clearly so the entire class would be able to take advantage of the technology.

Thematic Analysis of Technology Use

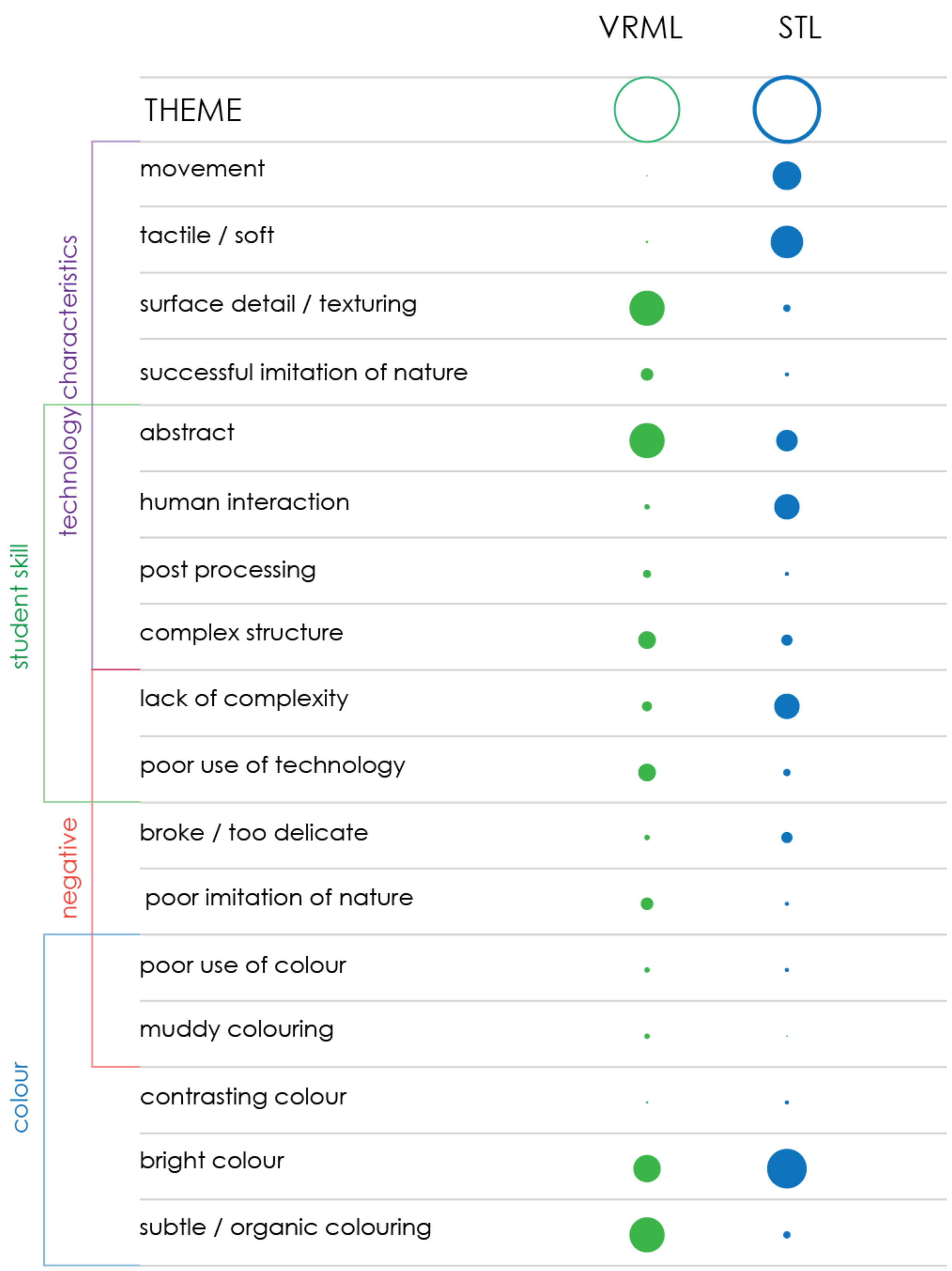
As the J750 had been released so close to the date of my proposal submission, there were hardly any useful precedents created using this new technology. In order to quickly and effectively understand the technology, I studied the outputs from the INDN332 Future Under Negotiation class to see the different ways this printing method could be used effectively.

Students used toys from their childhood to design a series of toys that would be used by their children, grandchildren and great-grandchildren. The medium of 3D printing was suitable for a speculative project that questions and suggests what the future might be like for generations to come.

After establishing an understandable workflow and system for the current methods Stratasys provides, I was able to discuss with the students the different ways they could use the process for their own work. One difficulty was that students imagined the future to rely heavily on Virtual Reality, so many decided to print a physical representation of a virtual idea. This lead to many students using the VRML method to print small avatars. Many other students were also fascinated with the opportunities the STL method could give them in terms of movement and transparency. Looking at the test prints Ross Stevens, Zach Challies and I had made was useful to them, plus the observation and interaction with the series of example prints Stratasys had provided.

After the students had printed and submitted their work, I analysed each print based on how the student utilised the printing technology. After writing notes on each one, I identified recurring themes in the prints, and quantified the number of times they were apparent in the batch of projects. I separated VRML and STL prints into two categories, so I could see how the dominant themes varied in each printing technique. This let me draw comparisons and identify the strengths and weaknesses in each method.

The themes I identified were based on the unique characteristics that the two different methods, STL and VRML, provided. I also identified themes that related to the students' response to the printing methods, and how the output was affected by their lesser technical experience.



The following listed themes display two percentage values next to their titles, which demonstrate the percentage of students in each group (VRML and STL) which correspond to that theme. In addition, each of these percentages are represented by a circle, the size of which corresponds to the value.

Movement 0% 44%

Naturally, prints using the STL method were able to create movement, while hard, static VRML prints were not. By using the soft Tango material, students were able to make articulating or flexible prints that responded to outside forces, like touch. Interestingly, there were fewer prints that could actually move than was expected. This could be attributed to the students not fully understanding the capabilities of the printer, or that they placed higher priority on digital, virtual work than physical printing. Also, through my own experience I have found it can be difficult successfully designing an object that facilitates movement, so the skill level needed for this may have been too high for some students.

Tactile / Soft 4% 50%

Due to the number of STL prints not having the movement expected, I approached the use of soft Tango material in a different way. Tango can create differences in the sensory experience of an object, due to the variation in material. For example, as well as flexibility, Tango can also create more friction and resistance due to its soft nature. Interestingly, the design of some VRML prints contained tactile elements too, relying more on form and shape than material.

Surface Detail / Texturing 65% 11%

Many prints had some form of texturing and detailing in the form of a surface variation in colour. As the VRML prints are more suited to this, most students took advantage of being able to create detail and texture on the hard surfaces of their print. From looking at the digital models, some students did this through painting with different kinds of brushes. Others applied texture from an image or other preset application. Meanwhile, surprisingly some STL prints were able to achieve similar effects through the use of detailed combinations of shells.

Successful Imitation of Nature 15% 17%

Representing natural, organic material with polymers can be difficult. Students struggled to replicate materials like wood and metal. Some prints almost got there - for example, Ethan Henley was able to create a small VRML scale model of a stone backplate. It obviously didn't feel like stone once it was handled, but surprisingly actually felt like a hard, light ceramic, not like a regular plastic print. Another example was Nicole Hone's STL creature. Although it didn't look like anything found on this planet, it was still a convincing representation of some kind of alien, futuristic wildlife. Other prints were simple and abstract enough that they obviously weren't real. The presentation of material qualities created successful experiences similar to, or reminiscent of, nature.

Abstract 54% 33%

The speculative, sci-fi nature of the paper combined with student skill and time constraints meant that a large number of prints produced were quite abstract in aesthetic. The students were also shown how to sculpt and colour models in programs like Sculptris, which may attribute to the higher percentage of VRML prints which fall into this theme. In hardly any time, a user can create a simple abstract form by sculpting and pulling a form in Sculptris, and would have been a quicker, newer, and more fun program to use than other ones they are more practised with. This would have combined with the fact that it is easy to paint some kind of abstract, colourful pattern onto an object, whilst it is harder to do something that is more true-to-life.

Human Interaction 8% 39%

This theme includes instances where students successfully designed their prints to interact with, or even be placed on, the human body. Due to the tactility and flexibility of STLs, this process is more likely to let the students easily create some form of interactive print. In fact, in a notable case where the VRML technique was used for an interactive print, I realised that the student should have used the STL method to achieve what they wanted. They printed a small VRML stalk which they attached silicon leaves to, which could then be pulled off the stalk and opened. If both the stalk and leaves were made using hard Vero and soft Tango, a similar, more polished effect would have been achieved.

Post Processing 12% 6%

Few students used forms of post processing after cleaning their prints, yet it remains a relevant theme to highlight due to the few cases where it was used. In those cases the print is enhanced and built upon when careful human craft is applied. If this is done clumsily, it may detract, yet even simple methods like skillfully sanding and adding a layer of varnish to a print improves the material quality and overall experience of the print.

Complex Structure 27% 17%

A small portion of the class were able to fully exhibit the complex forms J750 can create, a theme that is generally unique to 3D printing and therefore important to take advantage of. In both VRML and STL methods, most students chose to do more simple forms. Interestingly, one of the most complex forms was created by Daniel Cicchinelli using a simple process. He took advantage of a series of pre-programmed material patterning commands in Meshmixer, changing a simple form into something more complex and intriguing.

Fig. 2.24. "Close-up of a Selection of INDN332 Student Prints" *Author's Own Image*. Nov. 2016. Photograph.

Lack of Complexity 15% 39%

Due to similar reasons outlined in the Abstract section, some prints exhibited a lack of complexity due to the lower levels of skill and understanding the students had surrounding multi-material printing. Interestingly, the VRML percentage is much higher in the Abstract section than here. This is due to how easy it is to paint or apply a complex pattern to a print. While the form may be relatively simple, this is compensated for by the amount of detail on a print.

Poor Use of Technology 27% 11%

There were a few prints that I instantly reacted to as being a poor use of technology. Taking into account simple manufacturing and efficiency considerations, the size, or shape of the print would be completely illogical. In other cases, the colouring of a VRML was evidently a rushed job. I believe that VRMLs took a slightly larger percentage of poorly designed prints because the process required is simpler and more intuitive. As they were undergrad students, the range of skill and level of thinking was broader, resulting in some falling towards the end of the spectrum. A selection of students made disappointing decisions as they did not have the level of knowledge needed to design a 3D print. These students did not seem to think of the difference in limitations of the digital world, as opposed to the real world.

Broke / Too Delicate 8% 17%

To successfully design a print that celebrates the structural detail and complexity that a J750 or Connex printer can achieve, the designer needs to have a basic understanding of the limitations and strengths the technology provides. When they don't have this knowledge, there is a higher risk of the print breaking. Similarly to the above theme, some students did not consider dimensions and wall thickness when designing their prints. Many also did not think of how they would clean their prints, which resulted in some breaking when they tried to remove the support material. It is important to note that a few of the broken prints were made and designed carefully, with evident understanding of the manufacturing technology. This suggests that some breakages were also partially due to the fragility of the materials, especially Tango. This soft material is similar to rubber in many ways but one - it does not stretch, and can tear easily. In other words, the material has compression strength but not tensile strength.

Poor Imitation of Nature 19% 6%

As stated earlier, it is hard to accurately represent natural materials in a print. A piece of wood doesn't just look like wood - it also has material properties that make it feel like wood. In my previous chapter discussing film effects, I attributed this to a material-experience form of the uncanny valley phenomenon. This seemed to be most apparent when students simply applied an image of a texture around a print, without considering how the colour may relate to the shape and form of the object. In most cases, whether the prints were VRML or STL, it seemed that these particular prints needed a blend of both methods' capabilities to achieve the students' intentions.

Poor Use of Colour

8% 6%

While both of these percentages are small amounts, it is still important to highlight this theme for a few relevant reasons. First of all, most of the "poor uses" were due to a lack of knowledge of the J750's capabilities, or a lack of care and investment in the project as a whole. Therefore these students did not put thought into what application of colour would work well for the J750. This is especially true in the case of the VRML prints, as there were a few STL prints that were let down by a lack of skill, rather than a lack of knowledge.

Muddy Colouring

8% 0%

Some students who did have the best intentions still struggled to use colour successfully when working with VRMLs. I can attribute most of this to the transition between on-screen, RGB colours, and the final, CMYK printed product. Some colours looked dull and bled into each other, while some looked faded. In the next chapter I will further dissect the J750's colour system and why this happened. This only happened with VRML prints as the only appealing flexible STL swatches available are very bright.

Contrasting Colour

4% 6%

One way students avoided getting muddy colours was by applying colour theory when painting or selecting colours for their objects, whether this was intentional or not. For example, colours will contrast more and appear brighter if they are opposite each other in the colour wheel. This was also apparent in a couple of STL prints, where spots of contrasting colours were used to make the objects more vivid and interesting.

Bright Colour

42% 61%

Due to this being the students' first (and perhaps only) opportunity to test out a multi-material colour printer, many people naturally defaulted to using bright colours along the whole spectrum, making the most of the opportunity. Also in regards to the STL process, the palettes provided by Stratasys were legacy palettes used previously for a Connex3, a 3-cartridge printer, as opposed to the J750, which has 6 cartridges. Therefore, although it has the capacity to create more subtle, nuanced colours, it can't do that yet using the STL method.

Subtle / Organic Colouring

54% 11%

While many did chose to use bright colours to display the range of colours that could be created in one print, many also applied more subtle, often organic colour combinations. Due to the STL method's limitations as stated above, this was easier to do using the VRML process as this gave greater freedom in the way colour can be applied. A VRML is coloured using an image file that is wrapped around the mesh. Therefore every pixel on the prints surface can be completely different, or vary only slightly.

Further Individual Analysis

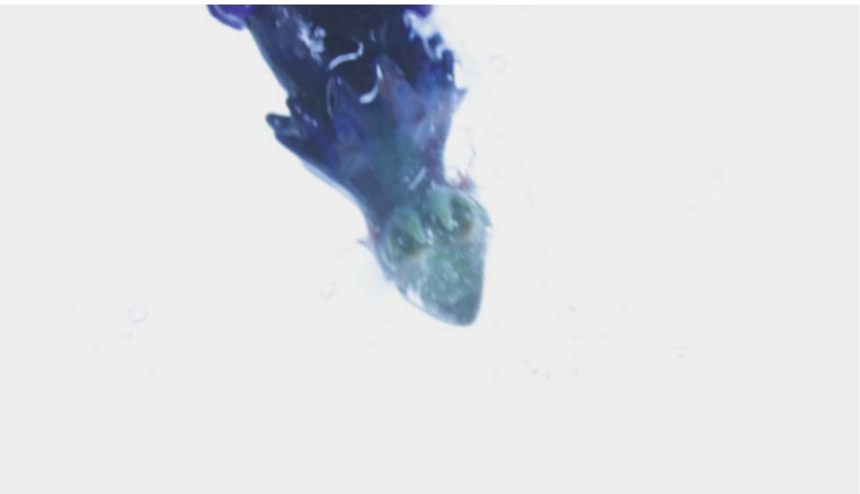
Jessica Saul used the STL method to create a small creature that could "birth" eggs. As she decided to use the project to learn Rhino, the design is relatively simplistic. As the moving scales were not as effective as intended, the interaction with the print on its own can be a little underwhelming. It is the introduction of other physical elements to the filmed scene that supplements the print and gives it life. Using tapioca pearls and golden syrup, she enacts the birth, complete with squishing sounds to fully emphasise the fascinatingly visceral process. This shows that even with low-level skill, designers can create some impressive and provoking effects if the filmmaking takes advantage of other physical elements available.

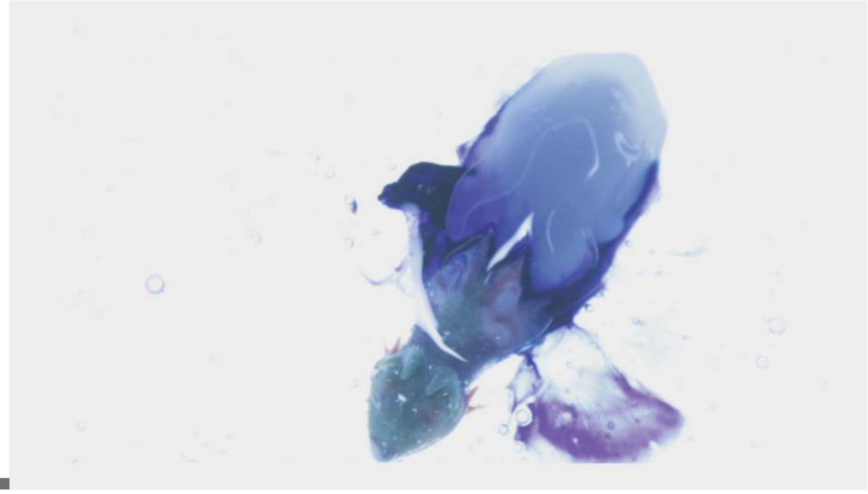
Fenella Richards printed two versions of her creature using the two different programs, which gives a useful opportunity to compare the differences between the STL and VRML printing methods. The VRML has a more organic texture patterned along it, however the rigid tentacles detract from this, emphasising the synthetic nature of the print. This seems to be why Fenella chose the STL print for her video, as the soft, slightly transparent tentacles seem more natural and compelling. What made her video far more successful was how the creature was filmed underwater, mixing water with dye and oil. The red bubbles floating in the green liquid contribute to building a viscous alien world, which seem more like the highlight of the video than the print itself.

Fig. 2.25. Saul, Jessica. "Tadpole." *Author's Own Image.* 24 Nov. 2016. Photograph.
Fig. 2.26 Saul, Jessica. "Tadpole." *Author's Own Screenshot.* 30 Jan. 2017. Screenshot.

Fig. 2.27. Richards, Fenella. "STL Squid." *Author's Own Screenshot.* 30 Jan. 2017. Screenshot.
Fig. 2.28. Richards, Fenella. "VRML Squid." 22 Oct. 2016. Photograph.

Matt Trevelyan was the only student to combine both the STL and VRML method into one print. Filmed in the style of a nature documentary, we watch as the hard body of the creature is pushed out of a soft casing. This effect is supplemented by the dye placed on the inside of the casing. This fluid effect enhances the relatively simple objects, creating a complex organic interaction with its surroundings. While the print is obviously not close to completely mimicking nature, the computerised voiceover gives this video a strong, eerie and stylised aesthetic which blends biological and synthetic themes.





Figs. 2.29 & 2.30. Trevalyan, Matt. "Squid." *Author's Own Screenshots.* 30 Jan. 2017. Screenshots.

Further Discussion

After I guided them through Photoshop, students found the VRML method to be an intuitive way to apply colour. The textures and patterns they created on their models demonstrate the capacity the VRML method has to create detailed, organic blends of colour. While it is not yet a simple process to translate to softer, 4D printing, it shows the potential this technology could have in the future.

The opposite page shows some of the most successful works produced using the VRML method. These prints were selected due to the way they utilise the unique qualities of this method. By comparing this collection, an understanding of the VRML print's range of strengths can be reached. As it was the first time these students had used a full colour printer, it was apparent that it was sometimes tempting to apply the entire colour spectrum to a print. While these vibrant prints are quite compelling, there is also something intriguing about the more subtle, natural blends of a more refined colour palette.

Dark lines cut through some of the prints depicted in this chapter. This is due to an error in the J750, where certain layers were cured incorrectly. While these lines aren't exactly desirable, they help to highlight the slow, layer by layer printing process, which is reminiscent of the growth rings in a tree.

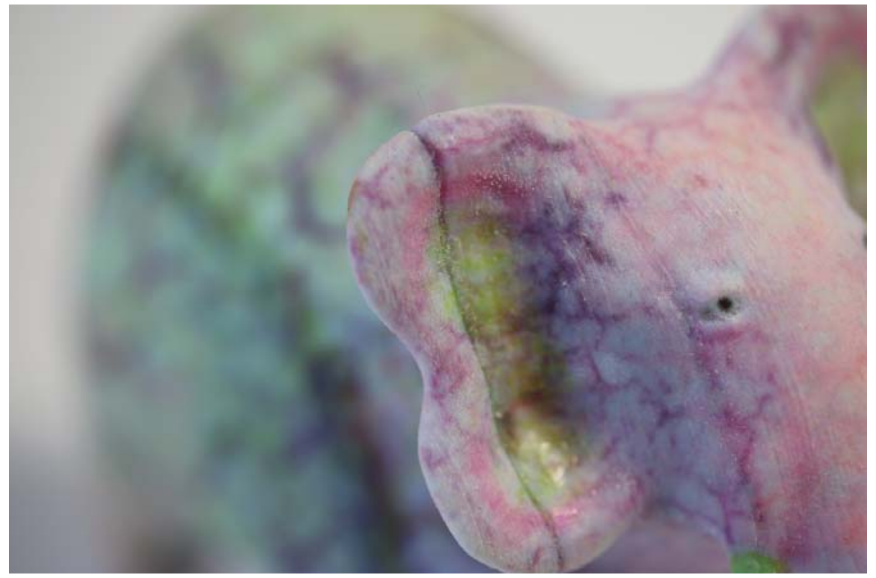


Fig. 2.31. Brunt, Nisha. "Ele." *Author's Own Image.* 24 Nov. 2016. Photograph.

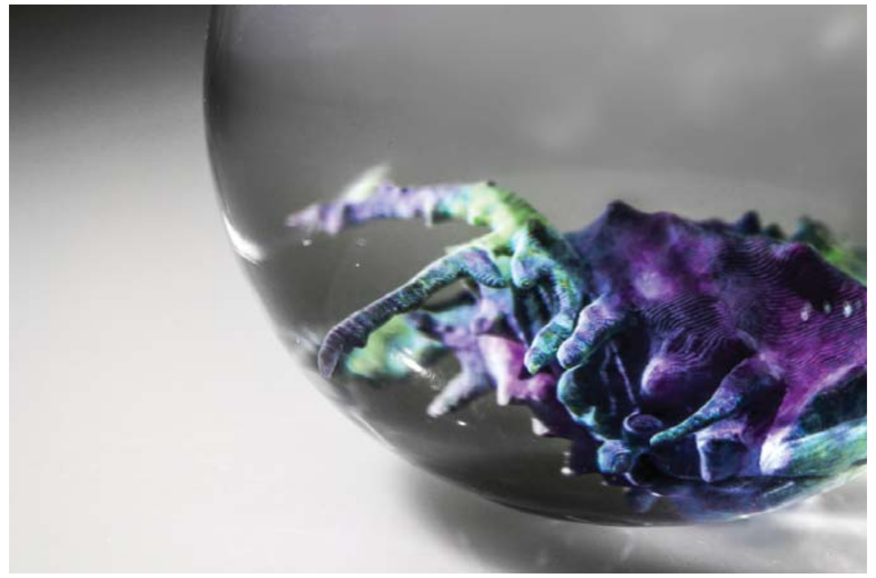


Fig. 2.32. Kennedy, Ashleigh. "Celausis". 26 Oct. 2016. Photograph.

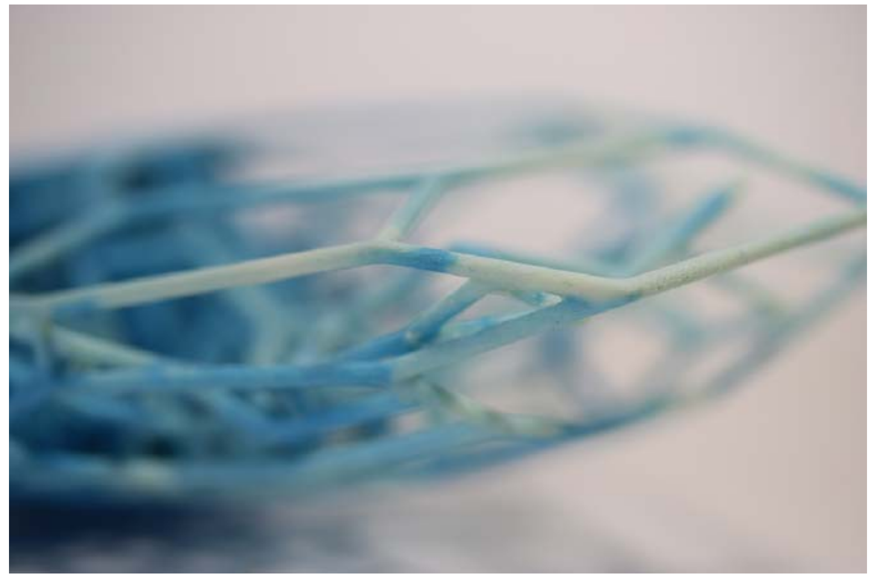


Fig. 2.33. Cicchinelli, Daniel. "Block." *Author's Own Image.* 24 Nov. 2016. Photograph.

Fig. 2.34. Hone, Nicole. "Fly." 26 Oct. 2016. Photograph.

In addition to some of the prints filmed above, there were also a few interesting examples of creative ways to use the STL method.

While Sophie and Nicole's work contrast in degrees of simplicity and complexity, their use of soft materials makes their work appealingly interactive. The way the prints spring back when touched is a surprising and satisfying experience. They combine this with their use of colour, creating unique objects that celebrate qualities unique to the J750. Sophie's print contains the colourful, highly detailed brain and heart, adding intriguing detail to an otherwise simple but playful form. Nicole assigns the tip of each tendril a slightly different colour profile, giving her creature natural gradients of colour reminiscent of nature.

I identified a couple of issues with how the students approached the opportunity to use the J750. Firstly, many of their projects didn't gain anything from being printed - they just printed a figurine of a virtual design, or something different. Secondly, many of them didn't really have the CAD skills to create something that fully takes advantage of such a detailed and complex printing process. These issues should not be viewed negatively; rather they should be acknowledged and explored to understand how despite this, some students still managed to create compelling work.

These issues could have been circumvented with a better knowledge of the unique attributes multi-material printing can create in an object. It is important to draw on the past experience of others. For example, from observing projects such as *Lissom*, it is apparent that a multi-material print can be successful through exploiting really simple elements, like the way a tendril has a memory of its printed form. When moved, it will naturally flex back to its original orientation. This is a unique characteristic of the flexible properties of the Tango material, and when combined with the hard Vero materials, a print can behave in surprising ways, even with a simple form. With the introduction of colour to this attribute, students have a range of opportunities they can take advantage of to create a successful project.

Therefore, with the appropriate knowledge of the printing process, a student can use critical thinking to design projects that can effectively make use of the J750, even with limited CAD skills.

It would greatly help accessibility to this manufacturing method, and indeed, 3D printing in general, if tools could be created that would allow anyone with design skill to create complex and useful objects, even with little CAD experience.

Fig. 2.35. Hone, Nicole. "Claw." 26 Oct. 2016. Photograph.

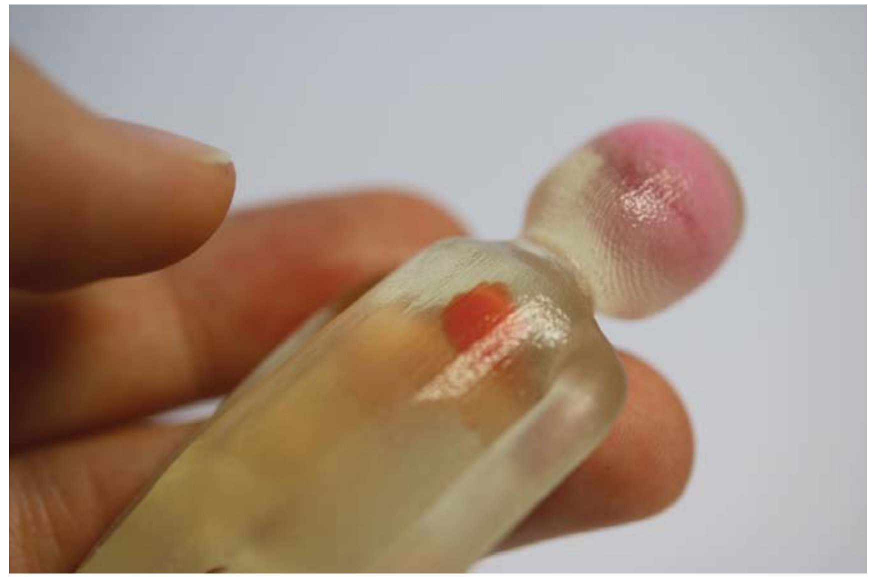


Fig. 2.36. Price, Sophie. "Person." *Author's Own Image*. 24 Nov. 2016. Photograph.

As explored in the earlier "Software" chapter, there are many programs available to create a print, depending on requirements. The complexity of the process will also depend on the type of 3D printing or manufacturing method. A single material printer is generally easier to prepare for than a two material printer, and even more so when a two material printer can output blends or "shore hardnesses" of these materials, like the Stratasys Connex. So, the process naturally gets even more complicated when the J750's colour is also introduced into the equation, especially when multi-material colour printing then also splits into STL or VRML printing. The students had to navigate their way through this complicated technology to find the easiest, most achievable, and most successful way to print the physical output of their project.

The VRML method requires skill with detailed form generation, sculpting and colouring to properly utilise its capabilities. And the STL method is even more complicated, as instead of colouring with a brush, the designer must make a series of STL 3D meshes, one for each colour or shore hardness. Separating a file into these different meshes can be difficult.

For example, when I prepared my Fantasy Fruit for printing, the modelling required progressing from Maya, to 3DS Max, to Meshmixer, and finally to Netfabb. This assured the resultant STL Assembly would be clean and error-free. I was unable to step backwards in this process, and if a higher form detail was required, more programs would be added. This is normal for most people who use 3D tools for a variety of digital and physical products. This complex process is largely inaccessible to someone technically inexperienced who is more focused on the creative design process.

One example of amateur-friendly CAD software can be found on the 3D printing marketplace, Shapeways. Shapeways is an online bureau which makes "product design more accessible, personal, and inspiring" by allowing anyone to upload, print, or sell their creations to the public (Richardson). Recently, it has begun to include "Creator Apps" which allow newcomers to 3D printing to create objects with little to no CAD experience. This is facilitated by visual inputs such as sliders or user-drawn pictures, meaning a unique object is created every time due to the individual user's input ("Easy 3D Printing Creator Apps").

The Shapeways Creator Apps are a precedent for what printing manufacturers, designers and engineers could create in order for their technology to be more accessible to society. It would be desirable if the J750 could come with a program that lowers the skill requirements needed to do operations unique to the manufacturing technology, thus allowing designers to focus on the actual design of the 3D printed object.

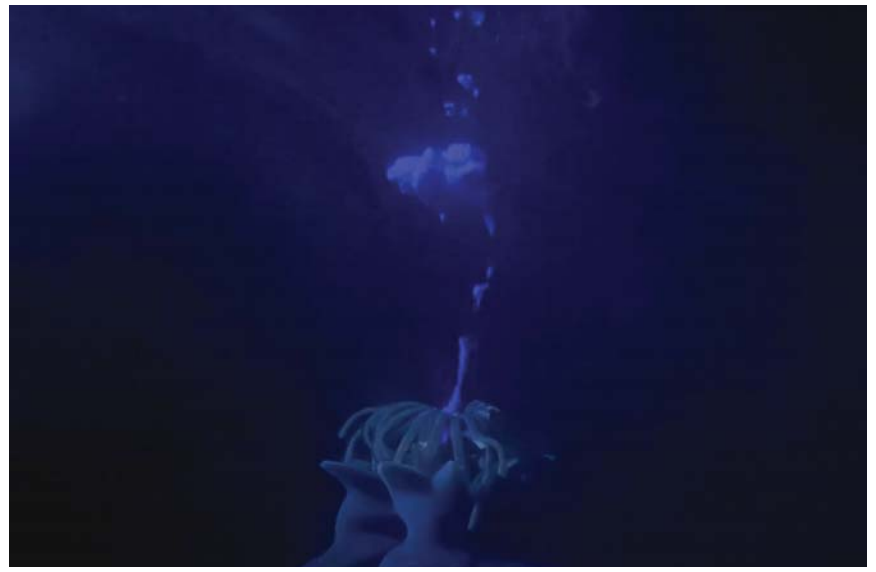



Fig. 2.37. Chung, Sang. *Author's Own Screenshot*. 8 Mar. 2017. Screenshot. Fig. 2.38. Conelly, Tyler. *Author's Own Screenshot*. 8 Mar. 2017. Screenshot. Fig. 2.39. Bird, Morgan. *Author's Own Screenshot*. 8 Mar. 2017. Screenshot. Fig. 2.40. Cox, Andrew-Jack. *Author's Own Screenshot*. 8 Mar. 2017. Screenshot.

Fig. 2.41. Bowles, Jacob. "Cosmic: Aquatic." *Author's Own Screenshot*. 8 Mar. 2017. Screenshot.

DSDN104 BRIEF ANALYSIS

Introduction

As their final project for the year, a large class of first-year students created small multi-material prints using the University's two-material Connex printer. The course was DSDN 104: Digital Creation, taught by Bernard Guy. As this research focuses on the portrayal of 4D printing through film, it was useful to study the filmed outputs these students created. While this analysis is not as rigorous as the evaluation of the INDN 332: Future Under Negotiation prints, it still provides the relevant insight into techniques that can elevate simple works.

As one of the tutors for the course, I shared my knowledge of 4D printing with my students, explaining the unique nature of multi-material printing. The project brief asked students to develop a concept surrounding pattern, then use that to create a small object exploiting the qualities of 3D printing. As part of their final project presentation, they had to create a short 8-second video communicating the unique qualities they were expressing in their prints.

What follows is a selection of the projects most relevant to my thesis, classified by the different methods the students chose to film their prints.

Submerging in Water

Many prints were filmed in water, partially taking inspiration from *Lissom*. I noted that simply dropping a print in water wasn't always that effective. It could trap bubbles on the surface of the print, but this was not as interesting as some of the other techniques students employed. Adding something to the water, like ink or dish-washing liquid, was far more effective in adding depth and complexity to the short video. The introduction of a coloured liquid to an otherwise dominantly black-and-white colour video also allowed those videos to stand out and become more engaging.

Other Water Use

Other students simply wet their prints, giving them a shinier, less dull look. The water emphasised their physical presence, making them seem more like organisms present in nature. My favourite object in this category consisted of many thin layers of Tango, which trapped liquid inside them. The student added a small amount of soap to the water, so that when squeezed, small bubbles came out of the object and onto the student's hands.

Slightly differently, a few other students encased their prints in ice. I found the film quality a little insufficient for the majority of these, as filming timelapses is quite difficult. I have included the best example here, as the video was of a high quality and well produced. I found it interesting how the ice slowly revealed the print inside, which made a simple form far more entertaining to look at.

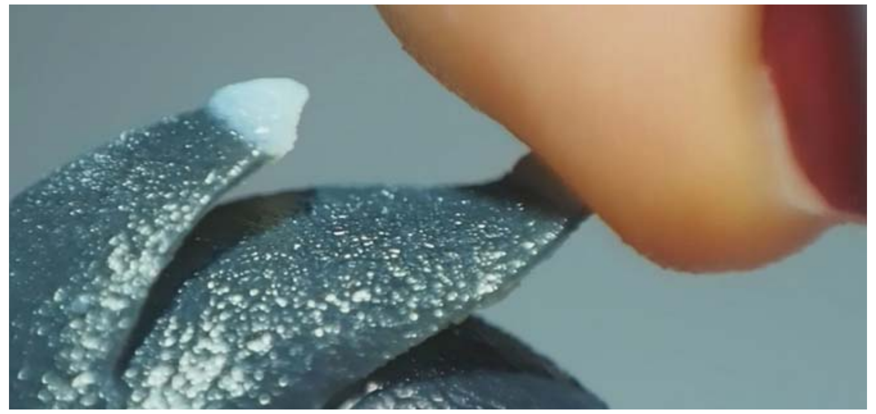


Fig. 2.42. Weir, Charlotte. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.43. Coulson, Patrick. "Loptica." *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.44. Douch, Laura-Jane. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.45. Wong, Gabrielle. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.46. Urquhart, William. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot.

Contextual Placement

A few other students placed their prints in situations outside of the photography studio, giving their projects more of a context and story. One of the most amusing ones was where a student pretended it was a piece of live sushi, using chopsticks to catch it, before bringing it towards the camera to be eaten. By putting these strange-looking prints in a familiar environment, we are able to make them more comprehensible and interesting to watch.

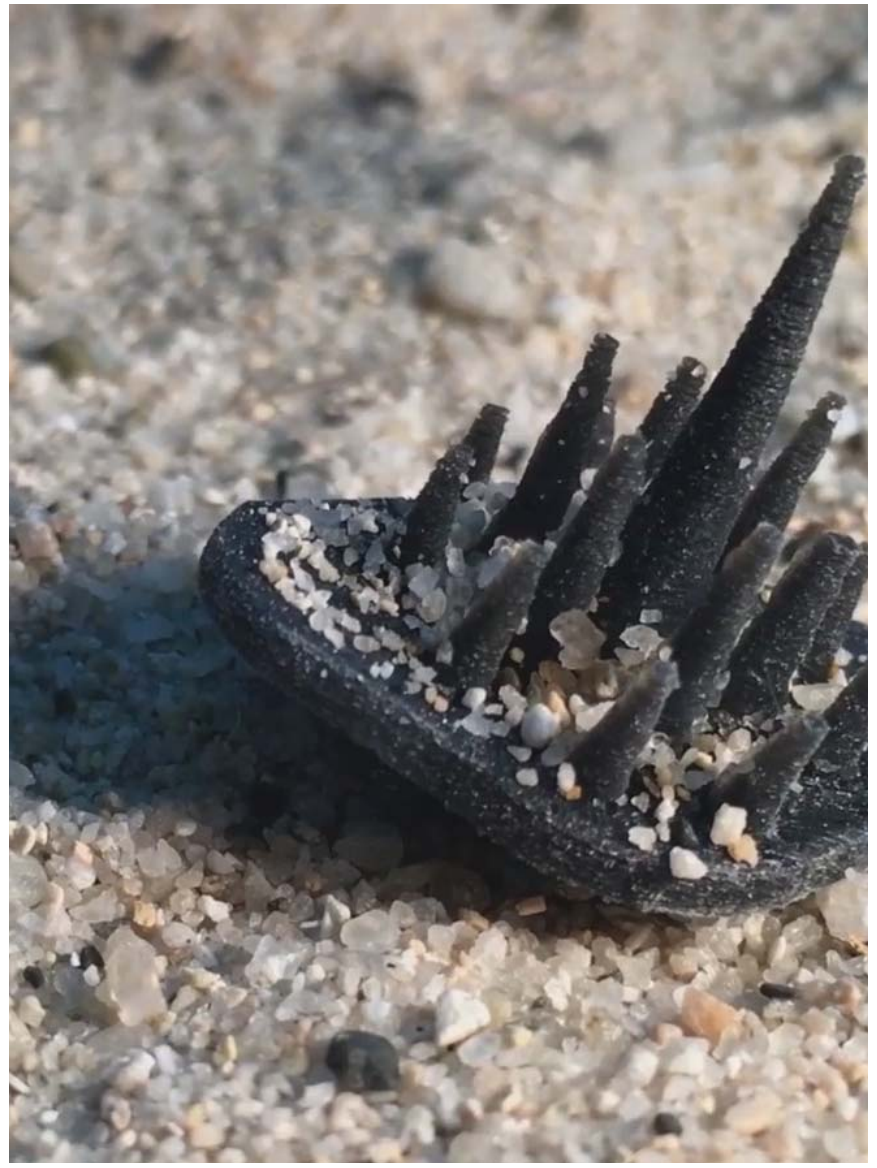


Fig. 2.47. Xu, Stella. "Grown." *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.48. Wright, Shannon. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot. Fig. 2.49. Xu, Xinru. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot.

Introducing Movement

Finally, some other projects stood out due to the inclusion of interesting movement and articulation in the design, which was portrayed in the video. One print was folded out, and the video showed it slowly returning to its original form. The Tango material is interesting, as it is flexible, but not stretchy. It also has a strong form memory, which was great to see exploited in these projects.

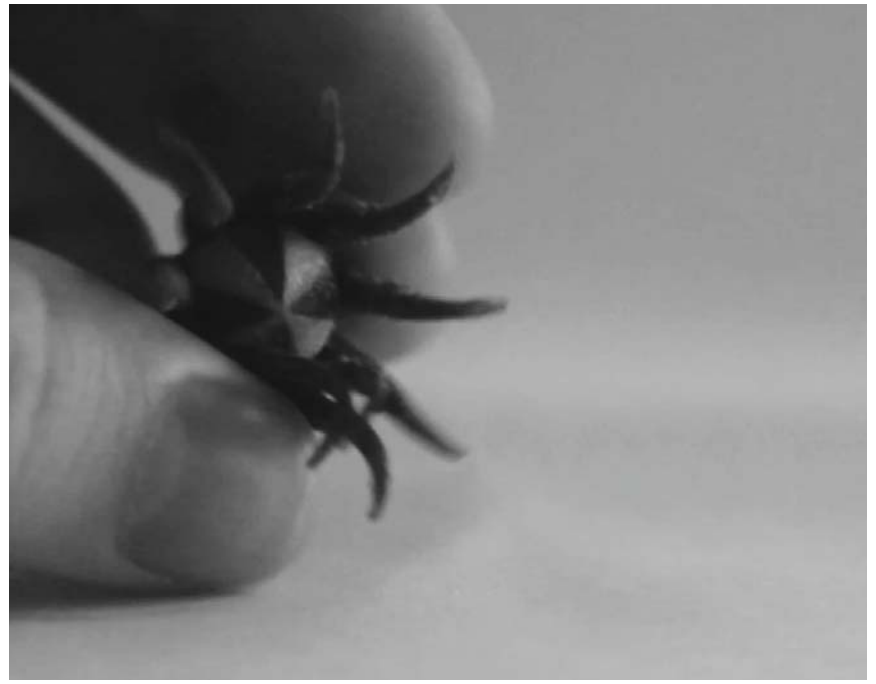


Fig. 2.50. Thomson, Grace. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot.
Fig. 2.51. Currie, Jack. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot.
Fig. 2.52. Bain, Justin. *Author's Own Screenshot.* 8 Mar. 2017. Screenshot.

Conclusion

Naturally, many of the most successfully produced videos listed here had good production quality - good resolution video, crisp focus and lighting, and sensitive and effective post-production editing and colour grading.

Many of the videos I found so compelling were ones where the student's hand was present in the video, interacting with their print. This was opposed to the use of string, which was very apparent and distracted from the materiality portrayed. This revelation also connects back to the theme surrounding believability and audience knowledge. Seeing a hand squeeze or squash a print effectively demonstrates how dynamic and truthful the interactions with CGO can be.

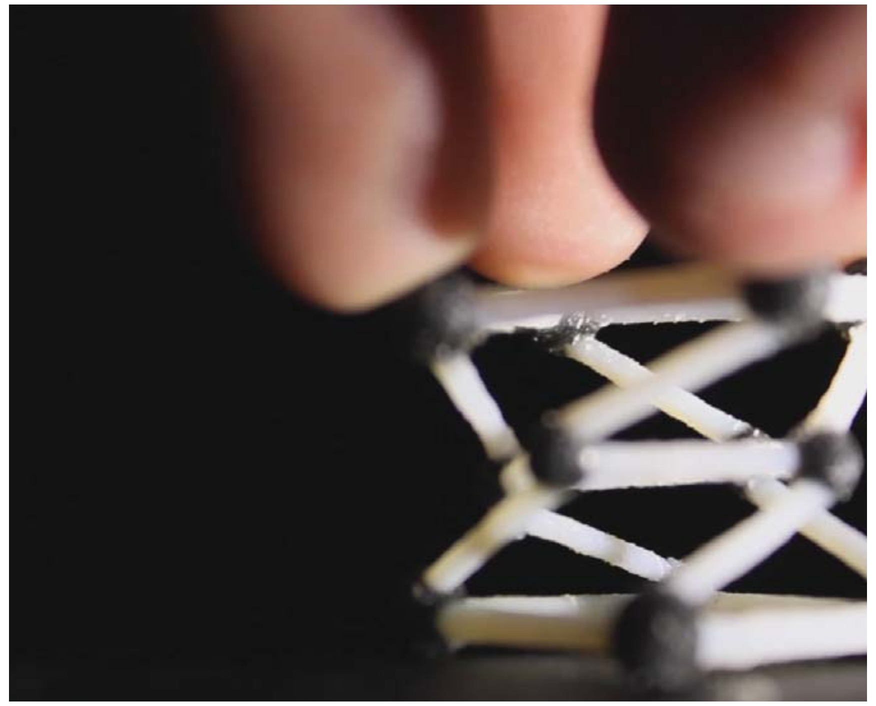


Fig. 2.53. "Test Fruit Film" *Author's Own Screenshot.* Nov. 2016. Screenshot.

UNIQUE QUALITIES

Exploiting Materiality in J750 Prints

After studying examples of multi-material printing, I found it was important to record how they can be portrayed in film. The dynamic qualities of the J750 are compelling, but they can only be fully exploited in film with the assistance of other material elements. What follows are the results of my extensive research into all possible actions that can be performed to transform a multi-material print into effective CGO. In the interests of brevity, they have been listed in bullet-point form. These filming techniques are simple to perform, but their effect is complex in an organic, physical way.

Support material

- *Carving / cleaning off the support.*
- *Injecting support-filled cavities with dye.*
- *Reinforcing structure of support with a printed lattice.*
- *Shining a light through support material, showing the denser form of the print inside.*
- *Squashing a support-filled "bubble" of Tango, causing the support to ooze out.*
- *Swirling the support-sediment and the print in water.*

Water or Liquid

- *Dropping a print into water, causing air bubbles to rise.*
- *Suspending a delicate, soft print in water causes light, flexible components to float.*
- *Spraying a print with water causes it to shine, also making delicate parts sag and stick together.*
- *Injecting dye/goo through a channels in a print so it bursts out into the water around it.*
- *Use water currents to invisibly move the prints.*
- *Fishing line will be invisible if lit well, can articulate prints.*
- *Steam can evaporate and condense onto print, changing its form visually and physically (refraction of light through water and water weighs print down).*

Goo or Viscous liquids

- *Can use golden syrup, corn syrup, dish-washing liquid, or professionally produced special effects slime.*
- *Coating prints in viscous liquids causes them to flex more reluctantly.*
- *When flexed, strands of goo are will stretch between parts of the print.*
- *Can simulate bodily liquids and emphasise organic effects like transparent organs.*
- *Can add beads / small pieces to goo for texture.*
- *Can coat prints in a dissolvable goo/jelly then film it disappearing in water.*

Fizzing and Bubbling effects

- *Can use bath bombs, carbonation, soap or other chemical reactions.*
- *Carbonation can enhance the air bubble effects.*
- *Cover print in soap bubbles, which stick to the print and distort the overall shape. Can also come out of the print.*
- *Fill cavities in print with bath bomb mix and place in water. Can fizz out, or pressure can cause print to open.*

Ice

- *Freeze prints in an alternate position. As it thaws, it returns to its original shape.*
- *Freezing soap bubbles or goo strands with dry ice.*
- *Flash freezing delicate prints so they appear to wilt.*
- *Crushed ice or snow melts in a different way to solid ice.*

Human Interactions

- *Adhere print to skin so it moves naturally with body. Could include articulating parts.*
- *Squashing soft pieces.*
- *Breaking prints. Multiple print copies can be made for little extra cost.*
- *Utilising print memory to create parts that respond and move back after being touched.*
- *Biting prints. Eating is a very natural interaction.*
- *Creating articulating parts where the movement of one element causes another element to also move (Hone).*
- *Prints that physically behave and respond to touch contrarily to how they look (Voerman 194).*

Other

- *Sugar prints can dissolve in water.*
- *Silicon or latex strands.*
- *Soak prints in fuel, then burn prints.*
- *Heat Vero prints so they flex slightly.*

Fig. 3.01. "Large Claw Detail." *Author's Own Image*. Nov. 2016. Photograph.

PART 3:
FINAL PROTOTYPES

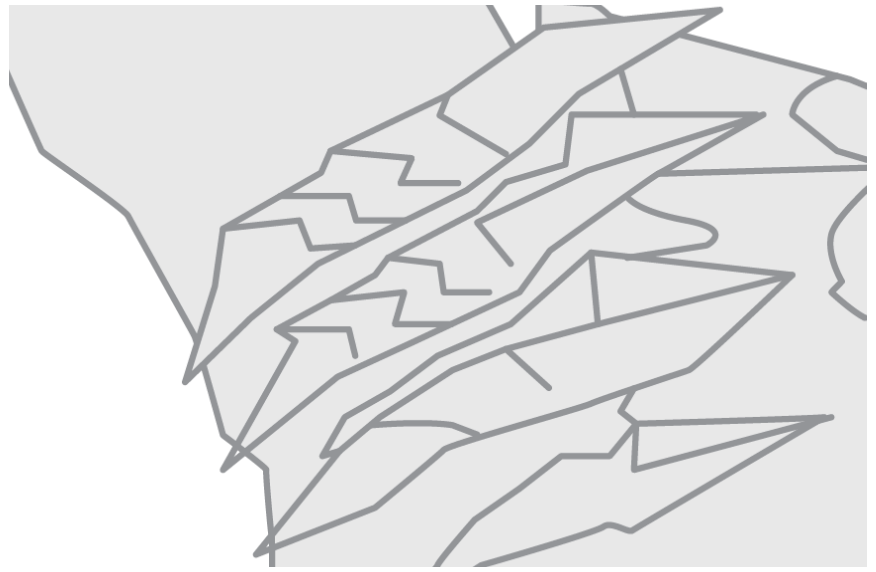


Fig. 3.02. “Nazgul Gauntlet.” *Author’s Own Screenshot.* 25 Jun. 2017. Screenshot Fig. 3.03. “Pan’s Labyrinth.” *Warnerbros.com.* Warner Bros. 17 Oct 2014. Screenshot. 25 Jun. 2017. Fig. 3.04. “Doctor Who: Chan Tho.” *Bbc.co.uk.* BBC. 5 Sep. 2008. Screenshot. 25 Jun. 2017. Fig. 3.05. “Gecko.” *Author’s Own Image.* 31 Oct. 2016. Photograph.

FINAL CLAW

Some of the most effective practical effects that 3D printing can do are those that connect with biology and the natural “real” world. One way to take advantage of this is to use multi-material printing for prosthetics. Earlier in my research, I had discovered that the soft Tango material was too delicate to facilitate this.

This led me to search for a solution to this issue. I needed to design a moving prosthetic that didn’t need the soft Tango material to articulate. I also wanted to build upon the potential of the small, coloured disc swatches. This led me to the decision to create a set of hard, coloured pieces that would fit onto the thumb and finger, similar to an armoured gauntlet. I originally thought about making all these pieces hinge together, but felt the detail would be unnecessary and would create extra bulk.

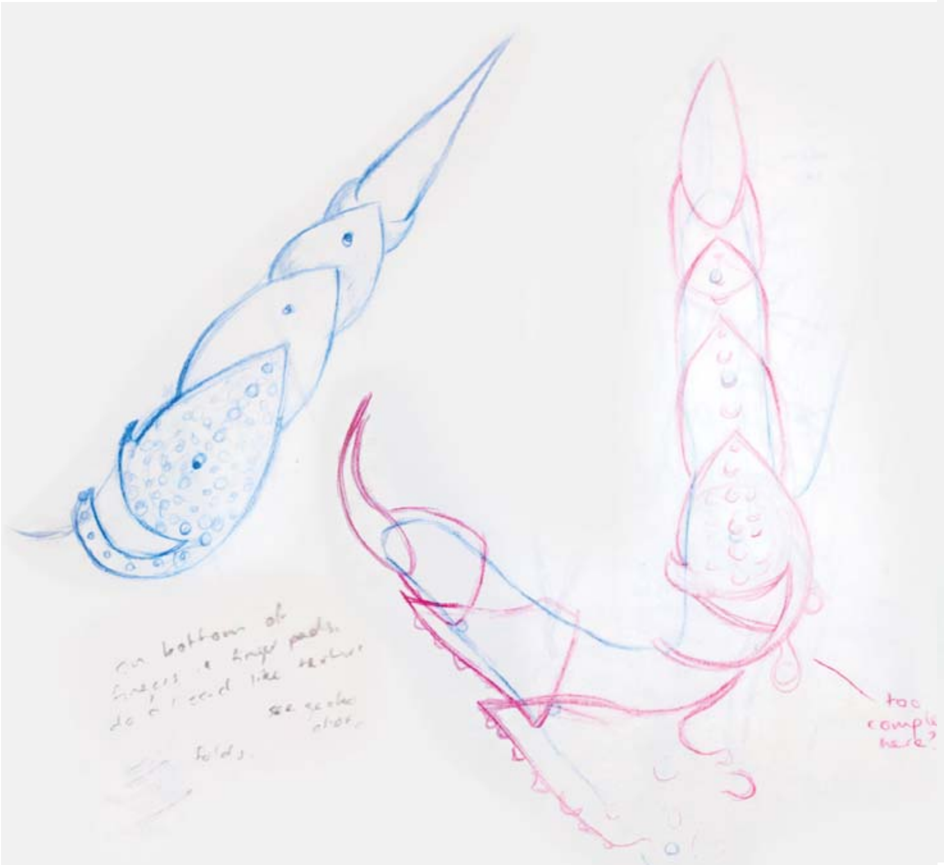
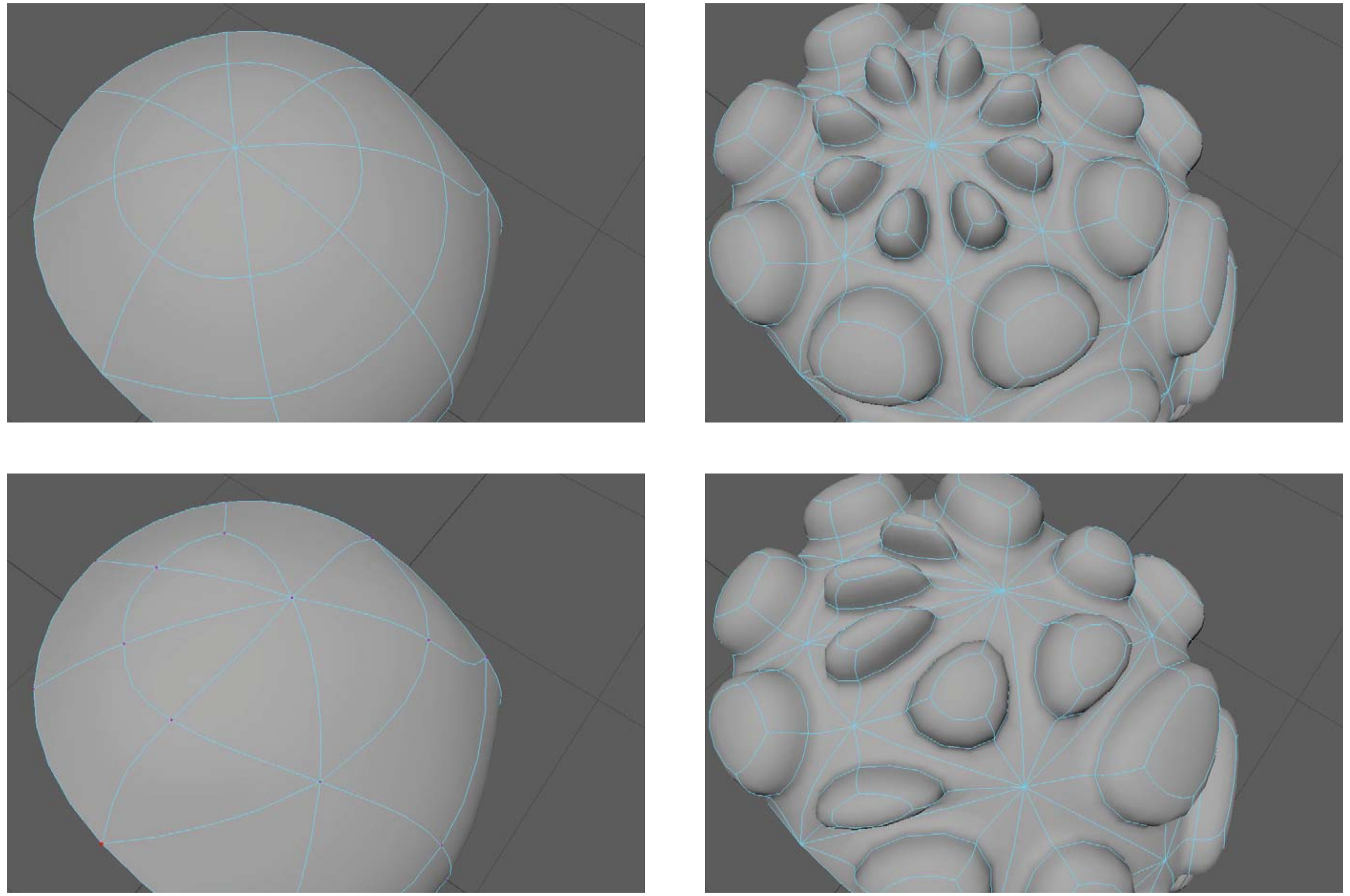


Fig. 3.06. “Claw Sketches” *Author’s Own Image.* Dec. 2016. Sketch.

I decided to create a two claws, one to fit my hand, and another that would fit Ross Stevens'. As most of the design was based on complex detail and 3D form, I found it a little difficult to sketch ideas. This resulted in me doing a lot of design iteration through 3D modelling. For example, I developed the idea for different patterns by learning different ways to split and merge faces on the grid-like mesh. When these individual faces were extruded into the little bump-like scales, they reflected the original faces' patterns. As seen in the images below, the faces can be changed with various mesh editing tools, which will influence the final form and design of the mesh.

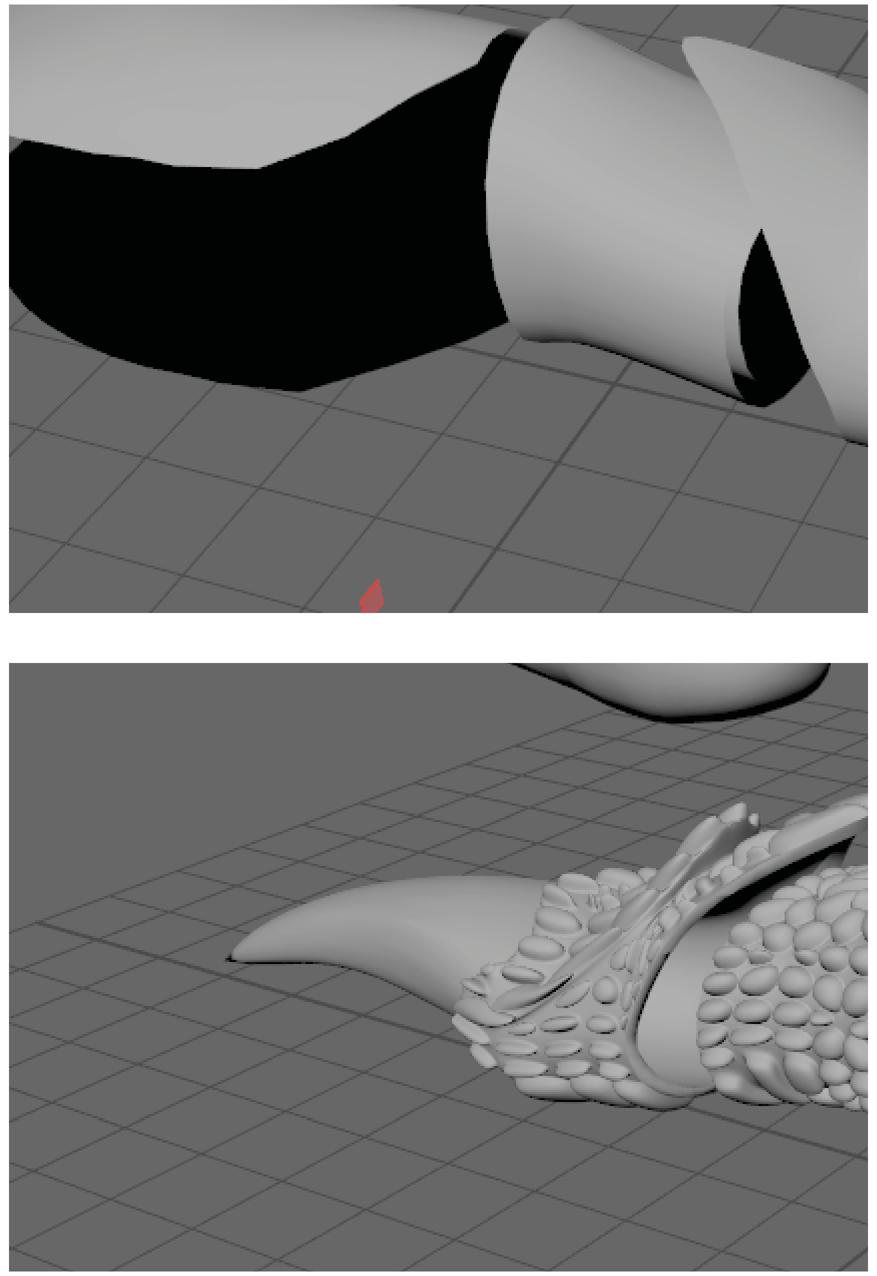
Although I was able to extrude different faces to create a pattern, I



Figs. 3.07 - 3.10. "Extrusion Scales Technique" *Author's Own Images*. Jun. 2017. Screenshot.

had to first ensure that the actual form of the shape was contoured correctly to fit my hand. I initially worked from photographs of different angles of my thumb and forefinger, and then modelled a fairly accurate representation of the shape and curve of my hand. To test that this worked, I printed out the thumb section on Victoria University's two-material Connex printer. I found that this worked for simple forms like the "ring" pieces, but it didn't work so well for the more complex "palm" piece. As this could not be a full ring, it had to grip onto the side of my hand, contouring perfectly to quite an irregular form. I decided that it would be best to get a 3D scan of my hand, and use that as a reference when building the forms.

3D scanning hands can be difficult, as they are quite difficult for scanners to interpret correctly due to the gaps between fingers, and



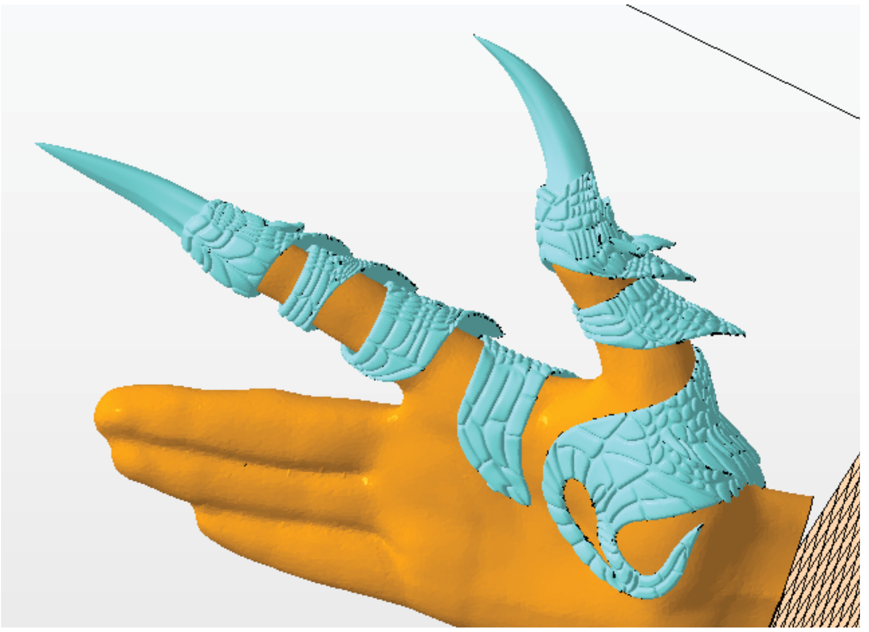
Figs. 3.11 & 3.12. "Claw Modelling Progress" *Author's Own Images*. Dec. 2016. Screenshots.

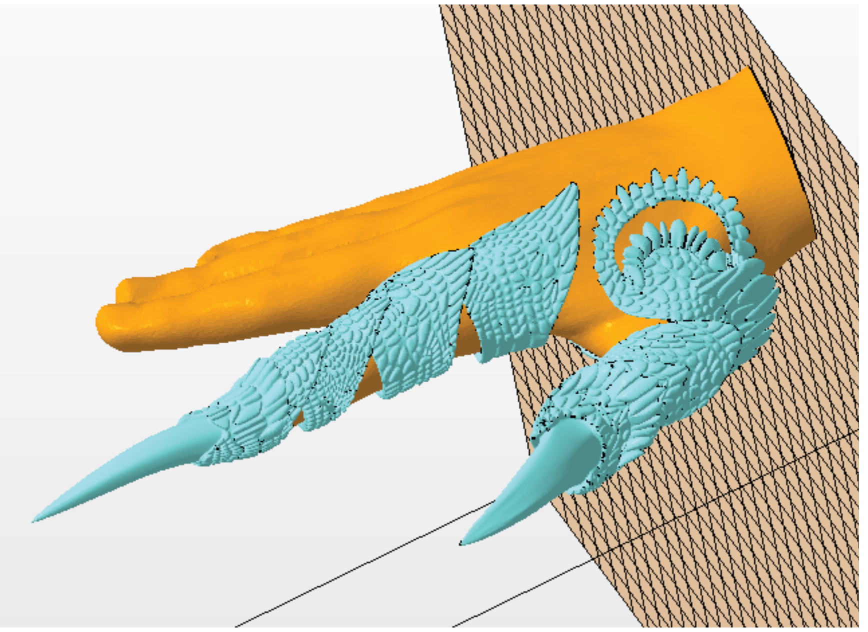
Figs. 3.13. "Claw Early Iteration" *Author's Own Image*. Dec. 2016. Photograph.

the slight movement the body has, even when trying to keep perfectly still. With the help of Zach Challies, who had scanned Ross Stevens' hand for the earlier Claw/Glove print, I was able to obtain a fairly accurate representation of my thumb and forefinger.

From there, I produced several iterations of the claw, testing out slightly different ideas and variations. In an effort to make the print integrate with the plastic more, I tried to make it look like the prosthetic was dissolving into the skin (Fig. 3.14 & 3.15). This resulted in the claw looking a little too gothic, and I was concerned the stylised curling forms would detract from the design once colour was added.

During this process, I also took an aspect from the Claw/Glove that I found the most compelling. This was the way the soft material met the hard base of the claw, as it was reminiscent of real finger nails and added extra realism and depth. The constraints of the J750 meant that





Figs. 3.14 & 3.15. "Later Iteration of Claw" *Author's Own Images*. Jan. 2017. Screenshots.

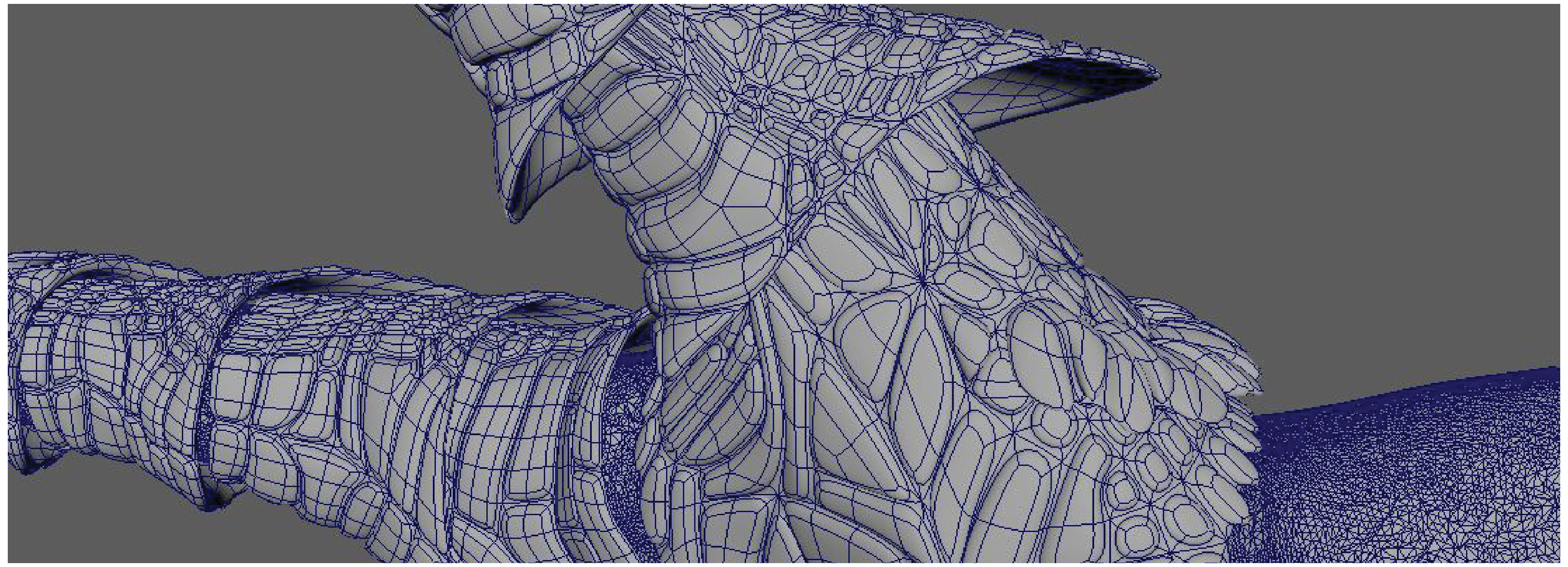
I had to separate the claw from the top thumb and finger pieces, and produce that using the STL method. I would then glue the VRML and STL prints together once they were printed.

Finally, I also added overlap on the underside of the fingers and thumb, so the gap of skin on each joint could not be seen. Originally, I had made the gap to give the wearer more freedom of movement, but this did take away from the illusion of the special effect. Ultimately, having the underside jut out and overlap offered a compromise between concealing the skin, and freedom of movement.

Before I began painting the form, it was important to test that the form was successful, due to the restrictive workflow. Both claws were printed on the two-material connex printer. This cost $980 for the two sets, which would be equivalent to the J750 cost. This demonstrates why I was unable to print all of my iterations, as each print had to be intentional, and was dependent on the resources and funding available. This would not be applicable in the industry I have designed these for, as a film would have a more than sufficient budget for this.

Fig. 3.16. "Final Claw Test Print" *Author's Own Images*. Feb. 2017. Photograph.

Fig. 3.17. "Final Claw Maya Model" *Author's Own Images*. Feb. 2017. Screenshot.



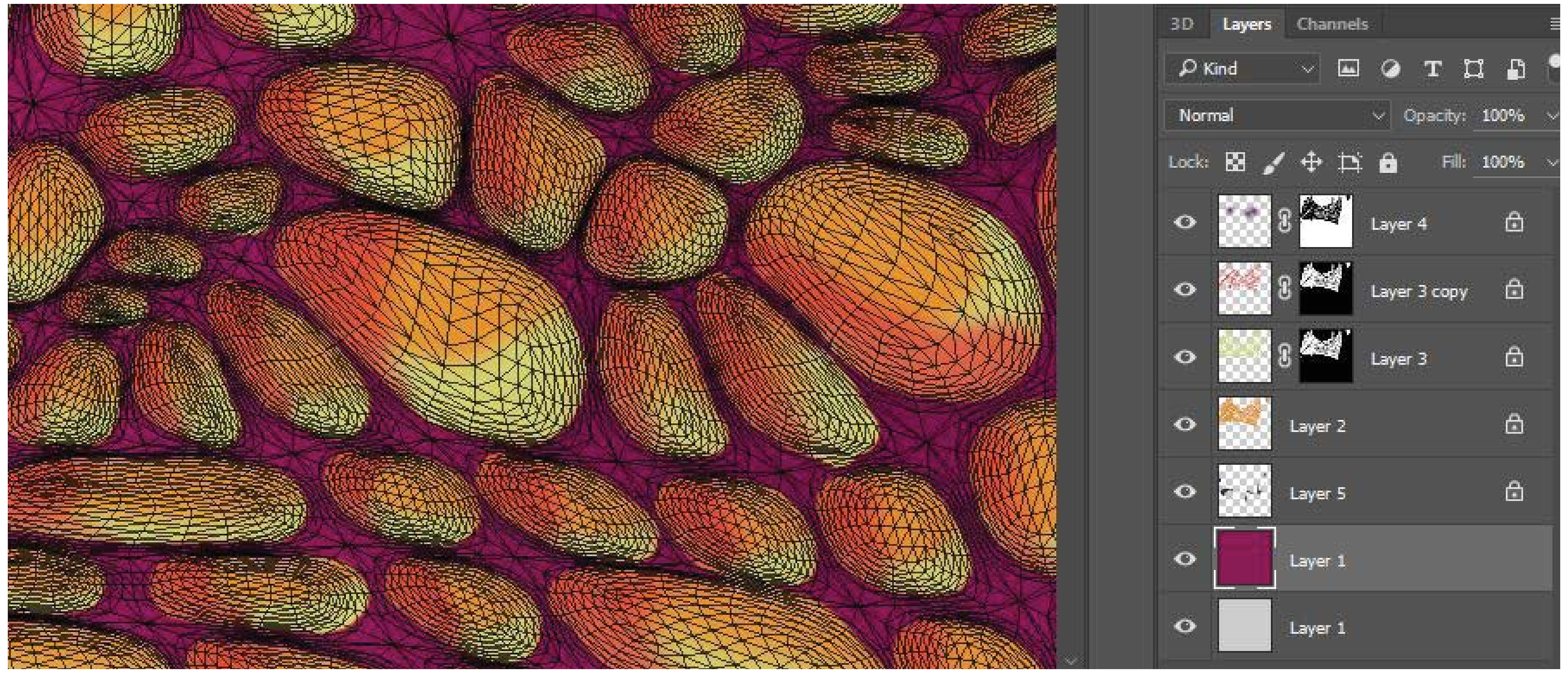


Fig. 3.18. "Photoshop Colouring Detail Large Claw" *Author's Own Image*. Feb. 2017. Screenshot.

Once I finalised the form, I was able to move on to painting the mesh. Unfortunately, the workflow process meant that I was unable to go back and forth between colouring and mesh editing. This meant that I had to be sure about the form before painting, so it was quite a rigid transition in the design process.

Photoshop CC allowed me to paint directly onto the meshes in the 3D workspace. It also allowed me to automatically generate the UVs, which is the net which wraps a flat JPEG around the 3D mesh. This was good, as I had little experience with 3D painting and managing UV maps, having never needed to know this before working with the J750. I found the 3D workspace clunky to work in, and there were little unnecessary things that irritated me. For example, the program required the manual placement of light points around the object before it could be seen properly. This is not the case for any other 3D modelling programs I have experienced.

Another issue I found was that to create a detailed, blended map, I had to paint everything manually. Using Photoshop tools such as layer masks and blending options helped to a certain degree, but there was still a lot of manual, time-intensive work that had to be completed accurately. Upon reflection, I feel that I could have found another painting program that would have been able to automatically complete many of these steps using algorithmic painting. However, at the time I did not want to risk the hours spent coding something that could have amounted to nothing, especially given my limited coding experience. I decided that manually painting the mesh assured me of a high-quality outcome, while investigating an algorithmic method was a lot riskier. Now that I have experienced the amount of time needed to manually paint such a detailed mesh, I would definitely investigate algorithmic opportunities for future work.

These steps were also completed to create the claw that fits Ross Stevens' hand, as he felt it was important that he had one that he could use for his own demonstrations to show the potential of the J750. This also allowed me to show the flexibility of 3D printing - I took the mesh that fitted my hand, and simply refit it to fit on his hand instead. This is another process that could be done almost instantaneously with an algorithm, meaning that variations of one model could be output depending on different user's needs. In the film industry, this has huge implications for the potential outfitting of multiple actors with a high turn-around. This larger hand was then painted manually

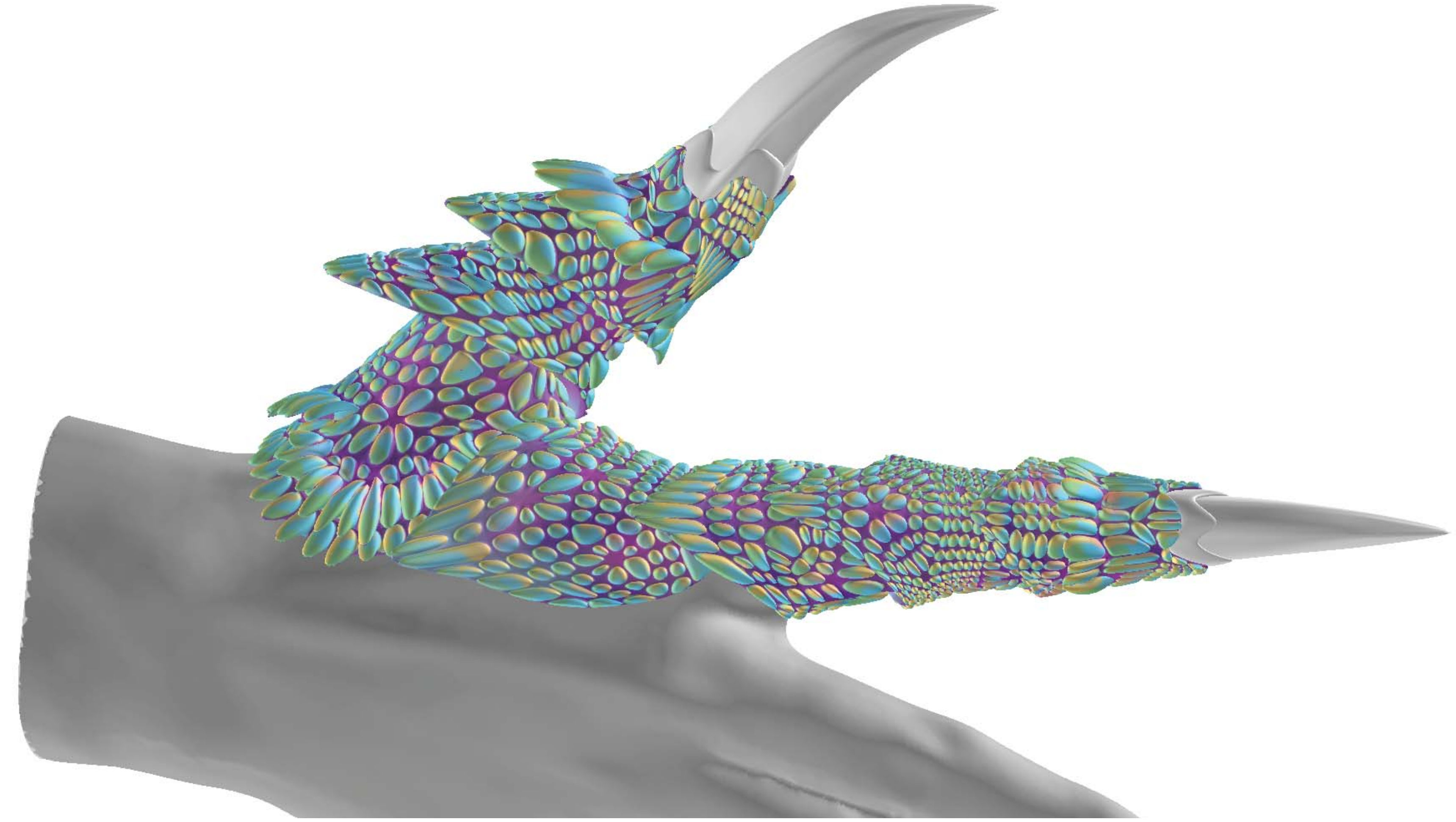


Fig. 3.19. "Photoshop Colouring Small Claw" *Author's Own Image*. Feb. 2017. Screenshot.

too, which again, demonstrates how some algorithmic painting would probably be necessary if this was implemented in the film industry. I chose to exhibit a different colour palette in this claw, choosing darker, fiery tones. Mine was more light, and watery.

We then printed Ross Stevens' claw in Hong Kong, while mine was printed a little later through a newly established partnership with Darlene Farris-Labar in Pennsylvania. Stevens' claw actually turned out a lot brighter than mine, which was quite different from my intentions. This did not have too much of a negative impact as I feel the claws still look effective, but I am curious about why this may have happened. One theory is that the VeroCyan material is known for being a little darker, and as my claw used blue-based colours, this would have darkened the entire print in comparison to the red-based one. Another theory is that these may have been printed using different software. Stevens' claw was sent directly to Stratasys, so they may have been using their in-house software. Meanwhile, Farris-Labar and I decided to trial the new GrabCAD Print software, which was much more accessible and user friendly than previous Stratasys printing softwares. GrabCAD Print may have processed the colour maps differently to the software Stratasys used, causing a difference in colour brightness between the two prints.

In either case, I would recommend further material testing be implemented before J750 technology is used in the film industry. It would be useful for designers to have access to swatches, as the design of a industry dependent piece requires highly precise colouring. Otherwise a designer might well decide to take the more reliable option of painting the prints by hand.

Fig. 3.20. "Claw Test Shoot" *Author's Own Image.* Apr. 2017. Screenshot.

FILMING CLAW

Preparation

As this print was only an example section of what could possibly be a bigger prosthetic covering the whole hand, I felt there wasn't enough opportunity to create a narrative-driven film. Instead, I decided to concentrate on communicating how the digitally created 3D print could interact with the physical world. As I had already extensively listed different interactions which exploit materiality in film, I selected appropriate ones and planned shots to display their use.

I knew from past experience that it is always a good idea to do a quick test film, if possible. I felt this was particularly a good idea in this case, as I was playing with a lot of unusual materials. By filming a test of these processes, I was able to discern the optimal way to perform with, light and film the different materials.

I decided to use a sheet of black acrylic as the background, as it was highly reflective and made the coloured claw stand out. White acrylic looked clean, but I felt it made it trickier to see transparent materials like corn syrup. On black acrylic, the lighting can be arranged to create strong highlights on the corn syrup.

I tested using fur and corn syrup. Fur was quite difficult to light, and corn syrup provided more performance opportunities. This helped inform what I would use for the final film. It was lucky that I had decided to do a test shoot, as it took me a little while to figure out how to make the best use of the camera equipment. I had issues with lights and white balancing the camera, but I was able to resolve or figure out work-arounds for the future.

Figs. 3.20 & 3.21. "Claw Test Shoot" *Author's Own Image.* Apr. 2017. Screenshot.

Filming the Claw

For the final film, I decided to use a range of material effects to demonstrate the different ways the 3D print could interact with the physical world.

Firstly, I lightly sprayed water onto the claws, causing water to gather between the "scales" and distort the form and colour intensity of the objects. Secondly, I felt that the simplest and most compelling way to demonstrate how visceral and tactile physical interaction could be was to show the claws ripping into fruit. I chose red grapes and mandarins, for their bright textural colour and the way the skins could behave when scratched and pierced. I felt that this could subtly hint at how a similar prosthetic could be used in a creepy, violent way in a horror or fantasy genre.

In the test shoot, the claw delicately played with a small circle of corn syrup. For this shot, I switched the corn syrup for bright red paint. While it isn't the exact same colour as blood, it alluded to films and scenarios where blood may be used. Finally, it was important to explore the potential of corn syrup, building on the experience of filming it in the test shoot. When dripped from above, it resembled monster saliva. I also liked how the entire surface of the black acrylic could be covered, which would then settle to be almost invisible. It was satisfying and surprising to run the claw across the surface, revealing the syrup as the claw made wrinkles and ripples through it. When the claw was lifted from this surface, it created complex gooey strands.

As I had already planned and practised filming, the shoot was relatively straightforward. I decided to use two cameras, one with a regular zoom lens, and one with a macro lens. This meant I could get full coverage over each material "performance", and gave me the option to switch between each camera when editing to hide mistakes and cut out the less compelling moments.

Each performance was relatively easy to "reset", even those with some cleaning required. This meant I could redo something straight away if it didn't look the way I wanted, or go as planned. This was something I hadn't been able to do when working with the test fruit, so I found it a more comfortable experience. I spent a few hours filming Ross Stevens' claw, and then several more hours filming mine, with the assistance of a friend. Filming both claws added more visual variety to the final film, and stopped it from becoming repetitive. I also think it hints at the greater potential of this small 3D printed prosthetic for other, more ambitious film projects.

After editing the first draft of the film, I noticed that the interaction between the environment had been addressed, but the physical interaction between claw and responsive human skin had not. This led to conducting a small extra shoot, which demonstrated how the skin of Ross Stevens and I behaved when lightly scratched. It was also effortless to act a "response" from the claws, as none of the acting had to be imagined. While the claws were not particularly painful, by editing the ripped fruit straight after, the film alludes to the violent potential of this CGO effect.

What follows is a storyboard outlining the final film, using stills which illustrate the key moments in the video. The film can be found attached to the physical copy of this thesis, or can be accessed online at torrobinson.co.nz.

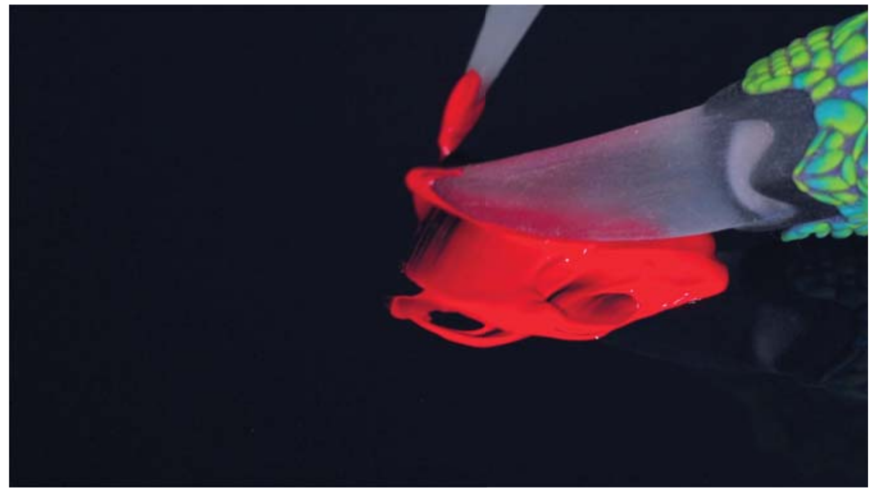
Figs. 3.22 & 3.23. "Screenshots from Final Claw Film" *Author's Own Image*. Jul. 2017. Screenshot.

Figs. 3.24 - 3.28. "Screenshots from Final Claw Film" *Author's Own Image*. Jul. 2017. Screenshot.

Conclusion

While the success of this film will be discussed and evaluated in a later chapter in relation to the final fruit film, I will briefly touch on the result and effect of the final film here. I was able to film the different interactions at a professional standard, demonstrating the potential this technology could have in a feature film produced by a professional production company.

The film communicates the design intent of the claw well, and carries through some key ideas discussed earlier in this thesis surrounding the link between materiality and believability. Simultaneously, the film is entertaining and compelling to watch for any audience.



Figs. 3.29 - 3.32. "Screenshots from Final Claw Film" *Author's Own Image*. Jul. 2017. Screenshot.

Fig. 3.33. "Screenshot from Final Claw Film" *Author's Own Image*. Jul. 2017. Screenshot.

Fig. 3.34. "New Agilus Material" *Author's Own Image.* Jun. 2017. Photograph.

UPDATE TO J750 CAPABILITIES

In March 2017, approximately three months before the completion of this thesis, Stratasys implemented some changes to software and support material.

Firstly, a new soluble support material was introduced to the J750. I initially hoped that this would be completely soluble in water, but I soon found out from the Stratasys representatives that it had to be a solution of 2% sodium hydroxide (NaOH) and 1% sodium metasilicate (Na_2SiO_3). As detailed in earlier chapters, I had previously found Stratasys' original support material constrictive. The removal process meant that delicate parts could snap if they were not cleaned slowly and precisely, and some more complex structures like 3D lattices were virtually impossible. This support solution would be used in a speciality cleaning tank placed next to the J750.

Stratasys also released a new, stronger material, Agilus. This will solve the issues found with the initial soft Claw/Glove, but the material cannot be used to make shore hardness blends as of yet. However, the Claw Glove was still printed in this material to draw comparisons, and the Agilus material proved to be much stronger than Tango.

In addition to this, Stratasys had recently released some software in partnership with the website GrabCAD, called GrabCAD Print. This made the process of preparing a print for the J750 much more accessible, as previously Stratasys' Polyjet software was hard to access if the designer didn't own the printer it worked with. GrabCAD was free, and with a friendly and simple user interface that was easy to understand. It also integrated tools that fixed meshes automatically - before, I would have to take all files into a program like Netfabb to ensure that they would be accepted by the Polyjet software.

GrabCAD Print also solved some of the issues I identified earlier in my research, concerning the limitations of colour picking. Originally, material specification was restricted to legacy palettes intended for a three cartridge system, not six. Now, GrabCAD used a simple colour picker to choose colour, and sliders to dictate transparency and shore hardness. There were still some slight restrictions - coloured Vero, transparent Vero (VeroClear) and soft Tango could not be combined into one material blend. Nevertheless, this change made a huge difference to the freedom I had as a designer to choose more subtle and organic colours.

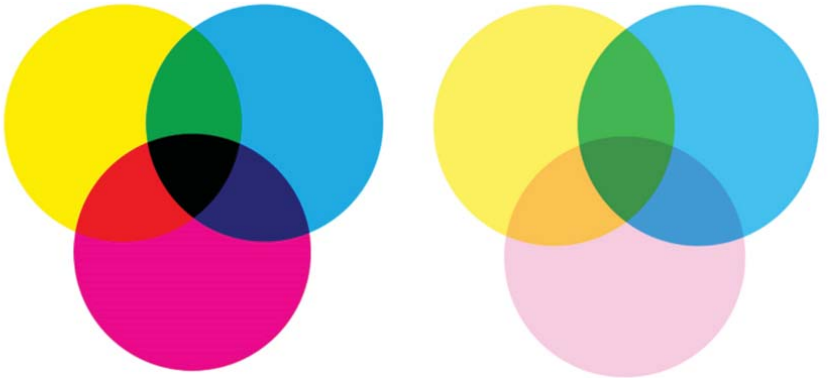


Fig. 3.35. "Demonstration of more nuanced colour potential". *Author's Own Diagram.* Nov. 2016. Diagram.

Fig. 3.36. "Charlie and the Chocolate Factory." *Author's Own Screenshot*. Screenshot. 25 Jun. 2017. Fig. 3.37. "Marie Antoinette." *Author's Own Screenshot*. Screenshot. 25 Jun. 2017. Fig. 3.38. "Avatar Fruit Scene" *Author's Own Screenshot*. Screenshot. 25 Jun. 2017.

FINAL FRUIT

Fruit in Film

Interestingly when searching for filmed examples of actors eating food and fruit, I found these instances were harder to find than I had predicted. A filmmaker is required to get multiple takes of a single scene to get the coverage required to construct the film. This results in actors refraining from eating, as the repetition could make them sick, and the disappearance of food could break the continuity of a scene. Filmmakers may construct a scene around eating, but use clever editing so we never see the actor actually taking a bite.

When food is present in a scene, it will often be shown as a background activity. A common example of this is where characters gather to convey information over a table of food. As this is an activity which everyone on the planet experiences from day to day, these scenes are often taken for granted. As eating is such an ordinary act, the use of food can be used to root them in reality, or show that they live in a day-to-day routine.

This gains new meaning when placed in a sci-fi or fantasy film, where the world presented to us is an imagined construction created by the filmmaker. Food can be used as a tool for world-building, a small, "everyday" detail to create a believable reality.

Food can sometimes be used in a sensual manner, to depict sexuality, or to show sensory, luxurious experiences. In these cases, the food may be the absolute centre of a scene, or at least be the key component setting the mood and feeling of the scene.

The scene, naturally, needed to centre on the fruit. Ideally, my film would depict two actors conversing and enjoying the food together. It did not necessarily have to be sexual - I thought that might distract too much from the focus of the film. But, showing the simple enjoyment of two people familiar with each other would be an effective experience to watch. By seeing someone enjoy something, the audience will also associate feelings of enjoyment with the object.

In regards to sci-fi and fantasy worldbuilding, this was absolutely the purpose of the fruit. I wanted the fruit to supplement the conversation and subsequently the narrative. In short films, the narratives naturally have to be rather simple, depicting small, meaningful moments or ideas. In this short film, I thought it would be relevant to depict one actor telling the other about this brand new planet he had just travelled to, ultimately trying to convince the other to come back with him.

I was also inspired by a short scene in James Cameron's epic sci-fi film *Avatar*, the worldbuilding of which is discussed in an earlier chapter. Early on in the film, the main character Jake experiences the world of Pandora for the first time. He stays inside the humans' compound, but is still able to sample some of the strange new world outside by picking an alien fruit from the compound's vegetable garden. This experience of discovery is tarnished somewhat by the fact that this is a CGI fruit. It is basically a thick sack that rips open to reveal juicy, jelly-like seeds, and contains little structure. There doesn't seem to be the right amount of response to this fruit from the actor, and the fruit itself seems slightly insubstantial. I believe this is because the filmmakers are depicting such an everyday, natural interaction, so we are able to instantly sense something not quite right with the depiction of the consumption of food.

The key theme of this short moment is the discovery of a new world through a small, everyday interaction. A 3D/4D printed effect solves the slight interactive disconnection found with a similar CGI scenario. Ultimately, I aimed to achieve something slightly bigger than this brief moment in Avatar, centering a pivotal moment in two characters' lives around the consumption of this fantasy fruit.

Designing the Fruit

The changes to some key Stratasys technologies were the catalyst for the design of this new, final fantasy fruit. As the restrictive nature of the support material was the main issue with my first fruit print, I decided to redesign my fruit to take advantage of this new technology.

First, I decided to do some loose sketching to explore any possibilities I may have missed when designing the first fruit print. As before, the key aim was to design a fruit that could be pulled apart and "eaten" by actors on camera.

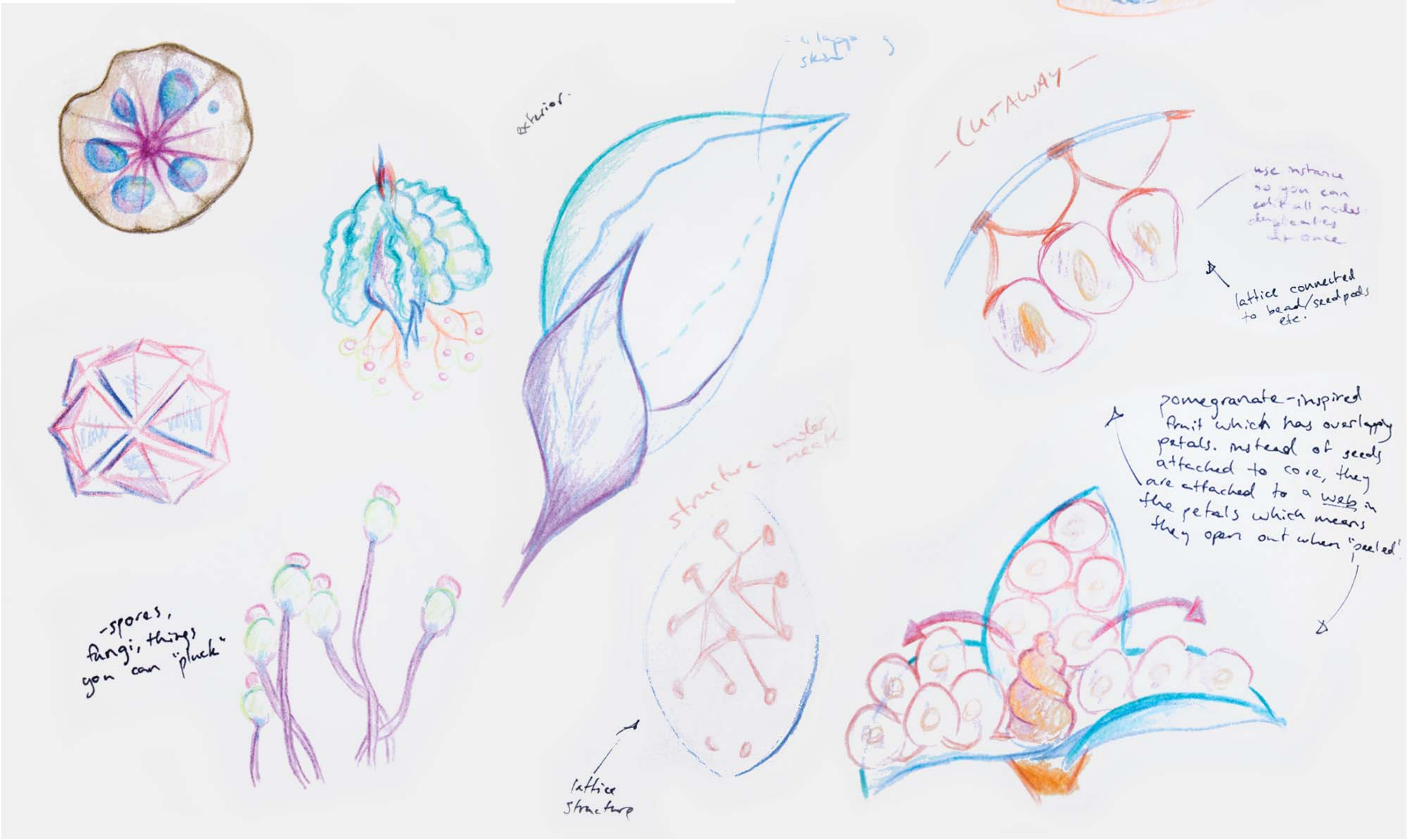


Fig. 3.39. "Fruit Sketches" *Author's Own Image.* Mar. 2017. Sketch.

Fig. 3.40. "Fruit Sketches" *Author's Own Image.* Mar. 2017. Sketch.

I found that the sketches didn't quite reach the scope of idea generation I wanted. Coloured pencils can only simulate texture and three-dimensionality so much, so I decided to do some collages using photos of real fruit to explore the different effects different kinds of fruits had. These collages definitely could not be literally translated into a final 3D model, but they allowed me to conceptually explore how "wild" I could go, before reining in my ideas to something more feasible and logical. I particularly looked into collaging photos of everyday fruit with more unusual fruit, to see how I could design something that looked vaguely familiar and recognisable as a fruit, while still retaining some fantasy qualities. I also used photos of flowers and seeds, as they all stem from the same biological process. While this fruit may be from an alien planet, it still has to be recognisable enough to the audience for them to be able to understand it as a fruit.

I first reflected on the successes of the first fruit print. I liked the general silhouette of the outside skin, and felt that if the original support material had not restricted it so much, it would have been able to peel away well. I also liked the idea of having internal pods which could be picked out, but they would be much more interesting if they

Fig. 3.41. "Fruit Collages" *Author's Own Image*. Mar. 2017. Digital Collages.

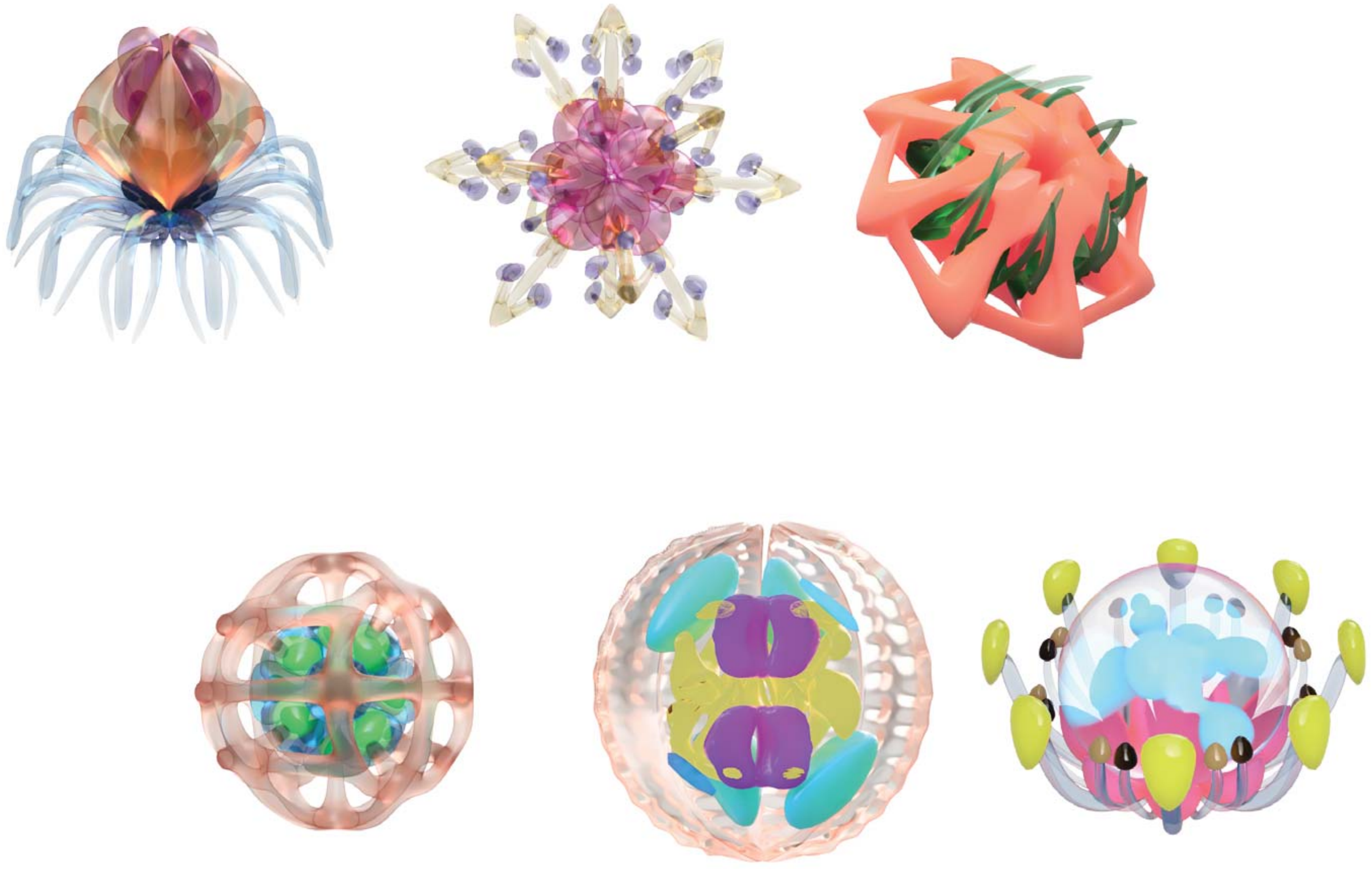


Fig. 3.42. "Fruit 3D Sketches" *Author's Own Image*. Mar. 2017. Renders.

were hollow instead of solid. I could then fill the pods with jelly so they could burst when bitten by my actors. Previously, this would have been impossible, as I would not have been able to remove the support material from the hollow forms.

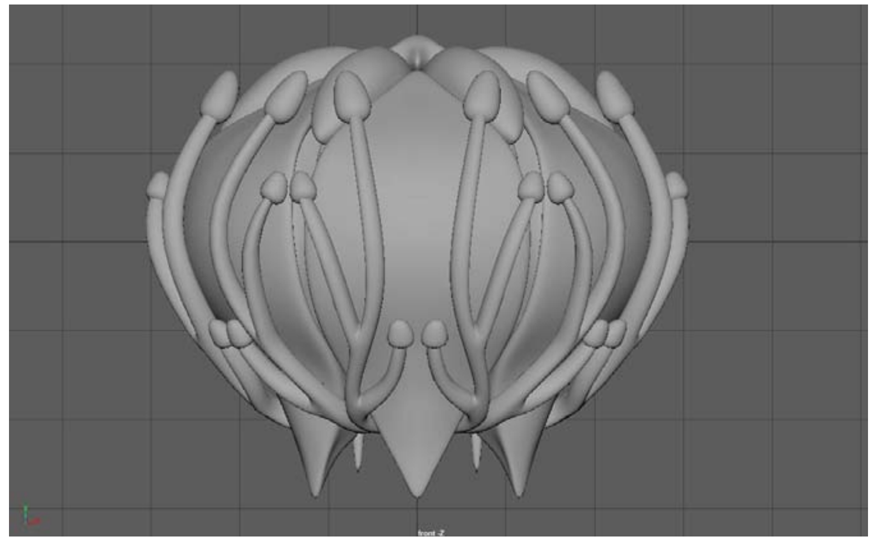
I ended up with something that had a relatively similar silhouette to the first test print, although I decided to make this one more spherical, meaning the skin would peel in a more uniform way. I also modelled the fruit as a hexagonally symmetrical shape, so the skin segmented into six instead of five shapes. This made it easier to model from a digital modelling perspective, as the forms would be symmetrical around more of the modelling axes. It also would produce more fruit pods, meaning I would have extra material to film - which is especially important as I would have only one opportunity to film the print as it would get pulled apart and destroyed during filming.

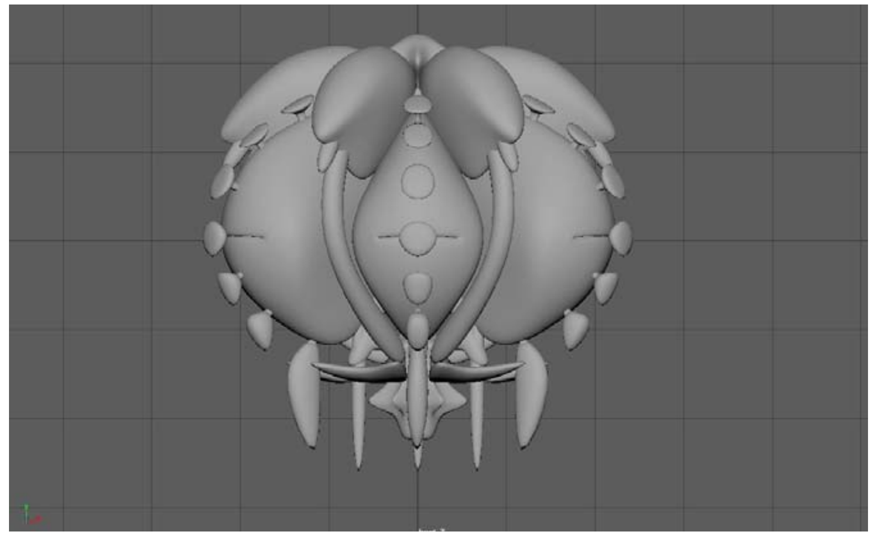
This "pulling apart" interaction was also improved for this print. Instead of pulling the inner fruit segments from the support material, my actors would be pulling the segments from the fruit itself. I attached each segment to the base and the stem of the fruit, giving the attachment enough thickness to stay together while being handled and cleaned, but making it thin enough to snap without too much force. This would also depend on the shore-hardness, as the softer blends would snap differently to harder ones.

I also added seed-pod tendrils to the outside of the fruit, to give it some more visual texture. These could also be pulled apart in a similar way to the interior of the fruit, and the actors could pretend to crunch them. The interior pods were also vastly different to the original, as the two types were originally layered next to each other, making them much more similar apart from size and colour. Having the smaller pods on long connections poking out of the skin gave more variety and interesting interactions.

Finally, I added small holes to all my hollow forms so that the dissolved support material would be able to flow out. I tried to integrate these into the design while being as practical as possible, and also decided to use them to help direct which way the pods would "burst".

Overall, I found I was able to make many small improvements related to my process and workflow, which made the modelling process much smoother. This also allowed me to create more precise detail, and design for a wider set of interactions.





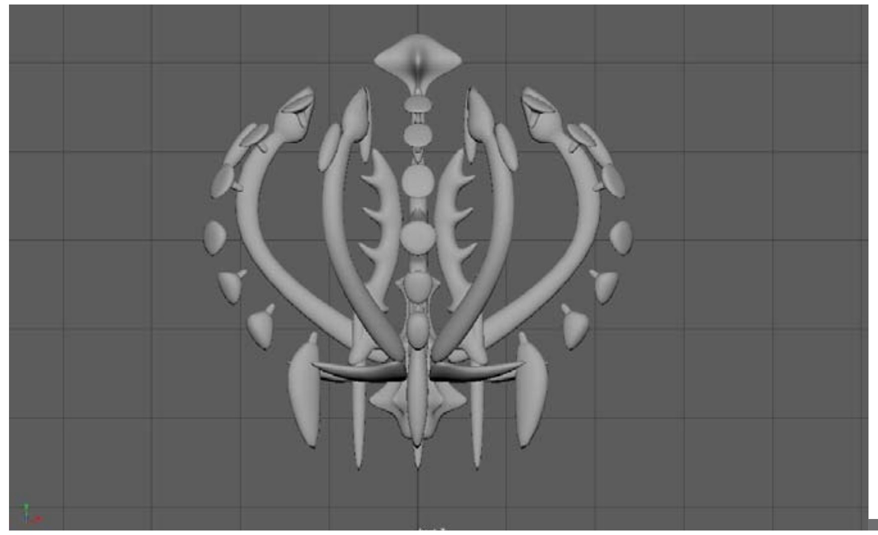


Fig. 3.46. "Final Fruit Model (Render)" *Author's Own Image.* Jun. 2017. Render.

Figs 3.43 - 3.45. "Fruit Final Model (Layers)" *Author's Own Image.* Apr. 2017. Screenshot.

Printing the Fruit

This was my first experience printing using GrabCAD Print, and I found the experience and workflow much more streamlined than my old method.

I still had to use Netfabb to boolean and separate meshes, but once I exported the correct mesh groups as STLs, material assignments were more intuitive. Previously when assigning materials to STLs, I would have to look through a PDF of material swatches and assign codes to the STL labels. Now, after importing the STLs as an assembly into GrabCAD Print, I could pick materials using a colour picker and sliders for shore hardness. As someone who has taught younger students about material specifications for Connex printing, this change makes working with STLs more intuitive and easier to understand.

I did still have some difficulty with knowing which exact hue of colour to pick. This is because GrabCAD gives a visual interpretation of what the colour will look like once printed, to try compensate for the difference between RGB and CMYK. This was still slightly dubious however, as this distorted colour was still being represented on an RGB screen so it was difficult to tell how accurate the colour was. When I saw the printed colours, I did feel that the orange was much dirtier looking than I would have liked, and the distorted colour caused me to pick too low a value.

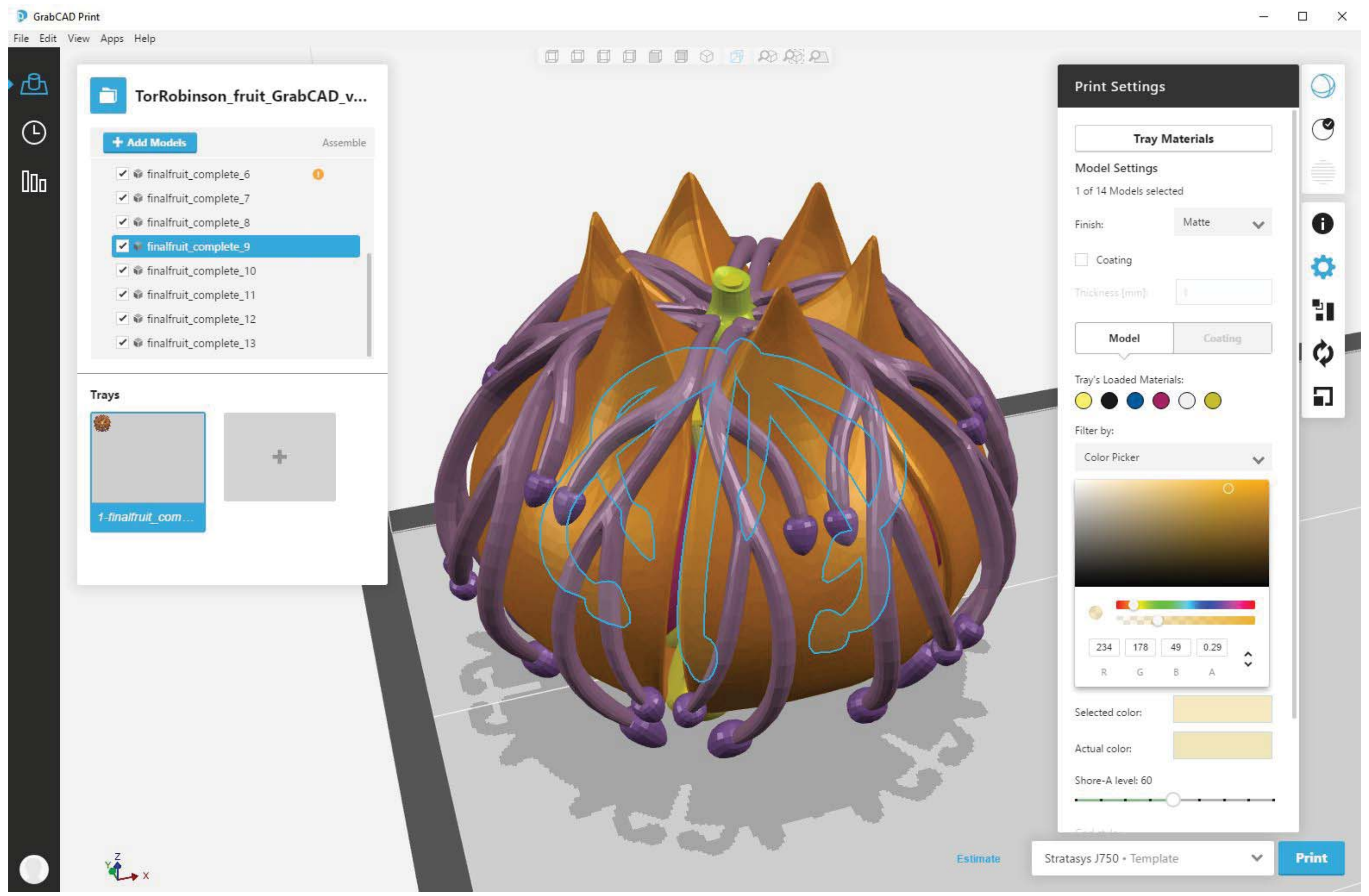


Fig. 3.47. "Final Fruit in GrabCAD Print" *Author's Own Image*. Apr. 2017. Screenshot.

Post-Processing the Fruit

As I did not have access to the speciality cleaning tank provided with the purchase of a J750, I had to separately acquire and use the cleaning chemicals independently. I worked with Susanna Leung from Victoria University of Wellington's Chemistry department, who helped me prepare and use the solution in their facilities.

Initially, we were concerned that the concentration of 2% sodium hydroxide (NaOH) and 1% sodium metasilicate (Na2SiO3) was too strong for the print, and could possibly damage it. As I only had the one print, this was potentially a huge risk. We decided to test out how the support material may dissolve with lower concentrations in case we needed to dilute it more. We also placed a piece of Tango material in the undiluted solution to check if it would corrode or delaminate in any way. Thankfully, we did not identify any issues, and moved on with the specified solution. This may have been unnecessary, but I hadn't been given much information about the process by Stratasys, and as I wasn't using the cleaning tank, it was helpful to guarantee the effectiveness of the process for ourselves.

I had hoped that the solution would completely dissolve the support material, and this probably would have been the case if the print had not been such a complex form. The skin of the fruit prevented the solution from permeating to the interior support, so I had to manually remove some of the half-dissolved material several times so the chemicals could reach interior cavities. This meant the cleaning process took a lot longer than expected, as I had to let the print soak for around five hours or more between each manual clean. I would still consider this new soluble support material a huge improvement over the older, non-soluble material.

Another issue that I ran into was that the Tango material turns opaque when soaked in liquid for a long time. I was concerned that this would be permanent, but it did start to return to transparent after a few days of drying.

Fig. 3.48 - 3.51. "Soluble Support Cleaning" *Author's Own Image*. May. 2017. Photograph.

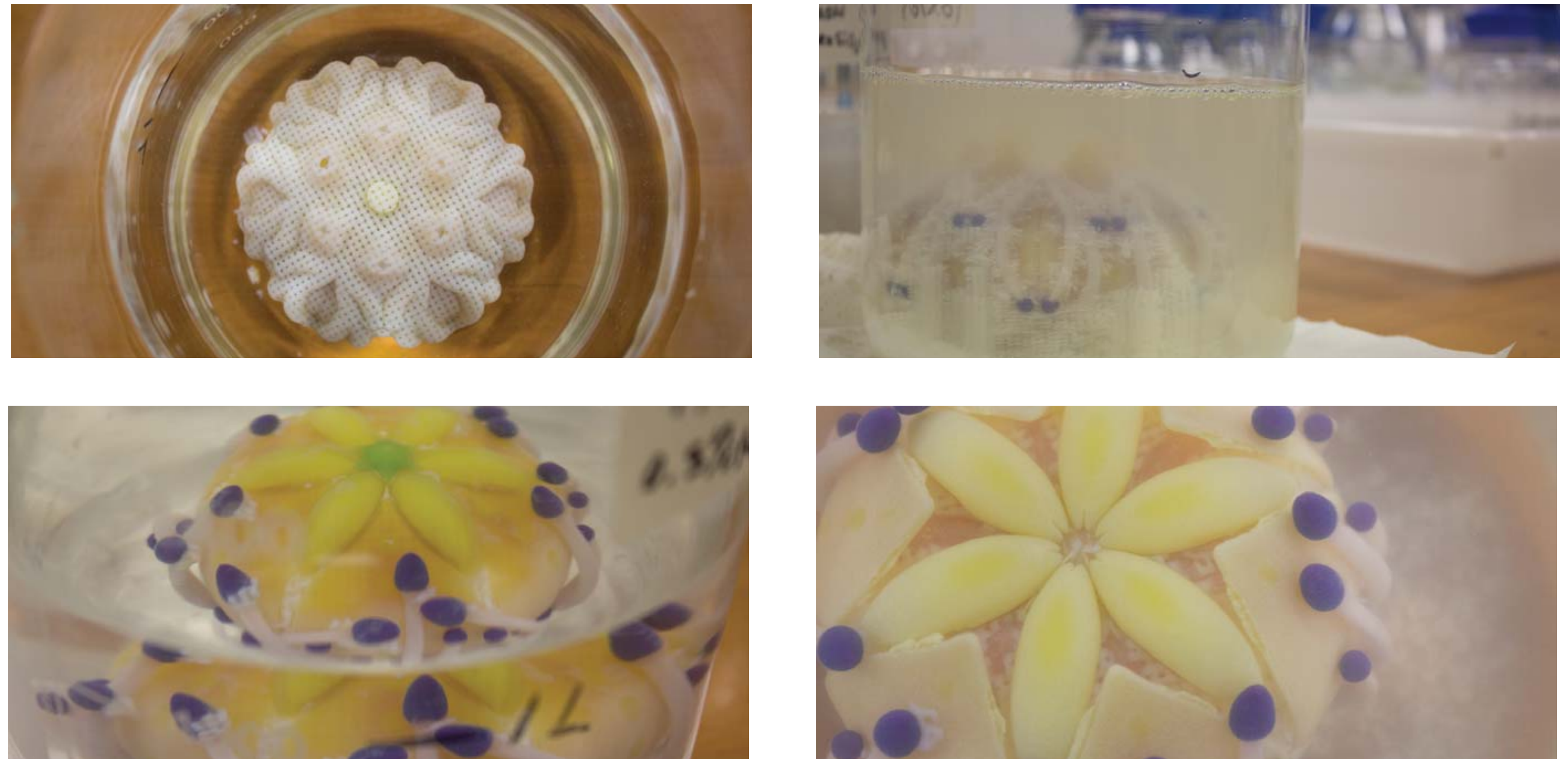


Fig. 3.52. "Final Fruit Print" *Author's Own Image*. Jun. 2017. Photograph.

FILMING THE FINAL FRUIT

Preparation

As I only had one chance to shoot this short film, I had to make sure I extensively planned every aspect to ensure it went well the first time. It was useful that I had filmed the test fruit, even though the focus of the film was a little different. I wanted to use two actors that knew each other quite well, so I ended up using a brother and sister. I wrote a script and planned out different shot types by mapping camera positions to get the sequence executed as efficiently as possible.

I also organised other props such as a table and chairs, tablecloth, and a plate that would work well with the fruit. I had designed my fruit with the purpose of filling it with jelly, so it would burst out of the pods when bitten, and hold the general form together. I tested out different densities, and decided to add chia seeds to the inside of the pods so there would be some additional textural variation when the pod segments were bitten.

Fig. 3.53. "Final Fruit Print" *Author's Own Image*. Jun. 2017. Photograph.

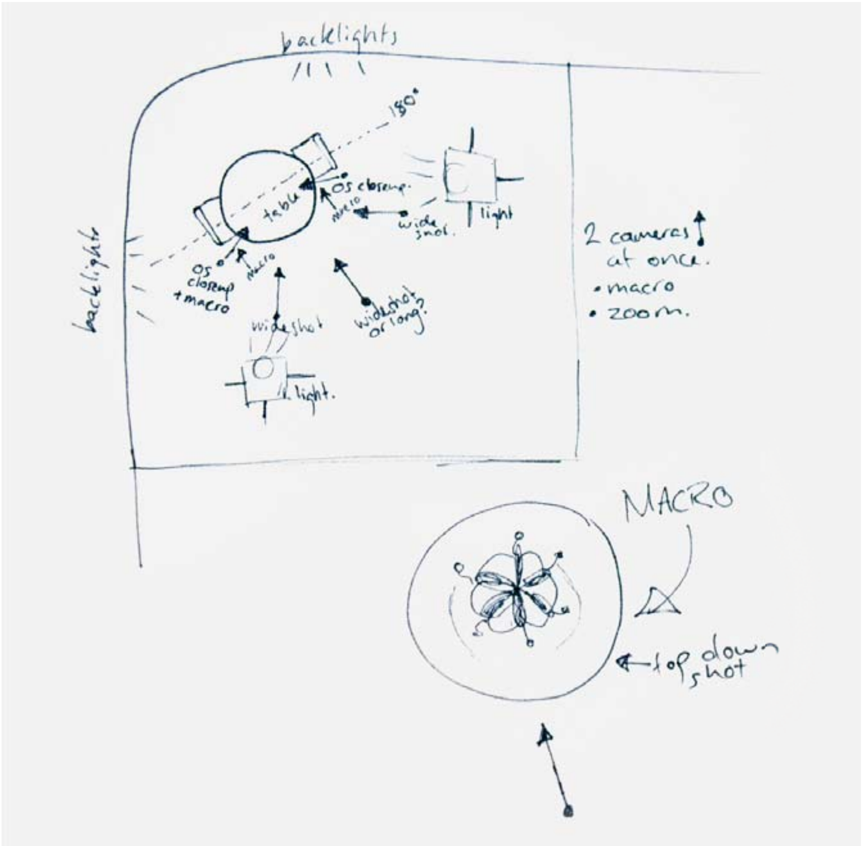


Fig. 3.54. "Filming Setup Plan" *Author's Own Image*. Jun. 2017. Photograph.

Filming the Fruit

While my actors were comfortable with performing and being in front of a camera, it still took longer than expected to film the initial dialogue scenes before they start eating. I knew the importance of getting these narrative-reliant scenes perfect, so I was willing to spend the necessary time on them. Unfortunately, this meant that the fruit ended up sitting in the middle of the table under hot lights for some time. This had caused the jelly to melt more than desired, so it would be mostly unusable for close-up shots. I decided to film what needed to be done that day, and come back for a reshoot with a higher concentration of gelatine in the jelly.

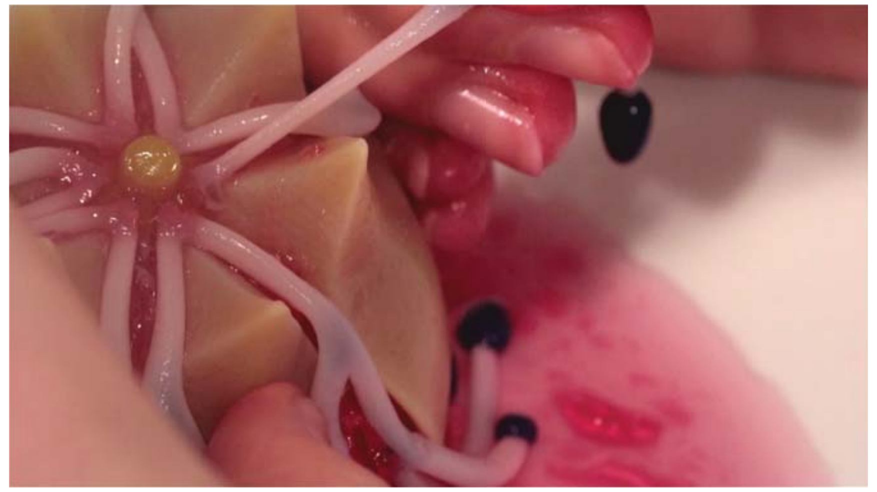
Unfortunately, the brother's schedule did not permit time for a reshoot the following day. However, I was able to work around this. I carefully pulled a selection of pods out so they could be glued back in at the base for the reshoot. This allowed me to capture all of the brother's coverage. I then washed and glued these pods back in, and reset the fruit in a harder jelly. The next day, I was able to film all the close-ups of the fruit deconstruction at the level of quality I intended, plus any shots of the sister I was not able to capture the previous day.

I then spent some time editing together all of the captured footage into a film. I was glad I had used two cameras, as similar to the claw film, I was able to edit around any errors or uninteresting parts. This was especially useful for editing the dialogue shots, as I was able to switch between different shots depending on the quality of the performance.

Upon reviewing the footage, I also realised I needed to re-record all of the sound, as the photography room I filmed in had a lot of background noise. Dubbing over dialogue turned out to be relatively easy, and I also spent some time pulling apart and dissecting some mandarins to get appropriate fruit dissection effects. By adding in these sounds, I was able to be more creative with the overall feel of the film, enhancing different aspects to be more effective than they had originally been. I feel that sound is often the most overlooked part of a film, as it cannot be seen, but I feel it made a huge difference to the final quality of the film. I also spent a while choosing the right soundtrack for the background of the film, as this can influence the mood, and subsequently the audience's opinion of the 3D printed fruit. As many sci-fi films can be creepy and scary, I wanted the audience to come away with a positive, contemplative feeling, to show that the future of 3D printing can be an exciting and compelling experience.

Again, the following screenshots illustrate the final film, which is attached to this thesis and upon publication, at: torrobinson.co.nz.

Figs. 3.55 - 3.65 (incl. previous page). "Screenshots from Final Fruit Film" *Author's Own Image*. Jul. 2017. Screenshot.



Conclusion

In the following chapter, I will discuss in detail the success of the two final films in comparison to each other. Overall I found the final result of this film successful. If I were to film it again, I would design certain aspects differently, and would be more aware of previously unknown issues when filming. Through editing, I have been able to iron out any mistakes that would detract from the overall goal of the video, and create a polished piece of work that communicates my research from the past year in a successful manner.

Figs. 3.64 & 3.65. "Screenshots from Final Fruit Film" *Author's Own Image.* Jul. 2017. Screenshot.

Fig. 3.66. "Final Fruit Print" *Author's Own Image*. Jun. 2017. Photograph.

DISCUSSION

Thematic Discussion

Earlier in this research, I state that the success of a special effect is the result of a number of themes: how it relates to the narrative demands of the film; the visual branding and how it contributes to believable worldbuilding; and the spectacular experience of seeing something impossible become real. I also comment on the degree to which some effects companies reveal the techniques and methods used for creating these special effects, and how this influences the believability and perception of the final film.

The claw film does not have a narrative, and is therefore more like a typical "product demonstration". The illusion of believability is broken by the fact that the claw only partially covers the hand, so it could not achieve all of the purposes a successful special effect typically has. However, the fact that it is only a "demonstration" is not a negative critique. It does this well, and the use of different material interactions forcibly communicates the potential this physical special effect could have in fantasy and horror films, due to the similarity of visual language and actions used throughout the film. These physical interactions indeed have a strong visceral spectacle to them. As well as confirming that the interactions we see are natural and believable, the ripping of fruit and dripping goo are fascinating and satisfying to watch from a sensory perspective.

As the demonstrative claw effect was unable to create a fully immersive sense of believable world building, the fantasy fruit had to completely demonstrate the narrative impact of a special effect. By presenting the fruit in the context of a pivotal moment in two characters' lives, I am able to use it as the key focus of the film, supplementing their conversation and motivations throughout the film. As I place the print in a minimal, futuristic environment, the fruit assists me in grounding the film in a believable world. I also rely on the audience's past experience with sci-fi films, which feature alien, fantasy worlds, using appropriate phrases of dialogue to confirm the world the characters live in. Encased in jelly, the fruit also has quite a visceral effect, but is less creepy and sinister than the claw, giving it more of an enjoyable overall feeling.

I made the conscious decision to refrain from breaking the fourth wall as much as possible, only explaining how the special effects were made in a supplementary "behind the scenes" video which also explains my thesis intentions. Without prior knowledge of how my two prototypes are made, I hope this enhances the spectacle of watching two physical but impossible special effects interact with actors and the environment.

To compare the worldbuilding effect of the two prototypes, I think that the J750 output methods cause these to vary slightly. Disregarding the fact that the claw does not cover the entire hand, the VRML claw print is able to create more textured and believable detail to elicit a stronger visual brand. The slightly more simplistic nature of STL Assembly printing means that it cannot contribute in the same way to a visual style, but the transparent, flexible materiality of the print compensates for this in a different manner.

Evaluating the Design Process for Filmmaking

While these effects may have potential for use in the film industry, the workflow needed to create such effects needs to be efficient, otherwise filmmakers will resort to the more flexible option of CGI. One of the most important aspects of CGI is that the design can be changed right through the filmmaking process until post-production. Meanwhile the design of physical objects have to be finalised in pre-production so they can be present for the shooting of the film.

After dissecting the workflow of J750 print creation myself, I believe that many different processes can be streamlined with code to reduce a lot of the manual labour associated with physical prop-making. Instead of comparing CGO production to CGI, the comparison of CGO production to traditional prop-making demonstrates how the production process can evolve. By implementing CGO in the film industry, the use of physical props and effects would have greater viability.

The separation of J750 methods into STL and VRML is still somewhat of an issue. For example, it would have been useful for the claw to have some inner softer parts so it could grip onto the fingers more effectively. Without these softer parts, the claw pieces slipped around quite a lot. If this print was being used on a film set for an entire day, I would suggest attaching it to the skin with latex or skin adhesive, which adds extra time for post-processing before use.

The fact that the support material does dissolve lessens post-processing time a great deal. There is still time needed for multiple soaking of the print if it contains complex layers and cavities, as my fruit did. This means that filmmakers will need to allow some time for this to occur, so a prop may not be able to be printed the night before a shoot. As filmmaking does require quick turn-arounds, some directors may find CGI more forgiving in this regard, depending on the effect required.

Finally, there are still some issues with colour unreliability for both STL and VRML methods. I do think that a designer needs to be able to be more confident about how the colour will appear when printed, especially when working for a director with specific needs. My green claw did appear much darker than the original design, which was remedied slightly with bright lighting but was still not that close to my original idea. Thankfully, this did not impact the overall effect of the film, although it did mean that I decided to push the spookier, darker vibe, rather than having something more light and magical.

Fig. 3.67. "Small Claw Detail." *Author's Own Image*. Jul. 2017. Photograph.

Similarly, the orange skin of my fruit was a lot duller than I would have liked, while the outer seeds were very dark in colour. This is partially due to my over-compensation of hue selection when working with GrabCAD and an RGB workspace, but production designers would probably need extensive swatches to ensure they are specifying the desired colours.

The issues discussed here can be solved with further research. For example, voxel printing has the potential to break down the barriers between the VRML and STL process, allowing designers to specify materials on a microscopic level. This will not be possible without the release of user-friendly software so that the use of voxel modelling is not restricted to those with high-level coding expertise at institutions like MIT and Harvard. It will be interesting to see what 3D printing companies like Stratasys will do to facilitate this, giving designers more freedom and making multi-material printing viable in a variety of industries.

Conclusion

Through the discussion of these 3D/4D printed prototypes in relation to the conceptual and practical needs of the film industry, I am able to demonstrate the potential multi-material printing has for revitalising the practical effects industry. This revolutionary printing method will make practical effects a more viable option for the creation of organic, physiologically based effects that will interact in a completely believable way with the real world.

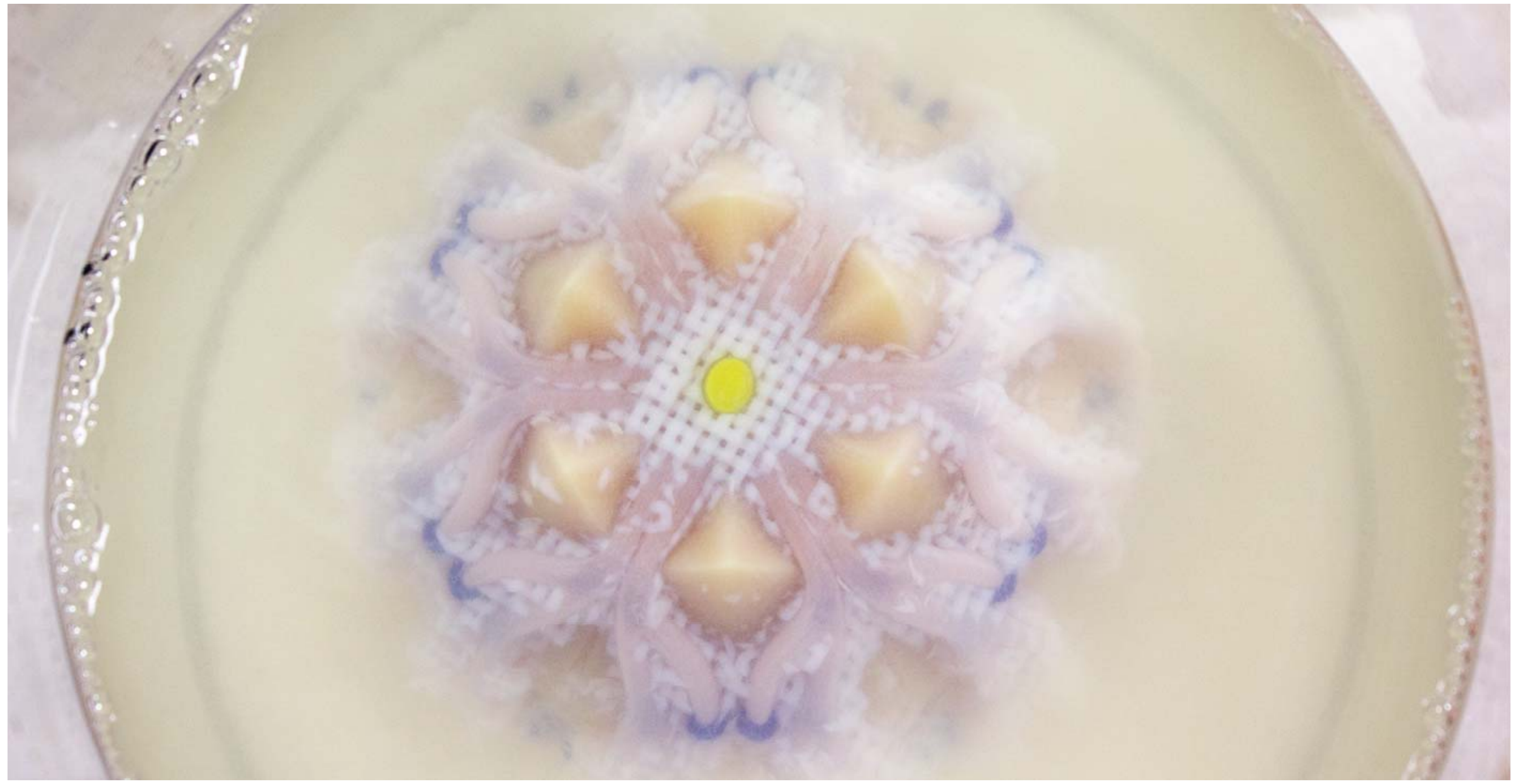


Fig. 3.68. "Soluble Support Cleaning." *Author's Own Image*. May. 2017. Photograph.

Fig. 3.69. "Large Claw with Grape" *Author's Own Image*. Jun. 2017. Photograph.

FINAL CONCLUSION

While the use of CGI is and will remain a dominant tool in the film industry, it is vital that filmmakers learn how to connect these digital illusions with the real world. This thesis proves that colour 4D printing has the ability to do this, creating digitally-produced sensory interactions with actors and the natural environment. Over the course of the year, the technology available for the use of the J750 has already improved exponentially, dismantling restrictions that have held back multi-material printing for years. With these improvements to technology and accessibility set to continue, filmmakers would benefit from the set of tools that the J750 offers to realise their visions.

Through systematic research methods, including qualitative analysis and research through design, I have rigorously investigated the Aims and Objectives outlined at the beginning of this thesis. In doing so, I have been able to make two strongly justified final designs, which clearly communicate my conclusions. These indicate the requirement for further research to implement an efficient workflow into the industry. This includes the investigation into the reliability of materials, and the complex possibilities of algorithmic colouring and form generation. Unfortunately, the field of voxel printing is still closed off to a select few, but the future creation and release of user-friendly software and code for voxel printing design will dismantle even more restrictions than before.

This thesis demonstrates the exciting future that the use of colour 4D printing presents for the film industry to create fantastical and highly detailed interactive digital effects on a potentially large scale. My two polished short films are examples of the possibilities that 4D printing presents, and, indicate the great scope that is now unfolding for more ambitious, industry-scale work .

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1: Script for Final Fruit Film "Okris Fruit"

Dialogue for final film may be altered slightly.

FRUIT VIDEO

A white room, with a single table and two chairs. A man sits on one of the chairs, nervously repositioning something on the table. Footsteps approach, and he is joined by a woman - his sister.

He sits up, and they rush to hug each other.

SISTER
Oh my god - I can't believe it's you - you're so tall -

BROTHER
(simultaneously)
I know, I know - how are you? How's mum?

In the foreground we see the thing on the table - a strange looking, alien fruit.

CUT TO the siblings sitting at the table. The BROTHER is motioning to the fruit on the table.

BROTHER
I never really got used to seeing a different star system, you know? Like the moon, you take it for granted - oh, peel it like this...
(pauses, peeling and eating a piece)
Good, huh?

SISTER
It kind of reminds me of apricots...

BROTHER
Huh, really? It kinda tastes a bit like a mix of strawberry and pear to me.
They grow in little clusters along the road out to the colony. You should see them in the starlight, they glow so brightly...

He pauses as they eat the fruit pieces.

BROTHER
You'd like it, you really would. There's loads of research to be done, you could help... you could bring Mum.

SISTER
I haven't seen my own brother in almost seven years... and now you want me to leave everything?

BROTHER
What's wrong about leaving 'this'? Just imagine, our family living on an entirely new planet, unstained by humanity -

SISTER
- I don't know -

BROTHER
Just think about it ok? Promise?

SISTER
I promise.

2: Submitted Supplementary Material

Three physical objects were created as the <u>final</u> prototype outputs of this research. As this thesis investigates the potential colour 3D/4D printing has for film, these prototypes were produced using the Stratasys J750. Images of the prototypes are displayed throughout this thesis.

- One small, green set of prints that fit onto the author's (Victoria Robinson) hand. These pieces assemble to create a claw on the forefinger and thumb.
- One large, red set of prints that fit onto the author's supervisor's (Ross Stevens) hand. These pieces also identically assemble.
- One 3D printed "fruit" (inedible). This was dismantled as part of the filming (final output) process.

Test objects were also created as part of the research into this thesis topic.

- Small coloured discs, which act as swatches for exploring the J750's potential for coloured detail.
- Two 3D printed fruits, early iterations of the final fruit listed above.
- Several iterations of the claws, printed in white.
- Note that other works, including a soft claw/glove, and a collection of student works, were analysed as part of this thesis but were not produced by the author. Therefore they are not considered part of the author's submitted output.

Three videos have been submitted as part of the <u>final</u> output of the thesis. Two are short films which express the intended purpose of my two final objects. The third is a "thesis" video, which briefly explains the intentions of the two final short films.

- *Keratos* is the short film of the final two claws.
- *Okris Fruit* is the short film of the final fruit.
- *Colour 3D/4D Printing* is the accompanying video to these two films, which illustrates the basic ideas behind this thesis to someone unfamiliar with the author's research.

Two supplementary videos have also been submitted, which are show the test filming done before the two final short films were made.

- *Test Fruit Film* is an exploration of one of the earlier fruit iterations.
- *Claw Test Shoot* is some initial video work done to test different filming methods available for filming the two final claw outputs.