

LOW-HANGING FRUIT

An Exploration of Procedural Modelling Tools to make Voxel Printing more Accessible

—

A ninety point research portfolio submitted to Victoria University of Wellington
in fulfillment of the requirements for the degree of Master of Design Innovation
in Industrial Design

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ABSTRACT

Recent advances in 3D printing technology have opened up voxel-based printing, which allows for control of the material of every sub-millimetre droplet that makes up the structure of a printed object. This full microstructure control opens up the ability to 3D print functionally graded materials. Typically, making dynamic objects involves using assemblies of discrete mono-material parts, each with distinct functions. Functionally graded materials instead allow for the creation of multi-functional single objects composed of complex heterogeneous material blends, gradually altering material properties to achieve their dynamic function. Current CAD and 3D-modelling tools and workflows are set up for the creation of assemblies of mono-material parts, where the designer only defines the outside shape of each part; this makes them inadequate for the full volume control needed to define every single droplet during voxel printing. While there has been some progress made in developing tools to address this problem, these tools currently require a high level of expertise to properly utilise. With this research, we seek to address this high barrier to entry by exploring intuitive digital workflows for making gradient material blends and utilising procedural modelling tools to create systems that allow designers to digitally tailor complex parts using simple parameter adjustments.



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CONTENTS

FM

FRONT MATTER

- Introduction 11
- Terminology 12

C1

METHODOLOGY

- Research Question 16
- Research Approach 17
- Aims and Objectives 18
- Methods 19
- Software Process 20
- Research Context 22

C2

BACKGROUND RESEARCH

- 3D, 4D & Voxel Printing 30
- Procedural Modelling Systems 35
- Soft Robotics 37
- Agriculture & Agritech in NZ 39
- Design Precedents 43
- J850 & Voxel Slicer 46

C3

DESIGN EXPERIMENTS

• Material Gradient Workflow	54
• MRI Manipulation Tool	70
• Voxel Printing Tests	87
• Procedural Soft Robot System	104

C4

DESIGN OUTPUT

• Material Gradient Workflow	116
• MRI Manipulation Tool	124
• Procedural Soft Robot	134

C5

DISCUSSION & CONCLUSION

• Discussion	140
• Conclusion	145
• List of Figures	146
• References	148



INTRODUCTION

Voxel printing represents a paradigm shift in the 3D printing space, unlocking unprecedented levels of material control. The entire microstructure of 3D printed objects is controllable, as the material of each sub-millimetre 3D printed voxel can be defined. This process requires that every single droplet of material is defined requiring millions to billions of points of data. Current 3D printing workflows are inadequate for this level of material control so new tools need to be built. This research explores how procedural modelling can be utilised to create intuitive tools and workflows that enable designers to take advantage of the complexities and capabilities of voxel printing, while keeping the process easy to use.

TERMINOLOGY

J850

PolyJet 3D printer capable of producing prints with full colour and blends of materials that vary in stiffness.

J850 Materials

VeroBlackPlus™

Rigid resin material coloured black.

VeroPureWhite™ or VeroUltraWhite™

Rigid resin material coloured white.

VeroClear™

Rigid resin material that is transparent.

VeroCyan-V™

Rigid resin material coloured cyan.

VeroMagenta-V™

Rigid resin material coloured magenta.

VeroYellow-V™

Rigid resin material coloured yellow.

Agilus30Clear™

Rubber like material, soft and flexible.

SUP706™

Removable support material.

3D Printing

3MF

3D Manufacturing Format, a type of 3D file used for colour printing that has geometry, colour and texture data.

Point Cloud

A set of data containing points in 3D space, for this study point clouds have uniform density so the points are evenly spaced.

Voxel Printing

A 3D printing process in which pixels of digital images represent printed voxels, each pixel is used to assign material properties such as colour or stiffness. Layers of PNG images are produced to produce a 3D matrix for voxel printing.

Mono-material

An object made of just one material.

Multi-material

An object made up of several materials.

Voxel PNG image stack

A stack of images for voxel printing. Each image represents a single layer for 3D printing, its pixel colours being used to assign material.

STL

Standard Tessellation Language, a 3D format commonly used for 3D printing. It only describes the outside shape of a 3D object represented as tessellated triangles.

OBJ

A common 3D file type, often used to transfer 3D geometry between different 3D software.

CAD

Computer Aided Design.

.bgeo

A standard Houdini file for saving and transferring geometry.

.gcvf

GrabCad Voxel File, generated from a voxel PNG image stack used for sending voxel print files to the J850 printer.

3D

Three dimensional.

4D

4 Dimensional, the fourth dimension here is considered to be time.

MRI

Magnetic Resonance Imaging, used to collect and display 3D volumetric images of inside the body. Produces a volumetric medical dataset.

Procedural Modelling

Techniques for producing 3D geometry using a set of rules and input parameters. These parameters can be changed to produce many different results. Sometimes referred to as Parametric Modelling.

Parameter

A variable factor used to define particular measurements in a system. Here it is used purely for procedural modelling systems and controls the shape and size of output 3D geometry.

Houdini

Procedural modelling software used to create 3D geometry and digital imagery, primarily used in the visual effects industry.

GrabCad Print

Software used to interface with the J850 3D printer.



Figure 2. Section of a voxel print slice.

CHAPTER 1

METHODOLOGY

RESEARCH QUESTION

How might we leverage
procedural tools and workflows
in order to make harnessing
the capabilities of voxel printing
more accessible?

RESEARCH APPROACH

This research utilises both Research for Design and Research through Design methodologies.

The first stage of this research employed a Research for Design methodology, here past and present research relevant to this study were explored and critically analysed. This process examines current knowledge in the research literature and real world contexts that act as a foundation for research and design experimentation. Through the examination of this knowledge base, the research question and initial experiment criteria are defined, providing direction for design research (Frankel & Racine, 2010; Frayling, 1993; Giaccardi & Stappers, 2017).

Exploring how to create intuitive workflows requires a practice-based research approach so the second stage of this research utilises a Research through Design methodology (Milton & Rodgers, 2013). This research approach acknowledges design practice as a way of generating knowledge (Frayling, 1993; Giaccardi & Stappers, 2017; Zimmerman et al., 2010), usually involving a practical iterative approach to exploration utilising an action-reflection method (Frankel & Racine, 2010; Zimmerman et al., 2010). This methodology is guided by a specific research question, using qualitative methods such as experimental prototyping, observation and critical reflection to form an iterative design process. Here each design experiment is analysed and this analysis is used to develop subsequent experiments as a means to answer the research question (Schneider, 2007).

This thesis combines Research through Design with a Criteria-Based approach (Rodriguez Ramirez, 2017). This approach involves developing a set of criteria to guide the experimentation process and discuss how successful each experiment is. The knowledge gained from each design experiment is then used to develop and change the criteria, so that both experiments and criteria evolve throughout the process. The final criteria are used to guide the final design outcomes from experimentation, and are used to assess how well this outcome addresses the research question (Rodriguez Ramirez, 2017).

AIMS AND OBJECTIVES

AIMS	OBJECTIVES	METHODS
1. Background Research: To investigate opportunities for procedural modelling systems to create easy to use workflows to access current 4D printing and voxel printing technological capabilities.	1a. Conduct background research investigating 4D printing, voxel printing and procedural modelling systems.	Literature and precedent review (Hanington & Martin, 2012).
	1b. Conduct background research into soft robotics, agriculture and agritech in NZ to provide real world context to research experiments.	Literature and precedent review (Hanington & Martin, 2012).
2. Design Experimentation and Application: To explore how procedural systems can be used to set up easy to use tools and workflows for producing complex voxel files.	2a. Explore workflows for creating volumetric gradients of materials.	Research through Design using a criteria-based approach (Rodriguez Ramirez, 2017).
	2b. Explore workflows for creating a tool to sample and cut volumetric medical datasets	Research through Design using a criteria-based approach (Rodriguez Ramirez, 2017).
	2c. Explore procedural systems to create soft robotic grippers for fruit picking.	Research through Design using a criteria-based approach (Rodriguez Ramirez, 2017).
	2d. Evaluate the final outcomes of design experiments to achieve their respective goals.	Testing each workflow produces desired result, is flexible and easy to use. Evaluating the final results against the overall aim of the research.

Figure 3. Aims and Objectives.

AIM 1 METHODS

A literature review was used to gain an understanding on past and present research (Hanington & Martin, 2012) into the current knowledge and capabilities of 4D printing, voxel printing and procedural modelling. Here soft robotics, 3D printed soft robotics, agriculture in NZ and agritech were also explored to provide a real world context for procedural systems.

An analysis of design precedents is also conducted during this phase, analysing how others have utilised 4D printing and voxel printing.

AIM 2 METHODS

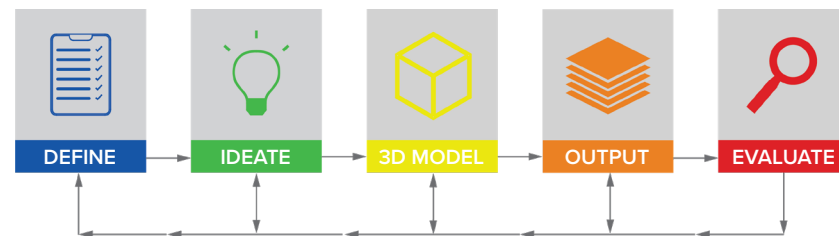


Figure 4. Iterative design process.

DEFINE

The aims of the research and knowledge gained from previous experiments define design criteria for each design experiment (Rodriguez Ramirez, 2017). These criteria define the aims of each experiment.

IDEATE

The ideation phase involves generating new procedural workflows based on experimentation with different tools and techniques.

3D MODEL

During this stage the idea is translated into a digital workflow and applied to a simple 3D form for testing. Here Houdini is used to create a procedural workflow and the digital tools used are adjusted and optimised to give the best result, outputting a 3D volume.

OUTPUT

The resulting 3D volume is given to the Voxel Slicer resulting in a stack of PNG image slices.

EVALUATE

This stage of the process is a stage of critical reflection, measuring each experiment against design criteria. The successful and unsuccessful aspects of the experiment are reflected upon, this new knowledge is used to develop the research incrementally making adjustments to design criteria and subsequent experiments until a resolved criteria is reached (Rodriguez Ramirez, 2017; Zimmerman et al., 2010).

Throughout this process new knowledge is gained that alters a designer's perspective of their research problem, hence throughout the iterations knowledge is built in a step-wise manner. An important consideration is that different stages of this process can be revisited when required, based on new knowledge gained (Milton & Rodgers, 2013).

SOFTWARE PROCESS

Houdini:

Houdini is visual effects software known for its procedural node-based workflow and its ability to make sophisticated particle and dynamic simulations (SideFX, 2022). Houdini is the chosen software used throughout this study, here are the key considerations as to why:

- The Voxel Slicer tool made for use in our research group is made in Houdini, so any other tools made can directly interface with it.
- Houdini's focus on simulation means that it is very efficient at dealing with the large amounts of data needed for voxel printing workflows.
- Houdini's focus on simulating smoke and fire means it has a robust set of tools for volumes, which are key to producing voxel files.
- Houdini's procedural modelling tools are very robust, meaning you can achieve complex procedural systems out of very few node processes.
- Houdini is made for flexible procedural systems, allowing for the creation of tools with a lot of flexibility.
- Houdini is excellent for its ability to use geometry made in other software, meaning that geometries made from other CAD tools that designers are more comfortable with can be used within the procedural voxel tools.

GrabCad Print:

GrabCad Print is the software released by Stratasys allowing users to load 3D files and apply material properties for 3D printing with their printers. This software has a Voxel Print Utility which is used to format the PNG image stack into a .gcvf file for 3D printing. Note that .gcvf files when imported to grabcad are displayed as low-poly grey approximations of the boundaries of the voxel print file, so you don't get an accurate display of the printed object.

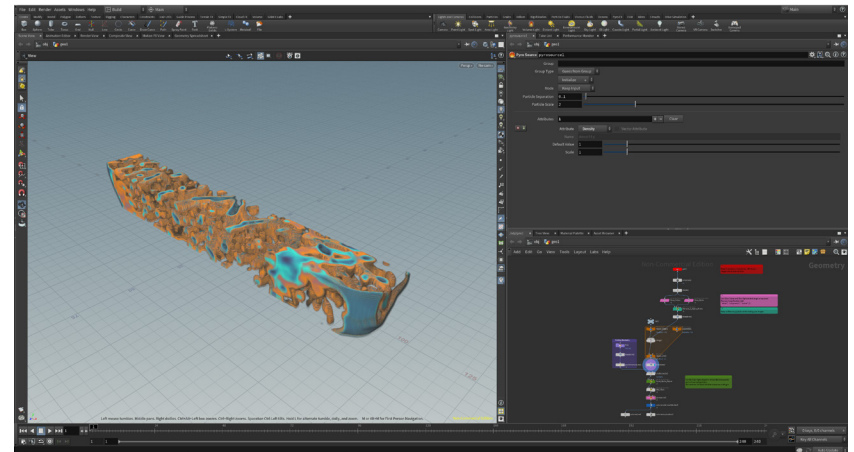


Figure 5. Houdini screenshot.

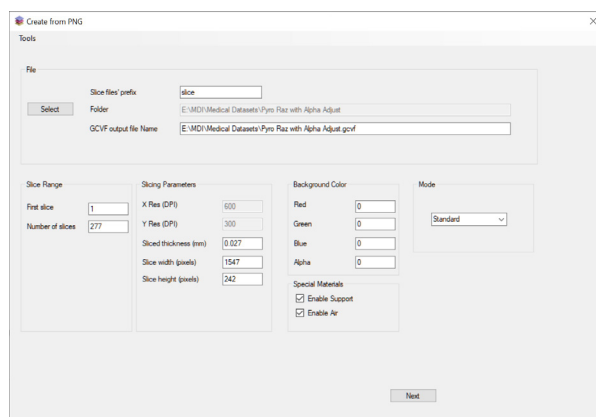


Figure 6a. Voxel Print Utility screenshot showing voxel slice settings.

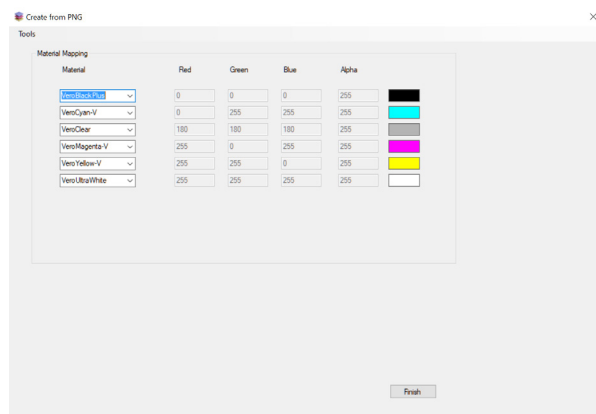


Figure 6b. Voxel Print Utility screenshot showing voxel material selection.

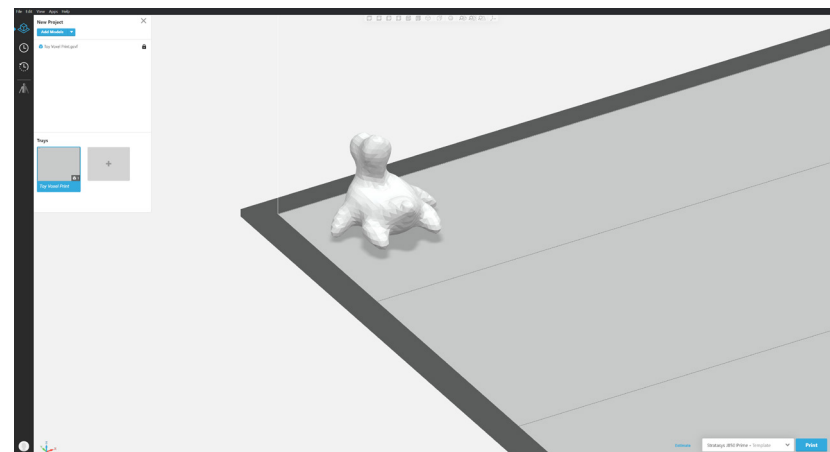


Figure 7. GrabCad Print screenshot showing how gcvf files are displayed.

RESEARCH CONTEXT

The initial focus of this research was building up towards physical voxel printed objects being the final output, however throughout this research this focus changed to exploring tools and workflows. It became apparent that focussing on producing intuitive workflows had more value as a research output as they can lower the barrier to entry for designers wanting to utilise the capabilities of the printer, allowing many more ideas to be explored. This section will highlight the experiences throughout this research that drove this change of focus, as a way to justify why we feel this has more value as a research output.

At the end of 2020 a new workflow was released that links Keyshot, 3D rendering software commonly used by students in our Industrial Design program, and Grabcad Print, the software used to send print files to the J850 3D printer. This workflow utilises a 3D file format called 3MF, which contains geometry, colour and texture data. Keyshot was given the functionality to export these 3MF files which can be imported into Grabcad Print for full colour printing (Grabcad, 2020). What this means is that designers 3D print their render file, retaining all the colour and texture they have assigned while rendering with basically no effort, quickly going from digital visualisation to physical object (see figure 8). The key benefit of this 3MF format is that it taps into designers already established workflows, lowering the barrier to entry and amount of time and effort required to produce complex colour 3D prints. Early in 2021 I suggested this workflow should be shown to students doing colour 3D printing projects, and made a series of tutorials teaching it to second, third and fourth year Industrial Design students.

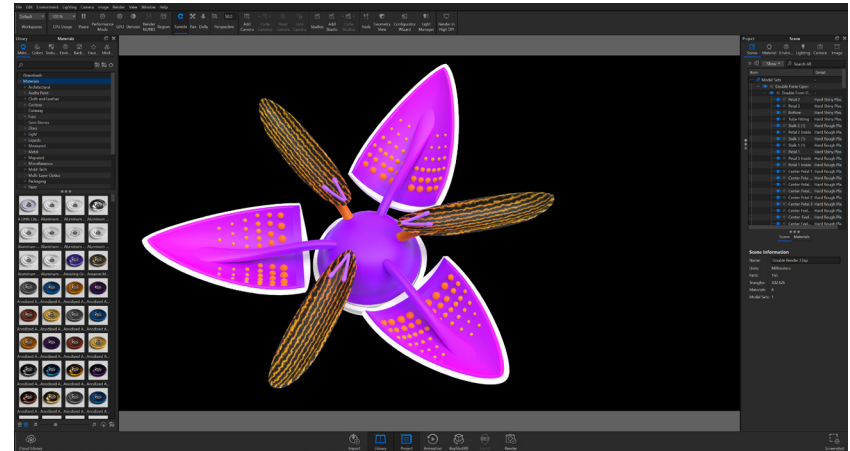


Figure 8a. Keyshot render screenshot.

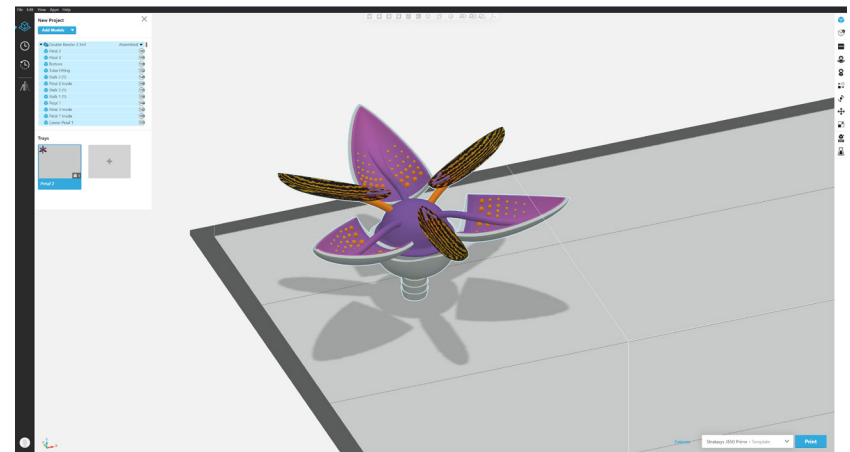


Figure 8b. 3MF file from Keyshot render in GrabCad print.

Work from INDN 332

INDN 332 is a third year Industrial Design paper in which students conduct a speculative project exploring how they can leverage future technologies to create objects that contain ideas, stories or experiences that they want to pass on to future generations.

Charlotte Frogley

Charlotte Frogley designed a necklace that contained photos of family Christmas trips from her childhood. Each of the photos is contained within a soundwave of the songs they used to listen to on a cassette tape in the car on these family Christmas trips. Future generations interact with it by placing the different images on a hologram projector, getting a projection of the image and playing the associated song. So this object is used as a way to share experiences and memories that meant a lot to her growing up, that can be passed on to future generations well past the end of her life. Charlotte has leveraged the 3MF workflow well here, using family photos as colour maps she was able to utilise a very quick and user friendly workflow to produce a 3D print that contains a lot of data on family memory and does a lot of visual story telling. (See figure 9).



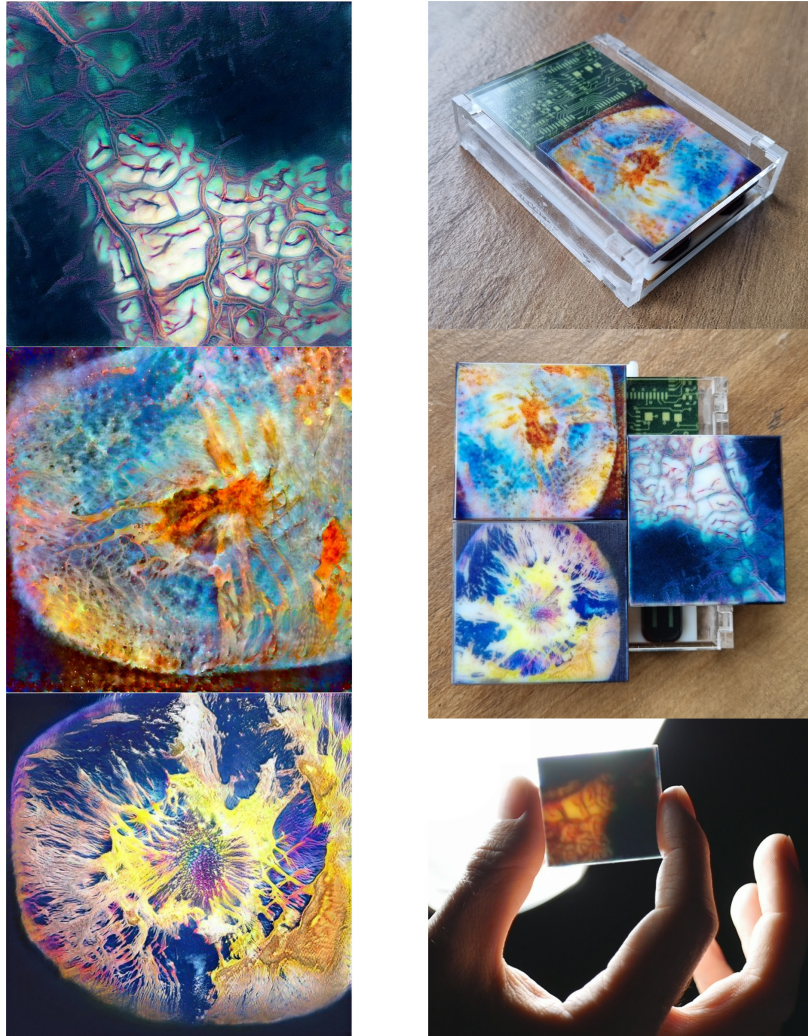
Figure 9a. Frogley, C. (2021). *Cassette Necklace - close-up shot* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.



Figure 9b. Frogley, C. (2021). *Cassette Necklace - in context shot* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.

Matthew Michelson

Matthew Michelson explored the future of data storage strategies, speculating that we will eventually rely on the DNA of organic materials to store data. He claimed that the data density of DNA will greatly expand the amount of data we are able to store in a small device as opposed to modern hard drives and SSDs, and can be made stable for a long time. To explore this idea Matthew used AI image generation, specifically StyleGAN2 trained to generate images based on microscope images. These images were then used as colour maps in Keyshot allowing him to print his AI generated images as 3D objects. The AI image generator he used was online and requires no coding or prior knowledge as to how the StyleGAN2 networks operate, it is simply trained by giving it a dataset of images. So Matthew has combined two very user friendly workflows that gave him access to complex procedures to produce really interesting, colour rich objects. (See figure 10).



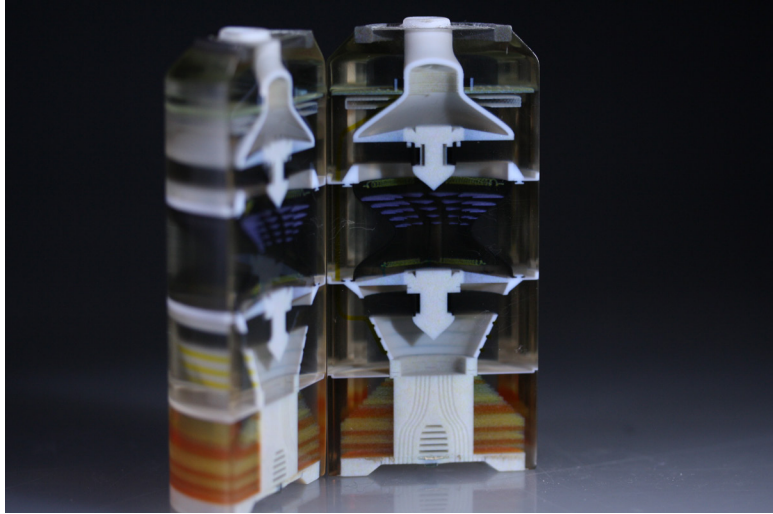
(Left) Figure 10a. Michelson, M. (2021). *Data of the Future - AI generated DNA images* [AI generated digital images]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. (Right) Figure 10a. Michelson, M. (2021). *Data of the Future - 3D printed DNA data storage* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.

Eliot Lundon Moore

Eliot Lundon Moore explored how we might pass on our experiences of Earth to future people on a generation ship, travelling to other galaxies in order to establish humans as a multi-planet species. He tapped into the idea of how evocative smell is to memory, and speculated that many of the smells of Earth won't be available to those who spend their entire life on a generation ship. So he explored a personal smell device, which can be loaded with cartridges containing the favourite smells from Earth of ancestors of those on the ship, so they too can experience them. Eliot spent a lot of time modelling a rendering a massive assembly of components that make up his speculated smell device. The 3MF printing workflow allowed him to take all that work and translate it directly into a complex full colour 3D print. (See figure 11)



Figure 11a. Lundon Moore, E. (2021). *Woofer - exploded render* [3D render]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.



(Top) Figure 11b. Landon Moore, E. (2021). *Woofers* - cross section [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.

(Bottom) Figure 11c. Landon Moore, E. (2021). *Woofers* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington.

Andrew Roberts MDI Thesis

Andrew was one of the fourth year students I taught the 3MF workflow to early in 2021, he has since utilised it as a key step in the work he has done for his MDI thesis. In his MDI Andrew has looked at how AI and colour printing can be used for creature concept generation for the film industry. This process begins with using CLIP, a neural network trained on a large variety of images and text pairs (Radford et al., 2021), this can be prompted with text to generate new images (for example Octopus Dog will make the network generate images that blend features of both animals). Andrew uses this to generate a series of images that he uses as inspiration for a new creature design. Then he moves to ZBrush digital sculpting software, to sculpt and colour the creature design based on the images generated by the AI. Once the sculpt is complete, the geometry and colour map are exported and taken into Keyshot, where the creature design is rendered and a 3MF print file is made. The printed creature can then be filmed, giving filmmakers an idea of what the creature would look like on camera. In this process AI image generation is being leveraged here to help expand the imagination of the creature concept artist. The 3MF workflow removes hurdles from the process, allowing them to rapidly transition from digital rendered concept to physical output. (See figure 12).



Figure 12a. Roberts, A. (2022). *Creature made with 3MF colour 3D printing* [Multi-material 3D print]. Work created for MDI Thesis: *Uncanny Bastards* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].



Figure 12b. Roberts, A. (2022). Creature made with 3MF colour 3D printing [Multi-material 3D print]. Work created for MDI Thesis: *Uncanny Bastards* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

MRI Manipulation Tool for Izzy Robb

Another MDI student Izzy Robb was interested in exploring voxel printing valuable objects by embedding them with medical data. She asked for my help in creating a tool that would allow her to sample and manipulate MRI data 3-dimensionally, outputting the result as a PNG image stack for voxel printing. Over a number of months this tool was developed and has allowed Izzy to create a series of voxel printed objects using this tool that allows for complex 3D manipulation. This process tapped into their already established MRI to voxel print process and only required fairly simple user inputs (this will be covered more in depth in chapters 3,4 &5 of this study).

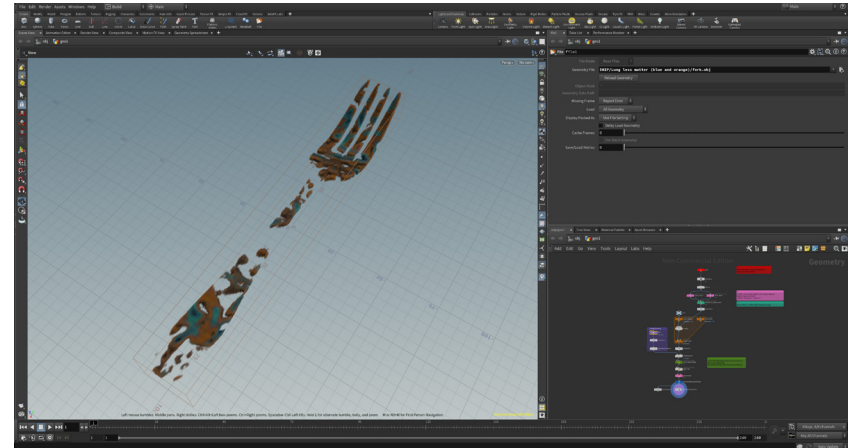


Figure 13a. Robb, I. (2022). Process cutting fork from medical data volume [Screenshot]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].



Figure 13b. Robb, I. (2022). 3D printed forks cut from medical datasets [Multi-material 3D print]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

Relevance to this Study

Watching students utilise the 3MF workflow and the development of the MRI Manipulation tool gave some valuable insights. User friendly tools that tap into pre-existing design workflows really remove hurdles from the creative process, and have allowed students to much better make use of the potential of the J850 3D printer. There is real value in focussing this research to try to do the same, like 3MF printing has eased the process for STL based colour printing, these tools and workflows will try to find intuitive workflows for voxel printing. By providing these tools and workflows, hopefully future researchers can avoid some of the difficulties faced by me and other early adopter voxel print researchers.

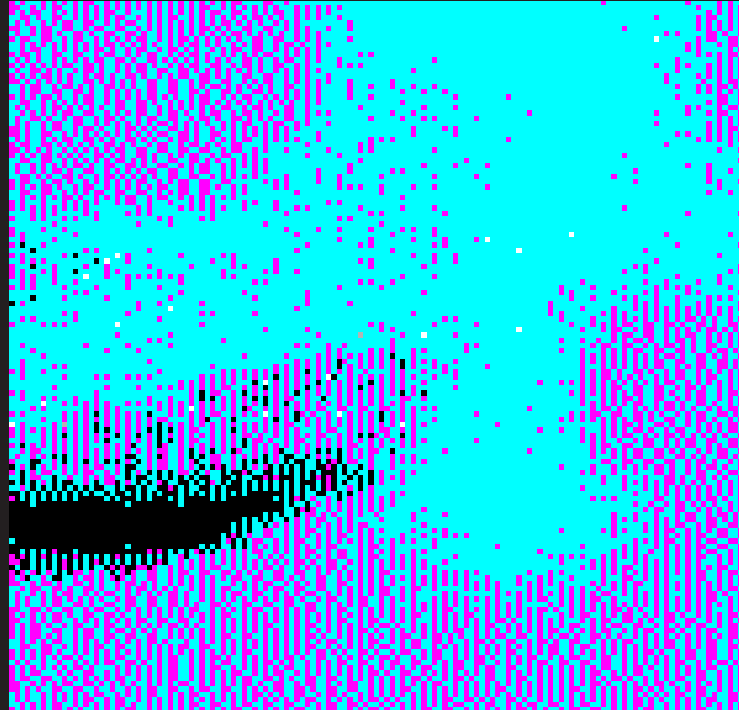


Figure 14. Section of a voxel print slice.

CHAPTER 2

BACKGROUND RESEARCH

3D, 4D AND VOXEL PRINTING

Multi-material 3D Printing

3D design software and 3D printing technology have unlocked the ability to deposit multiple materials simultaneously in a single print, this is known as multi-material 3D printing. This has opened up new opportunities to design and print objects with much more complexity and functionality by utilising multiple materials with different properties. While there are a variety of 3D printing methods that allow for multi-material printing, this research focuses on PolyJet technology (Stratasys, 2020). The PolyJet 3D printing process involves spraying droplets of liquid photopolymer in layers, the layer of droplets is then gently compressed with a roller and adjacent droplets are pressed into one another to form a solid photopolymer layer which is then cured by ultraviolet light. Many of these layers are printed sequentially to form a stack that makes up the final print. This layer-by-layer process enables the construction of high-resolution 3D objects (Prince, 2014; Rogers, 2017; Stute et al., 2018). Recent advances in this technology allow for the simultaneous deposition of up to 8 materials at once (Statasys, 2022). Materials include a rigid resin-like material called Vero™, this is available in black, white, cyan, yellow, and magenta. Also available is a rubber-like flexible polymer called Agilus™, and a jelly-like support material that can be printed to fill any gaps or overhangs and is broken away post-print. Finally, we can now print with encapsulated air gaps and a cleanser liquid support material. All of these materials can be printed simultaneously and blended to create composite materials, these are known as digital materials and allow designers to digitally tailor material properties such as flexibility, density and colour. Multiple digital materials can be combined in a single print, with this precise control over placement and tailoring of material properties designers can create objects with dynamic functionality.

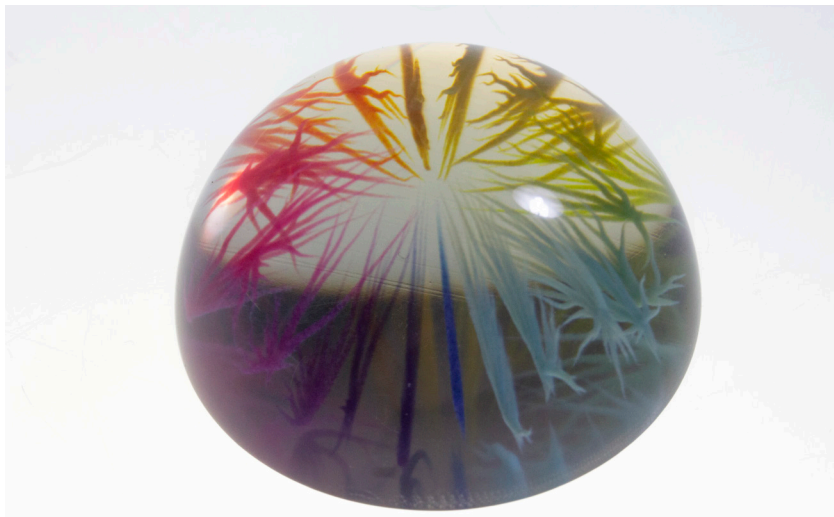


Figure 15. Full colour PolyJet print.

4D Printing

4D printing refers to 3D printed objects that have dynamic properties as a result of the relationships between their form and materiality. The fourth dimension here is time, so 4D printed objects are characterised by their ability to transform over time (Momeni et al., 2017; Pei, 2014; Tibbits, 2014; Tibbits et al., 2014). When 4D printing the designer is acting both as sculptor and choreographer, designing not only an objects shape, but how the shape and materials interact with one another to give the printed object its dynamic properties that allow for this transformation, thus digitally defining its movement. Multi-material 3D printing with its precision and ability to deposit and mix digital materials allows for the creation of complex composite parts, opening up new opportunities for designers to create structures with intricate dynamic functions that would be difficult to create by any other means of fabrication (Rafiee et al., 2020; Tibbits et al., 2014). Much of the research into 4D printing looks at the use of smart materials that change their shape in response to stimuli such as heat or moisture, but as Pei points out 4D printing should also refer to objects that achieve their dynamic function through multi-material printed structures (2014).

4D Printing Research

4D printing research can be grouped by transformation through smart materials, through fluidic actuation or through direct physical interaction.

4D Printing with Smart Materials

One example of 4D printing with smart materials looked at biomimetic 4D printing. Researchers used hydrogels with cellulose fibrils that aligned with the printing pathway. Utilising the structure of the extruded material they could control the alignment of these fibrils to restrict and predictably control the swelling and shape change of their printed objects when exposed to water. The researchers were able to print a structure mimicking the organic twisting movement of an orchid (Sydney Gladman et al., 2016).

Another example looks at the use of micro-printing of shape memory polymers. These are materials that can be reshaped or programmed post-printing and will return to their original form in response to heat. In one of their examples they printed a multi-material micro-gripper with arms that would bend to close and grab an object when heated. This gripper also had tips made of a printed rubber-like material to ensure safe contact with the gripped object (Ge et al., 2016).

One final example is the bioLogic project utilises *Bacillus Subtilis* Natto a microorganism found in dry rice stalks that expands when exposed to heat and moisture. Researchers utilised this organism in a printing process to create natural actuators, creating garments with flexible flaps that open up in response to body heat and sweat. These actuated flaps act as vents allowing the sweat to evaporate and the body to cool (Tangible Media Group, 2015; Yao et al., 2015).

4D Printing with Fluidic Actuation

Another branch of 4D printing research looks at utilising material flexibility and actuating the transformation using hydraulics or pneumatics. One example comes from the MIT's Self-Assembly Lab they utilised a 3D printing method called Rapid Liquid Prototyping in which a silicone material is extruded into a gel which suspends and supports the material as it cures. This printing method gives relative geometric freedom and allowed the researchers to print flexible enclosed structures that can be pneumatically inflated to transform their shape. Their recent study utilised this method to create a soft-robotic gripper that they found was much more effective than using the same silicone in a casting production method (Self-Assembly Lab, 2018; Sparrman et al., 2021).

In another example researchers developed a new printing system called multi-material multi-nozzle 3D which uses high pressure valves to allow rapid and seamless switching between 8 different materials. These materials are viscous inks that can be printed 3-dimensionally and post cured using heat. They printed a pneumatically actuated soft robotic walker composed of a rigid and soft elastomer that has alternating rows of feet, each with their own pneumatic channel. To actuate this robot researchers could sequentially apply a vacuum to each alternating channel sequentially compressing the feet and create a walking movement (Skylar-Scott et al., 2019).

This content is unavailable. Please consult figure list for further details

Figure 16. Hone, N. (2018). *Feather nurse -a pneumatically activated 4D print* [Multi-material 3D print] In *Tangible Animation—Designing Organic Performance with Multi-Material 3D/4D Printing* [Victorial University of Wellington]. <http://researcharchive.vuw.ac.nz/handle/10063/8063>. Copyright 2022 Nicole Hone.

4D Printing with Physical Interaction

A third area of 4D printing research looks at the printed objects transformation from direct physical interaction. One area of this is looking at the use of PolyJet printing for anatomical models. Utilising patient's MRI or CT data surgeons are able to use soft printable materials to rapidly produce patient specific anatomical models that can be interacted with and operated on. This gives surgeons the opportunity to plan and practice surgeries on an accurate representation of the patient's organs. The major advantages are the speed at which these can be produced is important for emergency cases and the ability of the 3D printer's materials to recreate human anatomical elements give surgeons the advantage of experiencing and feeling the surgery before they have to perform it (Boissonneault, 2019; Lo, 2019).

Footwear design is another area seeing human interaction 4D printing. Nervous System collaborated with New Balance to explore 4D printed midsoles for running shoes. They created a proprietary system that used foot pressure data from runners to generate midsoles with variable density cushioning that is customised to how a person runs, the generated forms were then printed using a rubber-like material (Nervous System, 2015). Other recent examples of 4D printed footwear include 4D Running shoes from Adidas and Flyprint by Nike (Adidas, 2022; Nike, 2018).

Voxel Printing

Voxel-based 3D printing is the latest innovation in 3D printing offering unprecedented control over material deposition. Voxel here refers to a volumetric pixel, each one of these voxels in a digital file represents a single droplet of liquid polymer from the printer. This kind of printing grants voxel-level control meaning that the material of every single droplet can be defined, giving users full volumetric control over the material properties of every resolvable point in a printed object (Bader et al., 2016, 2018; Stute et al., 2018). Each voxel, subsequently each printed droplet of material, has a size of 0.0423mm by 0.0846 with a layer height of either 0.027mm or 0.014mm (Grabcad, 2020), at this scale it means that voxel printing gives you full microstructure control of printed objects. Full microstructure control moves beyond the digital materials paradigm, where you could only create material variance using an assembly of separate bodies, assigning each body a singular material with its own material properties. Instead voxel printing unlocks the ability to distribute materials heterogeneously throughout the entire volume, meaning that properties such as colour, translucency, stiffness and density can vary continuously throughout an entire print by controlling the structure and concentration of voxels of the base materials (Bader et al., 2016; Kolb, 2017). Users are no longer bound to assemblies of mono-material parts, opening up new opportunities to print high-fidelity, data-rich and incredibly variable composite materials difficult to produce using any other means of fabrication.

Limitations of Current 3D Printing Workflow

Current 3D printing workflows utilise traditional CAD or 3D modelling tools where users design parts by only defining the external shape of the geometry, these models are then exported in an STL format which is a simple mesh that only represents the boundaries of defined geometry. The 3D printer then puts material within these boundaries. These workflows rely on the idea that each part is made of a single material with known properties, and dynamic function is derived from using assemblies of these mono-material parts (Bader et al., 2018; Doubrovski et al., 2015). The simplicity in the CAD to STL process means its ill equipped for voxel printing in that it lacks the sophistication to produce the large amounts of data needed for voxel printing (over 10 million voxels per cubic centimetre), so cannot exploit the heterogeneous material opportunities through the entire volume of the print (Stute et al., 2018). So in order to exploit voxel-level control a new workflow is required that allows users to define the material of every single voxel in a 3D print.

Voxel Printing Process

Voxel printing requires that every single droplet in a 3D print be defined, to get this information to the printer stacks of PNG images are used, with one image for each layer. The resolution of these images matches the 3D printer's droplet resolution, so each 2D pixel represents a 3D voxel. The colour of that pixel dictates what material is placed by the printer, with particular colours corresponding to the base materials in the printer. The entire stack combine into a voxel matrix defining the material for every single droplet in a

3D print (Bader et al., 2016, 2018). In order to get this stack of PNG images a 3-dimensional volume must be created that has colour data throughout its entire extent. A flat sampler plane moves through this volume picking up the colour data where it intersects. The colour data of the volume where that plane intersects gets turned into a PNG image. As it moves throughout the volume this sampler plane gathers the data for every layer needed for a voxel print, producing a stack of images, one for every layer. Once the data is gathered a custom dithering algorithm is used to convert the RGB colour data into only the colours that correspond to the base materials for the printer (Robinson & Furneaux, 2019).

Voxel Printing Research

Currently three groups have done significant research into voxel printing strategies: MIT Mediated Matter Group, Weta Workshop and researchers from Fraunhofer IGD and NTNU who developed the software Cuttlefish.

MIT Mediated Matter Group

MIT's Mediated Matter Group have a few pieces of research looking at how to utilise the heterogeneous material placement through voxel printing. One piece of work looked at how voxel printing enables the physical visualisation of scientific data, bridging the gap between digital information commonly seen on a screen and its physical manifestation. Key to this work is that by using heterogeneous colour distribution throughout a volume and the complexity available through voxel printing they can physicalize data without any loss of information. They argue that these physical manifestations of data can leverage spatial perception skills to enable a more comprehensive understanding of the data, through tangible interaction viewers get an intuitive understanding. Screen based visualisations and augmented reality lack this tangible interaction (Bader et al., 2018).

Another study looked at how patient data from MRI or CT scans can be utilised with voxel printing to create physical models of individual patient anatomy. The volumetric data captured by MRI or CT scans translate to the volumetric 3D prints voxel printing allows for, using this method they are able to drastically improve the speed and accuracy of the printed anatomy as compared with their old method involving segmenting the data into STL files. Using this technique they were able to produce physical renderings of patient data using either heterogeneous distribution of colour or stiffness, opening the ability to produce biomechanically accurate models. These physical manifestations of patient data allow physicians, scientists and patients unprecedented level of interaction with medical data and can be leveraged for pre-surgical planning, medical communication or education (Hosny et al., 2018).

A final study looked at using voxel printing for variation of material stiffness in a custom prosthetic socket. The researchers explored how the voxel-level control of materials could be used to locally vary material stiffness aiming to reduce pressure on the residual limb. The material distribution was based on the tissue properties of the residual limb, and they were able to produce gradients of material distribution that gradually changed

their stiffness to meet their function. This gradual change in material distribution would be impossible to achieve in other 3D printing approaches. Finally, they were able to print channels in which they could insert optical fibre in order to sense the deformation of the socket as it was worn, testing that their multi-material distribution was in fact fit for purpose (Doubrovski et al., 2015).

Weta Workshop

Weta Workshop looked at how voxel printing could be used to create prosthetic eyes for use in film and exhibition. They identified that their traditional method utilising multi-stage casting and painting methods was labour intensive, had a high failure rate and was limited by the constraints of the materials. Voxel printing allowed them to replicate the complexity and translucency of a real eyeball, they achieved this by utilising the dimensionality and ability to blend opaque and translucent materials unlocked by voxel level control of material deposition. The accuracy and consistency of the printer made this process much more reliable, knowing that giving the same digital file would consistently produce the same result. They utilised a digital procedural workflow that allowed them a high level of control over the features of the eye, allowing for their eyes to be quickly changed in response to art direction, and reliably seeing those changes reflected in the printed output. Finally, the system also allows them to make a series of eyes for different characters simply by altering the parameter inputs. Their art directable approach allows them to be character driven, artistically achieving anatomical realism (Robinson & Furneaux, 2019).

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Figure 17. Robinson, T. & Furneaux, W. (2019). A series of 3D printed prosthetic eyes at varying scales and colours [Multi-material 3D print] In Voxel Printing using Procedural Art-Directable Technologies. *Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2022 Weta Workshop.

Cuttlefish

Cuttlefish software was developed to spatially vary colour and translucency in voxel printing. Their approach enhances realism in colour 3D prints by giving control over the perceived translucency of materials, allowing users to match the colour depth and spatially-varying translucency of real world materials, replicating the way light permeates those materials. Their software allows users to work with traditional 3D workflows, utilising 3D geometry and flat RGB colour maps (these maps have no thickness and are usually just applied to the outside of geometry) these colour maps are used as the input colour of the printed model and transformed from 2D into volumetric colour. The user then takes control of spatial translucency, able to create constant or translucency gradients, allowing them to replicate the way light moves through real world materials to control the perceived colour depth. Cuttlefish is intended to be used for aesthetic or visualisation/educational purposes with its ability to reveal complex internal structures (Brunton et al., 2018). This software was used by LAIKA studios in their stop-motion film the missing link, printing 106,000 full colour character face plates used to animate their characters speech and expressions (Koslow, 2019).

One of the key new 3D printing capabilities unlocked by voxel-level control is the ability to create variable material blends, allowing designers to control the stiffness of these blended materials at every point of a 3D print for much more sophisticated control to create dynamic function. This research explores strategies to create these material blends and how they could be used.

Functionally Graded 3D Printing

Functionally graded materials are those that are characterised by a gradual transitions in their material composition and structure, resulting in corresponding changes in material properties in order to perform their required function (Oxman, 2011; Pei et al., 2017; Zhang et al., 2019). In nature the performance of organisms within their environment doesn't come from the properties of their base materials, but from the ingenious way in which those base materials are structured to form organic composites (Liu et al., 2017; Oxman, 2011). Functionally graded materials are commonly found throughout nature as a way to efficiently to structure organic materials, unlocking their multi-functional properties through locally varying material structures that gradually transition. This local variation allows for the distribution of site-specific material properties, allowing a single organic composite material to perform a variety of functions (Li et al., 2020; Liu et al., 2017; Oxman, 2011). Inspired by these material gradients found in nature, functionally graded 3D printing looks at how we can utilise multi-material 3D printing to dynamically mix and vary materials within a 3D volume to create functionally graded materials. Allocating and gradually varying material structure throughout 3D space to achieve variable multi-functional performance from a single part (Ituarte et al., 2019; Loh et al., 2018; Pei et al., 2017). Voxel printing allows for full microstructure control of a variety of material properties, opening up new possibilities to create functionally graded 3D printed objects that would be very difficult to

produce with other methods of production.

This approach to tailor material microstructure to performance is a shift from a shape-centric view of 3D printing to a material-centric one (Oxman, 2011). Traditional forms of manufacture consider dynamic objects in terms of assemblies of mono-material parts with discrete functions, such as the way a car is made by assembling thousands of separately produced parts. Each part is made by defining only its outside shape made from a single material with a known property. Functionally graded 3D printing moves away from assemblies of parts and instead considers dynamic objects in terms of their material microstructures, heterogeneously distributing materials across a single object to achieve its dynamic function. This is more analogous to the way the human skin operates as a single object with that varies its structure to achieve multiple functions, thicker around the back and organs where it acts as protection, thinner around the face and joints and structured to stretch (Oxman, 2015).

Functionally graded 3D printing offers some key benefits. First, it allows for the optimisation of material distribution for both better functional performance and material efficiency (Oxman, 2011). Second, it allows for more morphologically complex parts that can have site specific properties tailored to small sections, allowing for more controlled and sophisticated dynamic properties (Ituarte et al., 2019; Loh et al., 2018; Pei et al., 2017). Third, the gradual change in material structure eliminates sharp interfaces where two dissimilar materials meet, that would usually lead to weak interfacial bonds and/or stress concentrations leading to mechanical failure (Li et al., 2020; Loh et al., 2018; Pei et al., 2017). Finally, the printed object can have the optimum properties of its constituent materials, allowing for example, the use of sections of soft material dispersed throughout a rigid material keeping its rigidity and offering impact resistance using the soft sections as impact force dampeners (Liu et al., 2017; Loh et al., 2018; Pei et al., 2017).

CAD and 3D modelling are set up for just defining outside shape of 3D parts, assuming that each part will be made of a singular material, thus they are inadequate for defining the material structure of an object (Oxman, 2011; Pei et al., 2017). While there has been some work looking at creating digital tools for the creation of gradient materials (Altenhofen et al., 2018; Patel & Kiatkulpiboone, 2020; Richards et al., 2017; Stevenson, 2018), there are still no publically available tools or agreed upon standard workflows.

Relevance to this study

Voxel printing has drastically expanded control of material deposition during 3D printing, opening up full microstructure control of printed objects. With this full microstructure control it is now possible to 3D print gradients of materials that are more sophisticated, capable of complex function and resilient than 3D prints made from assemblies of mono-material parts. This research explores how intuitive digital workflows and procedural modelling tools might help designers to design objects using these functionally graded materials for 4D printing.

PROCEDURAL MODELLING SYSTEMS

Procedural Modelling can be defined as a generative system where uses a set of input parameters or rules can be used to produce a wide variety of models. These input parameters form the characteristics of a 3D model and by manipulating these a designer is able to digitally generate a diverse set of variations (Smelik et al., 2014). One of the advantages of procedural systems is data compression, where rather than a storing all of the data for a complex set of 3D models, a procedural model can be represented by a compact set of parameters, only generating the actual geometry when it is needed. Another advantage is the non-permanent nature of the data streams in these systems, in that parameters can be repeatedly altered upstream or downstream to produce new results. Finally, procedural modelling systems have the potential to drastically reduce the amount of modelling effort needed to create a set of diverse 3D models (Smelik et al., 2014). Procedural modelling variability removes the necessity for the top-down influence of designers. Instead of manually modelling forms from predetermined ideas, procedural systems allow computers to act as co-authors, designer and computer each having a hand in the design of objects (Stevens, 2015). The use of procedural modelling systems are explored here for creative physical and digital outputs.

Cillia

Researchers from the Tangible Media Group at MIT developed Cillia, a procedural system for 3D printing hair-like structures on both curved and flat surfaces. Their system utilises height, thickness and angle parameters to control the geometry of the hair. It then uses density and location parameters to control an array that generated large patches of the hair structures on the given surface. These parameters are controlled through a graphical user interface utilising simple sliders, automatically generating structures with thousands of individual strands of hair. The resulting individual hair shape and hair array structure are visualised. The authors point to limitations in the current conventional top-down CAD pipeline using 3D geometry, making it computationally difficult to create thousands of tiny hairs. They instead propose a bottom-up 3D printing approach, where their procedural system directly produces bitmap printing layers without having to use a 3D model. The resulting printed hair arrays were then used for brushes, adhesion, actuation and sensing (Ou et al., 2016).

The Style Machine

Ben Jack and Bernard Guy collaborated to create the Style Machine, which uses generative design software as part of a wider design system. The four nodes of this system being the designer, the generative artist, the software and a 3D printer. The whole system worked as a feedback loop where the generated artefacts informed the generative artist of the designer's style and intent, helping guide the development of the software. The software produced is controlled by a simple set of sliders and curve tools, allowing the designer to play with parameters to generate new forms. This kind of system enables a new way of thinking about design, rather than a prescriptive top-down way of designing forms, instead this human-software co-design relationship allows the designer to explore and discover forms. The software is seen as a tool that streamlines and removes resistance from the designer's creative process, allowing them to rapidly iterate and explore, finding new designs that would not otherwise be possible (Jack & Guy, 2017).

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Figure 18. Jack, B. D. & Guy, B. (2017). *The style machine software interface* [Screenshot] In *The Style Machine: Digital Tactility Through Generative Collaboration*. 20th Generative Art Conference GA2017, 12. Copyright 2022 Bernard Guy.

Far Cry 5 Procedural World Generation

Etienne Carrier a technical artist at Ubisoft Montreal was part of a team that created procedural systems for generating environmental assets for the game Far Cry 5. The challenge they faced was how to create environmental assets that remain coherent with the terrain topology, while that terrain constantly changed over a multi-year development cycle. At the same time, they needed to keep level design consistent when managed by several different developers. A multi-layered set of Houdini-based procedural systems were produced that filled the world with natural looking environmental content. These systems used environment distribution systems to generate based on topology of the map and user inputs. The technical artists produced a set of simple controllable spline and brush based tools that quickly allow developers to indicate where they want environmental assets such as rivers, fences, roads or vegetation. A simple set of shelf tools are then activated and procedurally generate these assets based on where the developers have painted them. These shelf tools could be activated at any time in the process, regenerating these assets based on changes to the terrain or other points of interest being added to the map. These procedural systems were all linked so that when the assets interfered with one another, developers could reset using the shelf tools, and the system would detect these interferences and regenerate the assets to fix the issue. This procedural workflow utilised user friendly tools to streamline the developers creative process, making it easier for them to rapidly iterate and respond to changes in level and gameplay design. Further, the system could automatically respond to daily changes in terrain topology, keeping environmental assets natural looking and consistent (Carrier, 2018).

Voxel Printing using Procedural Art-Directable Technologies

Weta Workshop explored the use of procedural systems to digitally generate and voxel print large-scale prosthetics eyes. In order to generate the large amount of data needed to control every sub-millimetre droplet of material during voxel printing, they turned to the visual effects software Houdini. They identify the advantages of using Houdini are its capacity to process and handle the large amounts of data needed for voxel printing; second, the ability to sample and utilise geometry from other software; and third, its procedural node-based workflow, which allows them to create a reusable system with changeable parameters. This procedural workflow allows for the systematic creation of a vast amount of variations for different characters at various scales, simply by changing the parameter inputs. Utilising a procedural workflow was key in creating an art-directable system giving them complete control over the output. They used parameters to control things like the iris and sclera colour, limbus transparency and vein weight allowing them to easily make changes to the eye's appearance according to specific art direction. Combining their art-directable system with voxel printing also offered advantages. The high fidelity nature of voxel printing allows it to very accurately produce what the digital procedural system outputs, meaning the physical model aligns with the specific art direction given during

the digital stage. Compared with their labour intensive traditional casting method, which had a high failure rate, the accuracy and repeatability of the procedural system to voxel printing workflow allows them to quickly digitally alter and print files knowing what the final physical outcome will be (Robinson & Furneaux, 2019).

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Figure 19. Robinson,T. & Furneaux, W. (2019). **a)** The digital model is sampled by a slicing grid. **b)** Slice 650 of 992 images generated for a 2:1 eyeball. **c)** Visualisation of the voxels in a small section of the iris. [Multi-material 3D print] In Voxel Printing using Procedural Art-Directable Technologies. *Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2022 Weta Workshop.

Relevance to this study

Procedural modelling can be used to streamline workflows for generating 3D models, offering user friendly tools and simple parameter controls to quickly produce complex designs. The user friendly nature of these systems means they can open the door to users designing sophisticated models without needing the expertise to do so. A vast amount of variation is unlocked by these systems utilising parameters that can be adjusted endlessly. Procedural modelling also allows for rapid iteration, where users can test their designs and quickly make parameter adjustments to fit their needs. This research explores how procedural modelling workflows can be used to simplify the workflow for creating gradient materials, making this intuitive for designers. A procedural system for making soft robots is used as a demonstration of how these gradient materials might be used.

SOFT ROBOTICS

Traditional robots tend to be built from rigid links and mechanical joints, specifically programmed to repeatedly perform a single task efficiently. Soft robotics is a class of robotics that instead relies upon the use of compliant bodies made from soft materials, utilising stiff materials sparingly like we often see in nature. This soft material is shaped to deform in predictable ways in response to a given input. The continuously deformable compliant bodies utilise actuation that is distributed across the entire structure, resulting in much higher degrees of freedom than their rigid-bodied counterparts that only bend at the joints (Gerboni, 2018; Ilievski et al., 2011; Rus & Tolley, 2015). Designs for soft robotic actuators are often biologically inspired, frequently taking cues from incredible capabilities for complex movement, grasping and object manipulation of muscular hydrostats such as elephant trunks, cephalopod tentacles and the tongues of lizards and mammals. A muscular hydrostat is a biological actuator predominantly comprised of muscle, with no need for a rigid skeletal structure. Soft robotic designs often seek to mimic the structure or behaviours of these hydrostats (Ilievski et al., 2011, 2011; Ranzani et al., 2015; Schaffner et al., 2018; Shepherd et al., 2011). While some soft robotic designs are actuated using materials such as shape memory polymers, that react to changes in temperature, or electroactive materials, that contract in response to electrical voltage, frequently soft robots are actuated by changes in fluidic pressure (Hubbard et al., 2021; Rus & Tolley, 2015; Shintake et al., 2018). With fluidic actuation, internal chambers in the soft material is inflated either pneumatically (with air), or hydraulically (with liquid), causing the desired deformation in the soft robot body. Air and liquid driven actuation is used frequently in soft robotics because of its ability to get complex motion from a simple control input without the need of many active components (Ilievski et al., 2011; Rus & Tolley, 2015; Schaffner et al., 2018; Shintake et al., 2018).

Soft robots have some key advantages over their rigid-bodied counterparts. The first advantage is their compliance, the soft materials they are made from give them the ability to deform giving them an inherent adaptability. This means soft robots are well suited to interact with irregular environments or objects with shape variation, without needing any programming. Their compliant bodies simply deform to adapt to the situation as a result of the interaction. This compliant adaptability makes them ideally suited for applications such as produce picking and packing, where fruits and vegetables vary in shape and size. Rigid-bodied robots need a complex assembly of parts and programming to achieve their function and generally have very limited adaptability, where a soft robot is highly adaptable using only a singular soft body and simple pneumatic input (Ilievski et al., 2011; Ranzani et al., 2015; Rus & Tolley, 2015). Soft robots second advantage is their safety. It's common practice to separate human and robotic workspaces to mitigate potential for injury. Rigid-bodied robots often operate at high speed, so hit with a lot of force and risk injury. In contrast soft robots made from compliant materials will deform and absorb much of the energy during a collision. Further, their ability to conform and move means they are ideally suited to interactions with the human body or delicate objects, such as fresh produce, since they don't impart sharp forces that could lead to damage or injury (Hubbard et al., 2021; Ranzani et al., 2015; Rus & Tolley, 2015). The final advantage is that soft robots tend to require minimal assembly. Rigid-bodied robots typically consist of a large number of

links, joints, motors and electrical components, all requiring complex configuration and programming for them to move as desired. On the other hand, soft robotic actuators, typically made through a casting or 3D printing process, are functional as soon as the material is cured or printed and connected to the actuation system. Soft robots can achieve complex movement and adaptable interaction with very few of these compliant actuators and a simple actuation input such a pneumatic line (Hubbard et al., 2021; Rus & Tolley, 2015; Zhou et al., 2017).

A considerable amount of soft robotic research has focussed on utilising soft robots for gripping applications. Soft robotic grippers can adapt to object shape variation, without having to change the control inputs, considerably reducing system complexity and cost, while improving gripping performance (Ilievski et al., 2011; Shintake et al., 2018; Zhou et al., 2017). As previously mentioned, these properties make soft robotics ideal for tasks like fresh produce picking and packing, where adaptability to shape variety and risk of damage are key concerns. This research explores digital strategies to utilise complex multi-material 3D printing, which could better serve as to make soft robotics for these applications.

3D Printed Soft Robotics

3D printing technologies have become an increasingly prominent method for the fabrication of soft robots. Researchers have identified that 3D printing strategies offer greater design freedom than casting processes, in that they are capable of producing much more complex internal and external geometries that are easily designed and iterated through 3D modelling software. Utilising 3D printing allows for the fabrication of functional soft robotic geometries that would be impossible to reproduce with a casting process, printed in a single step and ready for end-use (Gul et al., 2018; Sachyani Keneth et al., 2021; Yap et al., 2020). Multi-material 3D printing has further extend the freedom of form, enabling a greater ability to create soft robots with complex functionality. The ability to deposit multiple materials in a single 3D printing process allows for the design of architectures that utilise a multitude of material elasticity and stiffness to obtain much more controlled and complex actuation. Seamless multi-material printing also removes the need for a multi-step casting process or assembly, while reducing the risk of interfacial delamination of the different materials, thus removing weak points for more resilient soft robots (Sachyani Keneth et al., 2021; Schaffner et al., 2018).

Schaffner et al. were inspired by fibrous architecture of muscular hydrostats and utilised a multi-material printing of silicone inks to create soft robotic actuators with tuneable deformation. They utilised a central soft silicone cylinder, which had stiffer silicone stripes printed around its exterior. These stripes restricted expansion when the actuator was inflates, and they could control the actuation movement by changing the angle of these restrictive stripes. This technique allows them to program movement into the material architecture (Schaffner et al., 2018). In another example researchers used PolyJet printing to produce fully integrated complex fluidic circuits, allowing them to control multiple

actuators from a single fluidic input line. They used a combination of soft and stiff materials for both their fluidic gates and actuators, making a three fingered hand in which a single line could actuate all three fingers independently, simply by altering the air pressure from the line (Hubbard et al., 2021).

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Figure 20. Coulson, P. (2020). Soft robotic *pneumatic finger capable of three-dimensional motion* [Multi-material 3D print] Well, Actuate(ly)...: Parametric Multi-Material 3D Printed Soft Robotics [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14072330.v1>. Copyright 2022 Patrick Coulson.

Finally, there are examples of functionally graded 3D printed soft robots. In the first example researchers utilised a PolyJet printer to produce a jumping soft robot powered by combustion. Their robot consisted of a rigid top hemisphere, and a soft bottom hemisphere, that utilised a stepwise gradient from fully rigid to fully hard material. The material gradient successfully reduced the stress concentrations between rigid and soft components on ignition, and helped to reduce impact force upon landing. This meant the robot was more robust and capable of better energetic locomotion. The researchers claimed that a completely smooth material gradient would have been preferable, but their transition utilising 9 bodies of decreasing material stiffness was effective (Bartlett et al., 2015). A final example saw researchers utilising PolyJet printing to create a functionally graded end effector made of sharp tooth-like elements for puncturing. Their end effector consisted of 6 of these tooth-like objects arranged radially that can puncture an object

placed in the middle. The teeth were functionally graded, transitioning from rigid at the top, to a flexible base. This gradient again was stepwise, consisting of multiple bodies of increasing softness. The researchers found the functionally graded structures offered significant advantages, effectively puncturing at low actuation pressure while minimising structural damage by reducing global and local strain at the interface between tooth and baseplate. Making a more resilient soft robot capable to apply highly concentrated force (Kumar et al., 2017). Both of these studies utilised a series of bodies with ever-increasing softness, their capabilities could be expanded by utilising voxel printing to produce full material gradients.

Relevance to this study

Multi-material 3D printing has expanded the functional capabilities of soft robotics. Voxel printing, with its full material microstructure control, can drastically expand the sophisticated material architectures we are capable of printing. Microstructure control unlocks fully controllable functional gradients, allowing for more operationally complex and resilient soft robots. This research explores how we might utilise digital workflows and procedural modelling to create functionally graded soft robots.

AGRICULTURE AND AGRITECH IN NZ

New Zealand Agriculture and COVID-19

New Zealand's agricultural or 'food and fibre' sector is comprised of the dairy, meat & wool, forestry, horticulture, seafood, arable and processed food industries. This sector represents a significant segment of the New Zealand economy making up around 82% of merchandise exports, 11% of gross domestic product (GDP) and 14% of employment, so the food and fibre sector is key to keeping the economy thriving, and for New Zealand's post-COVID recovery (Ministry for Primary Industries, 2021b).

When COVID-19 made its way across the world, it had immediate impact on global public health and the worldwide economy. Over the 2020 – 2021 period, the pandemic and multiple national and global lockdowns in response have posed significant and unprecedented challenges for New Zealand's food and fibre sector (Ministry for Primary Industries, 2020b, 2021a, 2021b). Two of the major challenges here have been labour supply and freight issues. Labour supply issues came from much of the sector's reliance on migrant labour for both specialised and unspecialised agricultural jobs (Ministry for Primary Industries, 2021b; Snow et al., 2021). The border closures as part of the government's response to COVID made it difficult for this migrant workforce to get into the country, leading to labour shortages. This has disrupted many businesses and caused workforce uncertainty across the primary sector. Air freight issues have arisen due to the massive reduction in passenger planes coming into and leaving New Zealand. Around 80% of air freight was taken in the holds of passenger planes, needing to replace these with dedicated air freight services has seen cost increases of 150-400% (Ministry for Primary Industries, 2020b). Sea freight has become disrupted, with reductions in services, delays, a less reliable service and difficulty sourcing shipping containers. With all of this comes a sharp rise in shipping cost, container cost rising 365% between November 2020 and November 2021 (Ministry for Primary Industries, 2021b). This not only affects our exports but also imports of key agricultural inputs such as agrochemicals, animal feed and spare machinery parts (Snow et al., 2021).

Despite these challenges our food and fibre sector has remained resilient (Snow et al., 2021). Primary industry exports rose 3.6% in the year ending June 2020 to reach \$48 billion, while this dropped slightly to \$47.7 billion in 2021, it is projected to grow 6% in 2022 to reach \$50.8 billion (Ministry for Primary Industries, 2020b, 2021a, 2021b). A few major factors that helped with this persistent strength in food and fibre exports. First, continued (and growing) strong demand for a lot of New Zealand's agricultural products overseas (Ministry for Primary Industries, 2020b, 2021a, 2021b). Second, communication between government and industry leaders which lead to government policy intervention and financial aid to help deal with labour and freight issues (Ministry for Primary Industries, 2020b, 2021a, 2021b; Snow et al., 2021). Finally, the willingness of those in the agricultural community to rapidly adapt to the new conditions (Snow et al., 2021).

Focussing in on horticulture, which represents a significant portion of New Zealand's food and fibre sector, its export revenue grew 6% in 2020 bringing it up to \$6.5 billion (Ministry for Primary Industries, 2020b), while it remained the same in 2021 it is projected to grow 5% to reach \$6.9 billion in 2022 (Ministry for Primary Industries, 2021b). So horticulture has continued its success and export growth over the difficult 2020-2021 period. Kiwifruit made up 55% of fruit and vegetable export earnings in 2020, growing 10% to bring in \$2.5 billion (Ministry for Primary Industries, 2020b). In 2021 kiwifruit exports increased 6% to \$2.7 billion, making it a total of 57% of total fruit and vegetable earnings (Ministry for Primary Industries, 2021b), the demand for kiwifruit remaining high across multiple overseas markets is attributed to growing consumer demand for healthy New Zealand products with strong environmental credentials (Ministry for Primary Industries, 2020b). Kiwifruit play an important role in New Zealand's export economy.

Regardless of the success of the food and fibre sector over the last 2 years, the people that make up our agricultural industries have continued to have to contend with challenges due to the COVID-19 related disruptions (Ministry for Primary Industries, 2020b, 2021a, 2021b). The cost and challenges of meeting demand are increasing, growers and exporters have, and will continue to need to, adjust their operations around the difficulties that come from seasonal supply labour shortages, logistical constraints and the rising costs of shipping, labour and production (Anthony, 2021; Ministry for Primary Industries, 2021b; Snow et al., 2021). For growers and industry leaders the difficult 2020-2021 period, and the further challenges ahead, have brought a renewed focus on human welfare. The mental wellbeing of growers and workers is being considered one of the key problems, and many have identified the need to provide mental health networks, social services and communication pathways to help people to deal with the pressures of current and future challenges (Anthony, 2021; Kelly, 2021; Snow et al., 2021). Along with this, growers have shown a general interest in pushing technology and automation in their industries to reduce the reliance on labour, this is not only seen to help relieve some of the pressures of labour challenges and rising costs (Snow et al., 2021), but also has the value of reducing time needed to be spent in the field. So we should expect to see accelerated investment in labour saving technologies and automation (Ministry for Primary Industries, 2021a).

Agritech

The world population is projected to reach 9.8 billion in the year 2050 (United Nations, 2017), in order to meet the nutritional needs of a rapidly growing population, food production and agricultural productivity will need to increase drastically. This is coupled with environmental challenges due to climate change and reduction of arable land due to increased urbanisation. Current farming methods are becoming increasingly unsustainable long-term, both in meeting future demand and through its environmental impact and soil biodiversity degradation (Benke & Tomkins, 2017; Ministry of Business Innovation & Employment, 2020; Spanaki et al., 2022). Agritech looks at how innovation through the use of smart technology can help the agricultural industry make the necessary changes to become more sustainable and productive (Ministry of Business Innovation & Employment, 2020; Spanaki et al., 2022).

The agriculture sector is seeing a data-driven revolution through agritech. Disruptive technologies such as mass multi-source data gathering, internet of things (IoT) connectivity, artificial intelligence (AI) and robotics are opening up new forms of precision farming that are allowing growers to produce more with less land, significantly lower resource use, more sustainably. Computer vision uses neural networks to process and understand the context of images, and is used for crop inspection purposes, allowing for early disease detection and optimal crop conditions (Mahmud et al., 2020; Spanaki et al., 2022). The use of sensors embedded throughout allow for real time collection of data of plant health and ground conditions, offering precise information on crop environment, nutrition and water needs. This data helps growers to be more efficient with water and agrochemical usage, such as fertilisers, reducing resource use and land degradation (Jha et al., 2019; Mahmud et al., 2020; Spanaki et al., 2022). Further, by using selective spraying systems, growers can utilise this sensory data to much more accurately apply agrochemicals such as pesticides and fertilisers only where and when they are needed, drastically reducing their use and negative effects on the soil (Jha et al., 2019; Mahmud et al., 2020). AI such as deep learning networks can utilise all of this collected data to provide recommendations, warnings and for efficiency monitoring to improve farming operations, finding optimal growing conditions to increase yield and reduce land degradation (Jha et al., 2019; Spanaki et al., 2022). IoT connectivity can give growers access to all of this data in real time, helping them to map fields, monitor crops, find anomalies and control agricultural systems remotely. Drastically reducing time spent manually inspecting and caring for crops (Jha et al., 2019; Mahmud et al., 2020; Spanaki et al., 2022). Further, data collection and digital technology can connect growers to business partners and end customers. This connection enabling a shared value creation. First, crops are traceable so customers are reassured on the sustainability of growing practices, as this becomes increasingly important in the market. Second, growers get access to consumer desires and needs, helping them make growing decisions based on demand, leading to less food waste (Rialti et al., 2022). So we see a technology enabled agricultural sector will help to aid growers in more precise, productive, resilient, responsive and sustainable agricultural practices.

Growing the agritech industry in New Zealand has become an area of significant interest for the government and across the food and fibre sector. In 2020 the Ministry of Business, Innovation & Employment released an Agritech Industry Transformation Plan outlining a series of actions for government, industry and research institutions to accelerate growth in New Zealand's Agritech sector (2020). Growth in this sector is seen as key to meet sustainability goals and contribute to solving global food demand issues, they also identify the opportunity for New Zealand to think globally, exporting agritech innovation to international markets. This plan outlines this shared vision for industry and government: "A globally competitive agritech ecosystem, producing ingenious value-adding companies that provide meaningful jobs, solving New Zealand and the world's sustainability problems" (Ministry of Business Innovation & Employment, 2020).

The Ministry for Primary Industries have also released their Fit for a Better World roadmap outlining ways to achieve the ambition for New Zealand's food and fibre sector to become more productive, sustainable and inclusive. This plan identifies science and innovation as one of key pillars to achieve this ambition (Ministry for Primary Industries, 2020a). Further, they have put together the Sustainable Food and Fibre Futures fund to support innovation in the food and fibre sector through investment (Ministry for Primary Industries, 2022). Finally, in 2018 Agritech New Zealand formed bringing together industry parties and companies, their role is to connect innovators, investors, regulators and researchers to grow innovation in New Zealand's primary sector (Agritech New Zealand, 2021). They provide a good industry-lead counterpoint to government activity in agritech.

In New Zealand the agritech industry took in a revenue of \$1.4 billion per year in 2019, 2020 and 2021 and globally agritech start-ups have seen a massive growth of investment from \$322 million in 2010 to \$30.5 billion in 2020 (Ministry for Primary Industries, 2021a; Technology Investment Network, 2020, 2021). So not only is agritech seen as important for solving climate change and food security problems, there is also strong global economic interest in growing the sector.

Harvesting Robotics

One of the key areas of interest for the Agritech sector, and one area of exploration of this study, is harvesting automation through robotics. Many high value crops, like kiwifruit, tomatoes and apples ripen heterogeneously so require selective harvesting of only the ripe fruits, this kind of harvesting also requires that fruits and plants remain undamaged. Both requirements have made selective harvesting difficult to automate, and have therefore relied on manual human labour, making it one of the most time-consuming, labour-intensive and expensive tasks for growers (Kootstra et al., 2021; Mahmud et al., 2020; Oliveira et al., 2021). Due to the labour-intensive nature, the need to compensate for labour shortages, and increases in demand to feed a growing population, there is a strong interest for development in automated robotic harvesting (Mahmud et al., 2020). Aside from labour saving, some advantages of robotic harvesting compared to human labour are greater consistency in the quality of operation in repetitive harvesting tasks, the ability to work night and day during tight harvest periods and the ability collect data to accurately monitor crop development during harvest, helping to improve and optimise crop management (Kootstra et al., 2021). Robotics and automation are seen as the two most vital innovative technologies for New Zealand's horticulture sector (Ministry for Primary Industries, 2021a), this is reflected in the development of a horticultural robotics institute being one of the key projects in New Zealand's agritech industry transformation plan (Ministry of Business Innovation & Employment, 2020).

To execute an autonomous selective harvesting process, several steps are required. First, the robot must identify and locate the fruit to be harvested, most harvesting robots that have been implemented utilise a computer vision system. These vision systems use cameras, such as and RGB-D camera (that captures image colour and depth data) or a binocular system (using two cameras to gather image colour and depth) to gather visual and depth information. The captured images are given to a deep learning neural network that has been trained to identify the ripeness of fruit and which are ready to be harvested (Jha et al., 2019; Kootstra et al., 2021; Mahmud et al., 2020; Oliveira et al., 2021). Second, the robot must undergo motion planning to get the harvesting end-effector to the fruits location without colliding with or damaging other fruit or the plant (Mahmud et al., 2020; Oliveira et al., 2021). Finally, the end-effector needs to grasp the fruit, detach it from the plant and place it into storage, all without damaging the harvested object (Mahmud et al., 2020). This study focuses on the final step, the end-effector.

As already mentioned the major challenge of the design of an end-effector is that it can effectively grasp and manipulate delicate objects with care, avoiding exerting excessive force and damaging the harvested fruit and surrounding plants (Mahmud et al., 2020). Another concern is object variation, since fruit is natural every instance will vary somewhat in size and shape, this lack of consistency presents a real challenge for traditional robotics that tends to work with consistent objects in controlled environments. Finally, there are safety concerns about these robots interacting with humans in the harvest environment (Kootstra et al., 2021). Rigid grippers are poorly equipped to deal with fruit variability

and softness, while keeping up with demand for short cycle times in harvesting. Instead compliant end-effectors that have shape morphing properties of soft materials make them better equipped to deal with the variation and fragility of fruit, and will absorb impact force when making contact with humans (Kootstra et al., 2021; Rad et al., 2020). So the compliant mechanisms of soft robotics have real potential to address these end-effector challenges.

One example of a robotic harvesting system is a kiwifruit harvester developed through a collaboration between the University of Auckland, University of Waikato and Robotics Plus. This system utilises a stereo camera system and computer vision to identify fruit to be harvested, then determines a harvest order to best pick the kiwifruit with minimise the risk of damaging adjacent fruit. Next, the system determines arm movement paths, placing the end effectors into position. Finally, the end effector grips the kiwifruit and rotates it to remove it from the vine, dropping it down a chute into storage (Williams et al., 2019). The end effector is made up of a claw style gripper made up of two 3D printed digits surrounded by moulded silicon. These silicon sections contain air pockets that allow them to conform around the shape of the kiwifruit both increasing contact area for more grip and reducing the peak pressure applied to reduce the chance of damage. A four bar linkage is used to create both the clasping motion of the gripper and the rotation to remove the kiwifruit from the vine. There are no wrist-like mechanics to orientate the end-effector relative to the robotic arm (i.e. rotating the gripper via a wrist joint), so the robot is limited to only the positional adjustments the arm produces and cannot rotate the gripper to avoid obstacles (Williams et al., 2019).

Root AI have produced another robotic harvesting system called Virgo. This system is made to work in greenhouses to identify and harvest ripe tomatoes. It uses a set of cameras and infrared laser to generate a 3d colour scan of the environment, their AI system uses this to assess tomatoes ripeness and position. Next, the system determines the least obstructive path to get to the fruit, placing the end effector into position. Finally, the gripper grabs the tomato, spinning to twist it from the vine and drops it into a storage bin (Kolodny & Black, 2019; Root AI, n.d.; Vegetable Growers News, 2021). The end effector uses three flexible plastic fingers around a central axis, with rubber tips for grip. Its gripper is actuated using a piston activated restriction ring that bends the fingers together to grip the fruit. The whole end-effector assembly attaches to the arm allowing it to rotate just in one axis, this limits its ability to change the approach angle of the gripper to avoid obstacles (Kolodny & Black, 2019; Root AI, n.d.; Vegetable Growers News, 2021).

Researchers from Monash University in Australia have developed an autonomous apple harvesting robot. Their system uses and RGB-D camera to capture environment data which is used by their deep convolution neural network to target apples for picking and environmental obstacles. Next, the motion planning computes the path and angle of attack of the end effector. Finally, once in position the end effector removes the apple from the tree and deposits it (Diemar, 2021; Kang et al., 2020). Their end effector utilises both a

pneumatic suction cup and a soft finger based gripper. The suction cup pulls the apple into position, the gripper is then actuated to grab the apple, and finally, the whole end-effector rotates around the robotic arm to twist the apple from the tree. The gripper is actuated using a dual linkage, and utilises compliant materials with large crumple zones to conform around the shape of the apple for grip. Their choice of robotic arm and fully rotating end-assembly allows for a lot of orientation adjustments for varying the angle of attack to avoid obstacles, but the complexity of needing to move the arm into position to deposit the fruit extends the cycle time. Finally, they note that when harvested apples are partially covered by leaves they can slip from the end-effector so need to further develop this design (Diemar, 2021; Kang et al., 2020).

Utilising robotic and automation technologies may provide some advantages with no direct economic return, the adoption of a combination of automation technologies in the dairy industry has reduced repetitive tasks, the number of people needed and overall work hours, allowing farmers to attend other tasks or have more social time (Eastwood, 2019; Kootstra et al., 2021). Factors such as these can help to ease some of the stresses and make agricultural work more attractive. Economic viability discussions often talk about robotics replacing human labour by 100% to be viable, technical limitations in implementation means that this line of reasoning can hamper innovation. Considering human-robot co-working, and the benefits of utilising both, is a good alternative to think about innovation in the agricultural sector (Kootstra et al., 2021). Nikki Johnson, the CEO of NZ Kiwifruit Growers, in an interview with Farmers Weekly stated that there is a lot of interest for transitioning to more automation, but the high upfront development and implementation costs are hindering this transition as the short-run nature of seasonal harvest make seeing a return on technology investment difficult (Johnson, 2021). The strengths of procedural modelling and 3D printing could be used to help ease development time and costs. Procedural systems coupled with PolyJet 3D printing can be implemented to rapidly produce one off soft robotic prototypes, which can be tested to see if the design meets their needs. Then quick adjustments can be made and a new prototype produced, allowing for rapid iteration until they reach a design that is fit for purpose. PolyJet 3D printing can just as easily produce one off prototypes and full bed production runs, so are suited for both the testing stages and producing large batches of the final product. This all saving labour and development time and costs, by removing the need for assembly and simplifying the iterative process. Further, by utilising an appropriately adjustable procedural system, the design of a picker for one fruit could then be adjusted to suit the needs for picking other type of fruit, simplifying the development process across the board.

Relevance to this Study

Agricultural industries are facing huge challenges that might be addressed by the implementation of digital technologies and automation. The kiwifruit industry continues to play a vital role in New Zealand's export economy with international demand growing. Already facing labour shortages the answer to meeting growing demand may come from automation and soft robotics. This research explores how procedural workflows might be used to simplify the processes for making functionally graded materials and soft robotics.

Conclusion

The full microstructure control of voxel-based printing presents new opportunities to 3D print functionally graded materials. So it is now possible to design with gradient material architectures that are commonly found in nature. A cross section of a kiwifruit reveals that it is made out of structures of gradient materials (see figure 21), with gradual transitions between the different parts of the fruit. The only sharp transition between parts is the flesh and the seeds, due to their function to separate from the fruit to be spread out and grow new plants. Functionally graded 3D printing brings the opportunity to start to make objects that interact with these fruit that utilise these naturally occurring gradual transitions of material. There are still no established tools or workflows to create gradient materials. This research addresses this problem, exploring how we might use procedural tools to create simple workflows for designing and utilising functionally graded materials.



Figure 21. Cross section of kiwifruit.

DESIGN PRECEDENTS

These precedents are all recent studies that have been conducted on 4D or voxel printing using PolyJet printing technology.

Nicole Hone – Tangible Animation

Nicole Hone explored how multi-material 4D printing could be utilised to achieve the aesthetics of organic movement. During this research a series of aquatic plants called Hydrophytes were 4D printed. The movement of these plants were activated using pneumatic chambers and the organic forms and compositions of the plants produced beautiful and convincing organic movement. This design outcome demonstrated a tangibility, animating objects to bring them to life in the same reality as the audience, with the intention that they could be used for immersive experiences or in the film industry (Hone, 2018). This is a key piece in the 4D printing space as it demonstrates how the fine material control of PolyJet printing can be leveraged to really choreograph movement for 4D prints.

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Figure 22. Hone, N. (2018). *Haven flower -a pneumatically activated 4D print* [Multi-material 3D print] In *Tangible Animation—Designing Organic Performance with Multi-Material 3D/4D Printing* [Victorial University of Wellington]. <http://researcharchive.vuw.ac.nz/handle/10063/8063>. Copyright 2022 Nicole Hone.

Patrick Coulson – Well Actuate(ly)

Patrick Coulson explored how multi-material PolyJet printing could be used to enhance the capabilities of soft robotics. This research utilised fine-tuned parametric control and equation-driven modelling to produce a series of soft robotic actuators. The geometric freedom and fine control over material placement allowed for some 3D printed actuators to outperform their actuators made from other techniques, particularly with twisting. These 3D printed actuators would not be easily replicated using other fabrication techniques. The final outcome of this study showed that it was possible to print a soft robotic limb with multiple motions and up to 5 axes of movement (Coulson, 2021). Patrick's research explores how multi-material printing can be used to make soft robotics overcome the limitations of other fabrication techniques, this research seeks to expand on this idea by exploring workflows to utilise material gradients in soft robots.

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Figure 23. Coulson, P. (2020). *Soft robotic gripper* [Multi-material 3D print] Well, Actuate(ly)...: *Parametric Multi-Material 3D Printed Soft Robotics* [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14072330.v1>. Copyright 2022 Patrick Coulson.

Ana Morris – Beneath the Skin

Ana Morris explored how multi-material voxel printing can be utilised to print medical models based on real world medical data, allowing for patient-specific models that emulate human physiology. These models could be used for medical education, informed consent, skills acquisition or pre-operative planning and surgical simulation. Biomedical imaging data was translated into 3D printed synthetic anatomy using a bitmap-based approach, translating the biomedical data into voxel print slices that can be read by the J850 3D printer. This approach allows for limited data loss allowing for highly accurate synthetic anatomy models (Morris, 2020). During this research Ana developed a workflow to translate biomedical data to voxel print images, this workflow was key in developing the MRI manipulation tool as it needs to translate the data produced during this process into something that can be manipulated in 3D (this is covered in chapters 3,4 & 5).

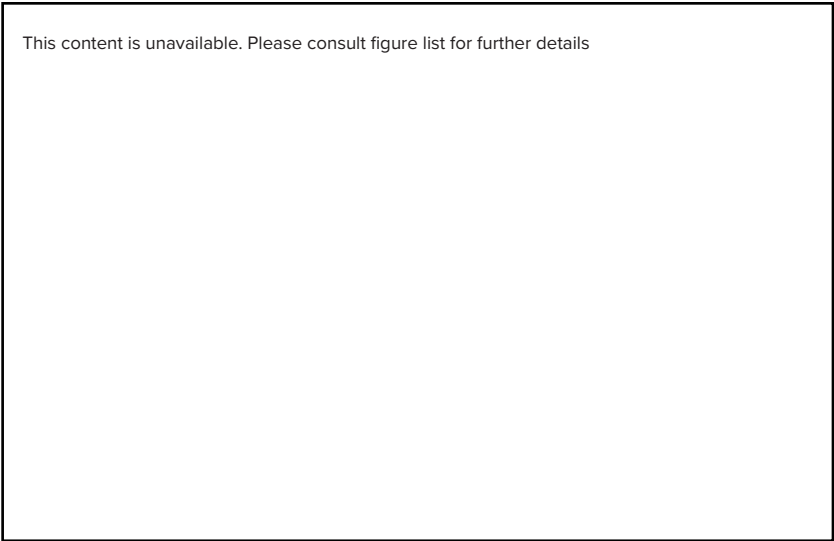


Figure 24. Morris, A. (2020). *Voxel woman* [Multi-material 3D print] In Beneath the Skin: Emulating human physiology using a novel bitmap-based “voxel” 3D-printing workflow. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.17151335.v1>. Copyright 2022 Ana Morris.

Jessica Salter – Fossils from the Future

Jessica Salter explored how procedural systems could be used to create a morphology that could be voxel printed for scientific communication. A narrative around ocean acidification was built and a procedural system created that generated a morphological timeline of possible outcomes for ocean creatures shell degradation due to ocean acidification. The designer only influences input parameters and the system generated a timeline of forms showing increased degradation over time. These timelines were used to voxel print shell samples that act as tangible examples of the future effects of ocean acidification, helping to communicate scientific information and spark discussion on these issues (Salter, 2021). This research really demonstrates the power of procedural systems for their ability to efficiently generate a large variety of outcomes with only simple user inputs. Voxel printing was shown to be an effective tool for physically outputting the complexities of the procedurally generated shell forms.

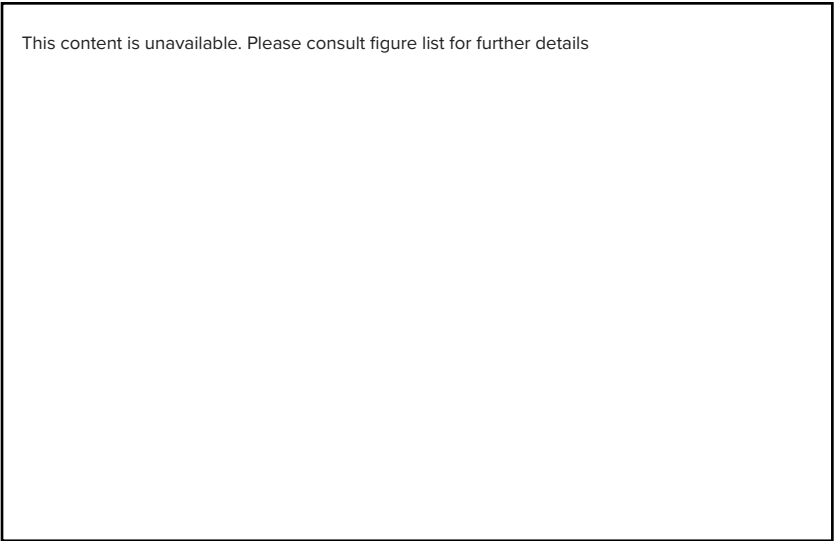


Figure 25. Salter, J. (2020). *3D printed future fossil* [Multi-material 3D print] In Fossils from the Future [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14060531.v1>. Copyright 2022 Jessica Salter.

Relevance to this Study

This research explores how procedural systems can be leveraged to expand our voxel printing capabilities for both 3D and 4D printing, demonstrating the efficiencies and ease of use these systems can bring. These precedents act as precursors to this study. The goal is that the tools and workflows developed here will be utilised in future research, helping the next researchers to expand upon the ideas explored in these precedents, leveraging the greater voxel print material control offered by the outcomes of this study.

J850 & VOXEL SLICER

This section will provide a technical rundown of how the J850 3D printer and the Voxel Slicer work. Though these were briefly covered in the voxel printing section above, it is worth clearly illustrating here as these concepts will be useful for understanding the design decisions during the next sections, developing workflows and tools.

J850 3D Printer

The J850 3D printer has 8 channels that can each be loaded with its own individual material. One of these channels is always reserved for a removable support material, leaving 7 different permanent materials that can be simultaneously utilised during a 3D print.

The typical material loadout for the printer is:



SUP706™

A jelly-like support material used to fill gaps and support printed objects. This is expected to be removed post-print and can be scraped away or dissolved in a chemical solution.



VeroPureWhite™



VeroBlackPlus™



VeroCyan-V™



VeroMagenta-V™



VeroYellow-V™



VeroClear™

A set of rigid resin materials, mixtures of these materials allow for full colour and transparent rigid printing.



Agilus30Clear™

A soft, rubber-like material that can be used to produce flexible prints. Mixtures of Vero and Agilus allow for printing with a variety of hardnesses.

All of these materials are photopolymers, deposited as liquid droplets and cured with ultraviolet light.

Each material channel has its own print head that consists of a row of very fine holes through which droplets of the material are jetted. (See figure 26).

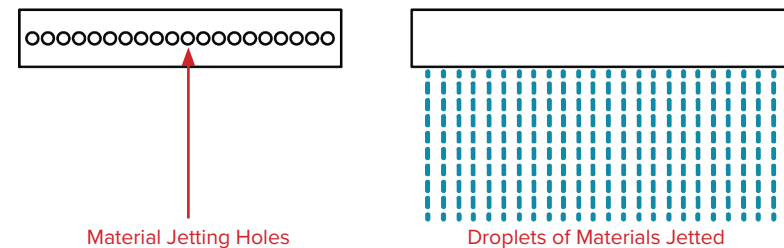


Figure 26. PolyJet print head diagram.

Once a layer of material is sprayed onto the print bed, it is then compressed with a roller to make the droplets the correct size to form a solid layer. After rolling this layer is cured with an ultraviolet light.

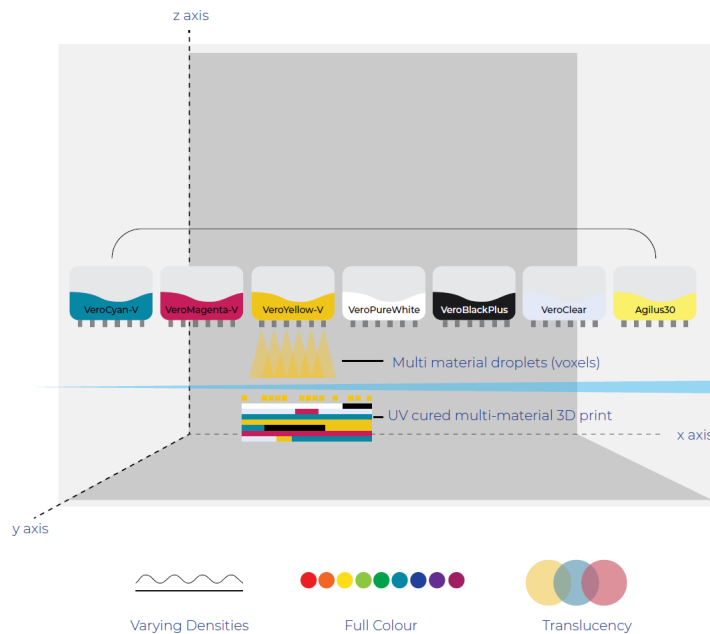


Figure 27. Morris, A., Robb, I., Guy, B. (2021). *J850 diagram* [Digital diagram] In *The Voxel Workflow*. Retrieved from <https://made.ac.nz/wp-content/uploads/2021/11/The-Voxel-Workflow.pdf>.

Each of these droplets once rolled and cured can be thought of as a physical voxel, these voxels all have a physical size of 0.0423mm in the X-dimension and 0.0846mm in the Y-dimension. In the Z-dimension (or layer height) voxels have a size of 0.027mm when set to high mix or a size of 0.014mm when set to high quality (Grabcad, 2020).

This means that every cubic centimetre contains 10,349,894 voxels the material for each capable of being individually controlled.

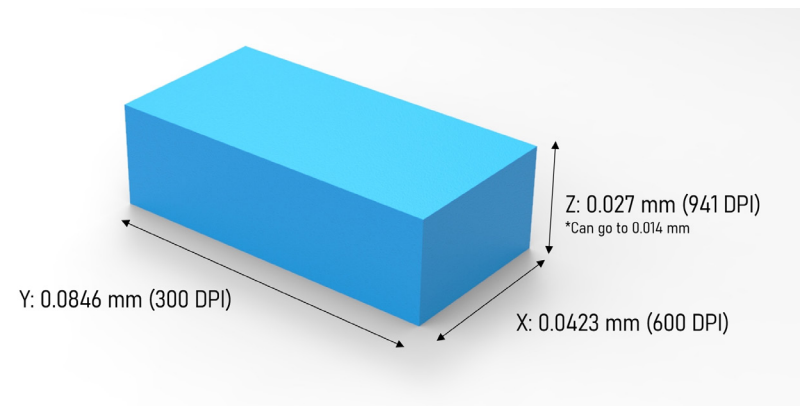


Figure 28. Single voxel scale.

Research Package Expansion

During this research we were given access to a Research and Education Package that added new functionality to the J850 3D Printer. As well as unlocking the ability to pause prints for embedding objects, this package unlocked the ability to print with liquid and air (Stratasys, 2021).

Liquid printing enables the use of a liquid cleanser material to be printed along with the other tray materials. It can be used inside of enclosed voids of a model as a support material, allowing for much easier printing of fluidic channels that can be used for hydraulics or pneumatics. The cleanser material can be fully enclosed and kept in the print as a hydraulic liquid, or it can be removed from the part post-printing leaving an internal channel. Prior to liquid support, when printing internal voids designers generally have to carefully consider how solid support material will be removed from those voids post-printing. This has limited the possibilities of printing with internal voids and fluidic channels. Printing with liquid support material, which can be drained away post-printing, removes this barrier and opens up the potential to print internal channels with much more freedom and complexity.

Air printing allows for air to be selected as a print material to print objects with air-filled voids. Prior to air printing being an option, any voids within an object would be automatically filled with support material by the printer. Creating air pockets would have to involve removing this support material post printing, making sealed voids impossible. With air as an option there is potential to utilise the flexible Agilus material and air to create soft structures with less density and more elastic adaptability, giving them foam-like properties.

Limitations to these new materials

Liquid printing requires that one of the material channels is replaced with the liquid cleanser material. This means that when printing with liquid supports, one of the other materials has to be sacrificed, so it cannot be included in your prints. On top of this, changing to liquid on one of the material channels requires that material within the channels loop needs to be flushed out and removed. This takes technician time and results in wasted material, which means there is a cost every time the printer set-up is changed to liquid printing.

Air printing is limited by the shape of the void that is possible to print. These voids must be designed in such a way that they will seal, to do this the voids must come to a point and the maximum angle of the tip must not exceed 9 degrees. This is a limitation due to the fine layer resolution of the printer and the need to have some overlap on subsequent layers, otherwise the printed material would collapse.

Voxel Slicer

In order to control the material of every voxel in a 3D print the printer requires a stack of PNG images, one for each 3D printed layer. In these images each pixel represents a voxel, and the pixel's colour dictates the material of the droplet placed there by the printer.



Figure 29. Each pixel in an image slice represents one voxel of material.

Since the J850 3D printer has limited material channels full colour 3D prints utilise combinations of cyan, magenta, yellow, black, white and clear droplets to achieve all of the desired colours. So voxel slice PNG images need to be limited to just this selection of colours. This is achieved using a dithering algorithm on full colour images, which translates RGB data in these images to being only made up of pixels of the limited colour selection required by the printer.

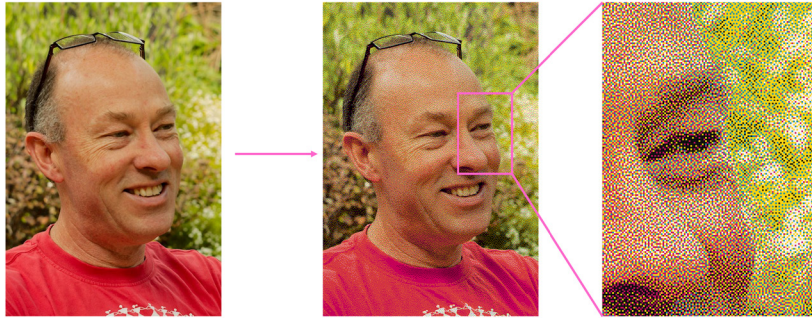


Figure 30. Demonstration of dithering of full colour image to just material colours of the J850.

Ben Jack, Dan Scudder and Zach Challies have developed a Voxel Slicer based in the visual effects software Houdini (SideFX, 2022) that is utilised by our multi-material 3D printing research group. This Voxel Slicer can accept either 3D geometry or a volume created in Houdini and slice it into a stack of dithered PNG images ready for voxel printing. In its basic set up users provide geometry (that can be produced in any software and sampled) and a colour map. (See figure 31).

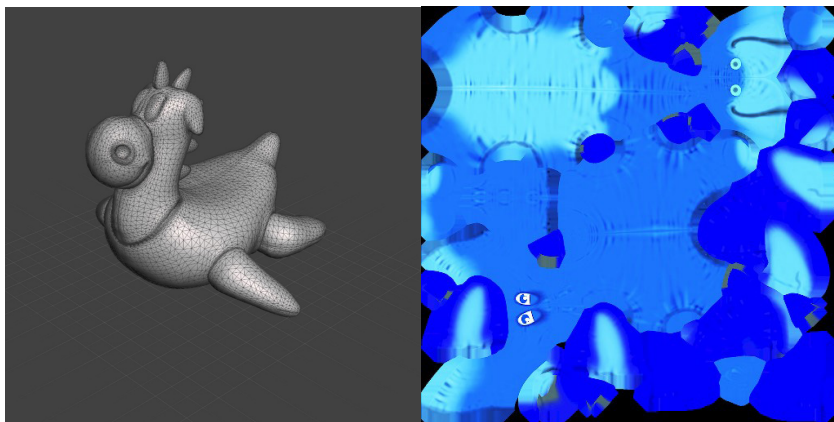


Figure 31. 3D geometry and colour map.

Since CAD and 3D modelling software produce geometry by defining only the outside form of the model, there is only shape and colour data on the outside shell of the geometry. Voxel prints require that the material of the droplets of the entire volume of the print be defined. So the input geometry needs to be translated into a digital volume that has this data all throughout its structure. The VDB from Polygons tool is used to create a digital volume from the input geometry, taking the colour data from the given colour map and pushing it throughout the entire volume.

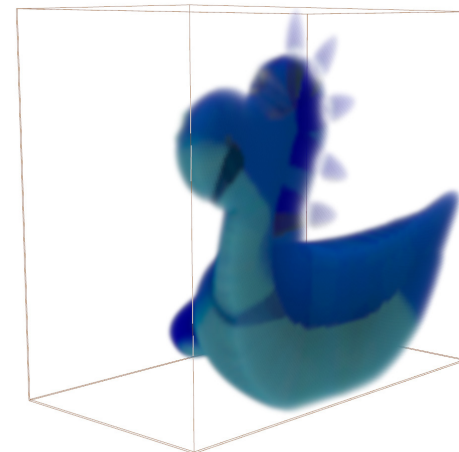
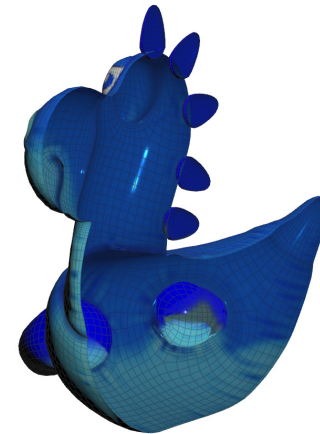


Figure 32. Top shows 3D geometry is just a hollow shell, colour only on outside. Bottom shows 3D volume with completely full interior and colour throughout.

A grid is animated to move throughout the volume, as it does so it samples the volume to produce a PNG slice image for each print layer. The sampling utilises three pieces of data, the RGB colour values, the mask and the alpha. The mask defines the boundary of the print, so where material will be placed and where it won't. The alpha generally defines the translucency of the colour which would indicate more clear material needs to be used. In this set-up however, the alpha is always set to 1 and clear material is defined by providing areas of a digital volume with no colour data. So for instance, to voxel print an object encapsulated in a clear box you would provide the box as a colourless volume.

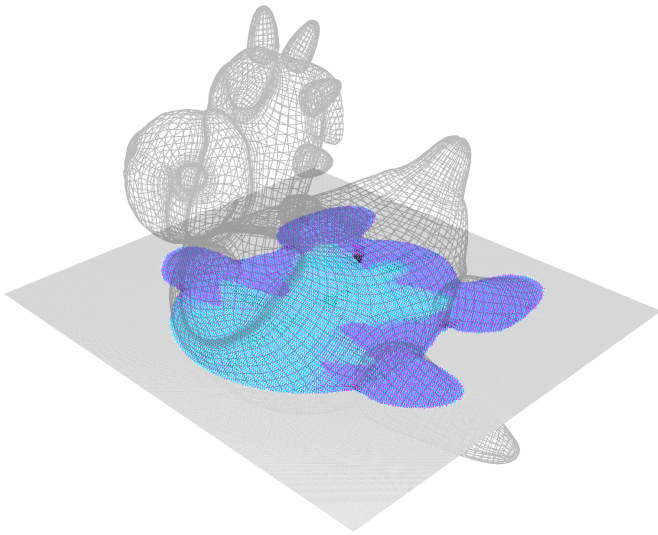


Figure 33. Sampler grid sampling colour from volume to make a PNG voxel slice. As it moves through a slice is produced for each print layer.

As the grid samples the volume it automatically dithers the colours of the image slices to match the required materials of the J850 3D printer, and it renders out these image slices as a PNG stack ready for voxel printing (figure 34 shows an example of output voxel slice images).

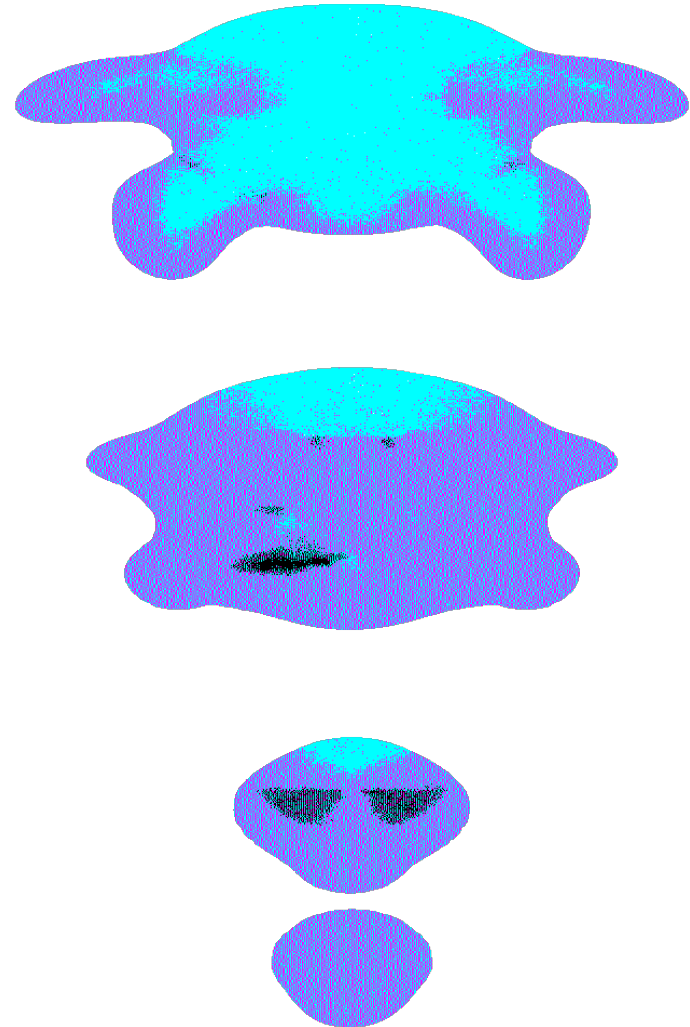


Figure 34. Random selection of image slices from the output PNG voxel stack.

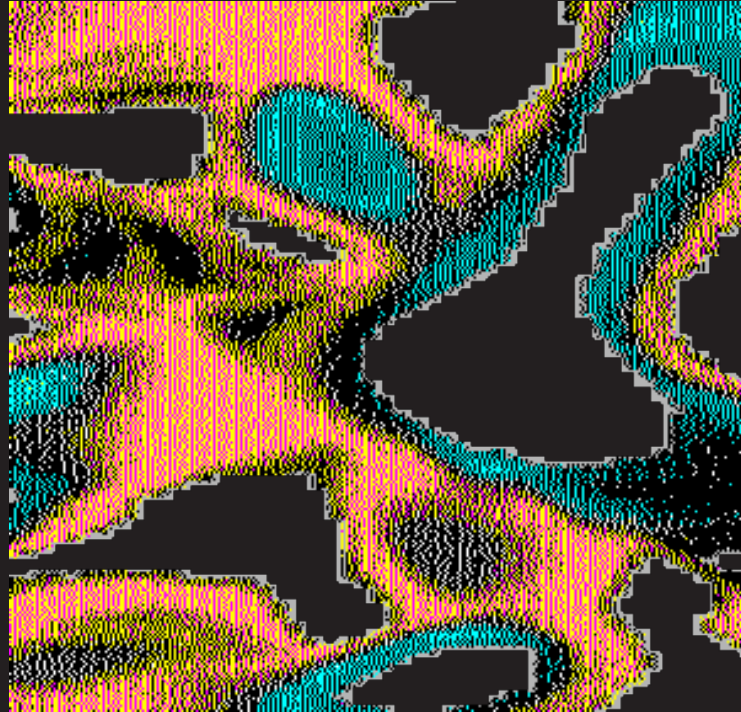


Figure 35. Section of a voxel print slice.

CHAPTER 3

DESIGN EXPERIMENTS

MATERIAL GRADIENT WORKFLOW

The following experiments outline the development of my material gradient workflow. This will not be an extensive list of every permutation of tools and techniques used in Houdini in trying to solve these problems, as I think there is little value in going over every dead-end. Instead, this is a focused list of the major techniques attempted, where either I could update the design criteria or I gained valuable insight that led to the final outcome of these experiments.

I had very little experience with Houdini and 3D volumes at the beginning of this process, so these experiments were as much about me learning to use the tools as they were about developing a material gradient workflow.

This workflow was developed with simplicity in mind. Trying to keep the workflow simple means there is less processing when the files start to scale up in size, volumes are very data intensive and get exponentially worse as they scale up in all 3 dimensions. Simplicity also helps it to be easily teachable, so other students will be able to quickly understand and make use of these tools for future research work.

Format of Experiments

Screenshot of the model in 3D space

This gives a visual understanding of what the test model is in 3D space.

Selection of voxel slice PNG images from the output stack

The images of the layer slices once the volume has gone through the Voxel Slicer. Since the pixel colour corresponds directly to a printed voxel material, these slices can be used to assess the efficacy of each experiment.

Description of tools used

Briefly describe the workflow.

Analysis

Reflective paragraph outlining the insights gained from each experiment.

Other

Other images used where applicable to illustrate key points about the workflows.

Colours Used

Throughout these experiments I have used white to stand in for the soft Agilus material and black to stand in for the rigid Vero material.

Initial Design Criteria

Produce a system that allows for full volumetric control to create gradients of materials for voxel printing.

Create an intuitive workflow that is simple to use and helps give a visual understanding of volumetric gradients.

Allows the sampling of geometry from other software and flexible enough to be used for any scenario requiring material gradients.

Works efficiently to produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

PHASE ONE – ATTRIBUTE VOP

The Voxel Slicer is presented to work using geometry and a colour map on the geometry, so my first attempt looked at giving it a piece of geometry with gradients of colour on its outside surface. Here I created a base box coloured white and a series of smaller boxes with gradients going from black in their centre to white on their edges (this simple example is useful for showing up issues with volumes in the slicer).

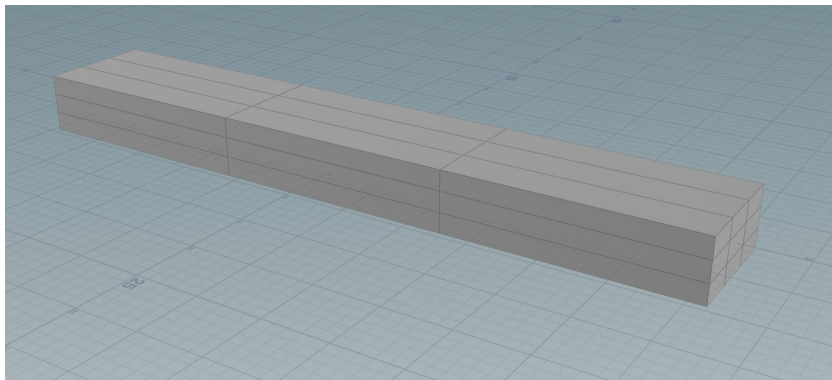


Figure 36a. Base geometry.

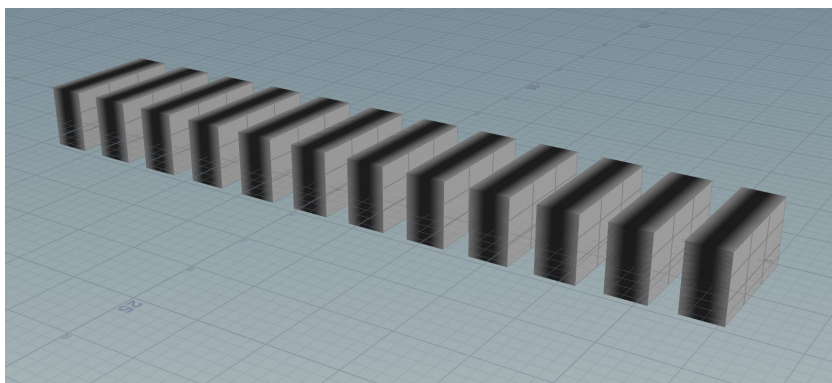


Figure 36b. Effector geometry with gradient.

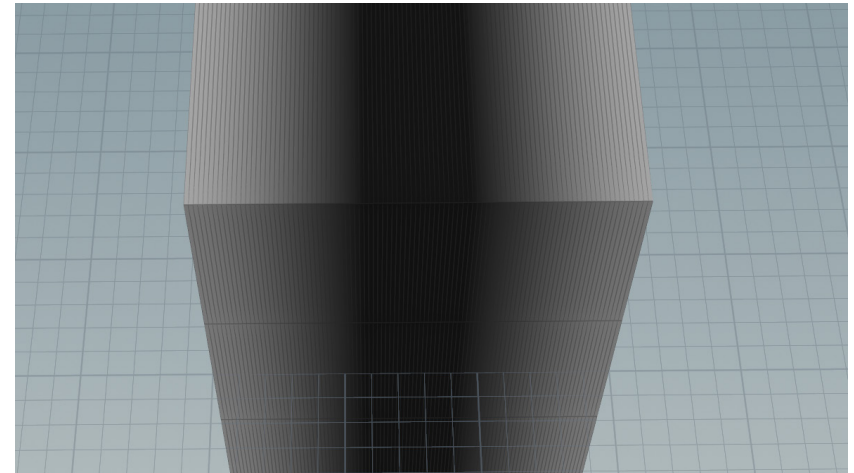


Figure 36c. Close up of gradient on effector geometry.

These gradients were made using an attribute VOP, which allows me to set up colour and curve controls to direct the colour and distribution of the gradients.

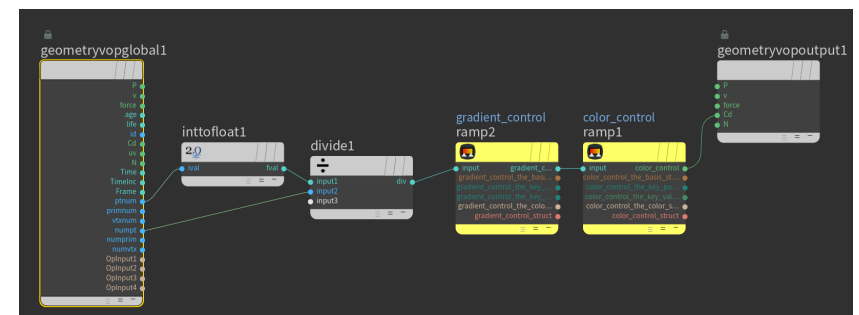


Figure 37a. Attribute VOP setting the geometry point colour based on controlled inputs.

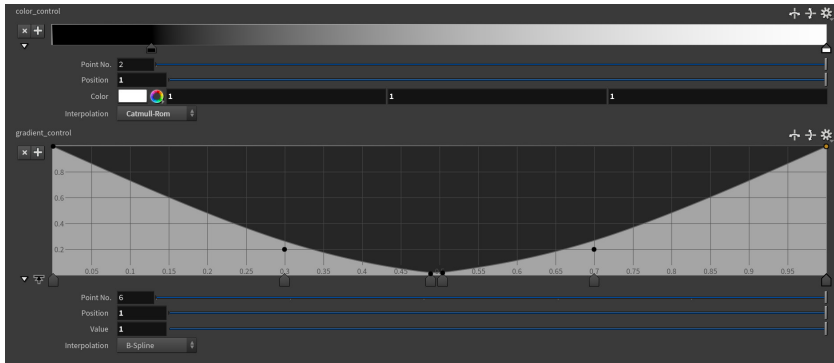


Figure 37b. Controls to set gradient. Top control sets colour gradient, bottom graph control sets the shape of the falloff.

These were turned into volumes using the VDB from polygons tool, (recall this takes input geometry and transforms it into a volume pushing the surface colour throughout the volume) and then combined to form a single volume with gradient strips.

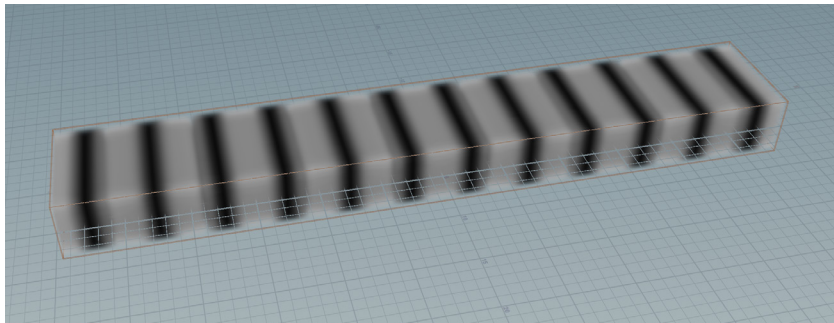


Figure 38. Resulting volume from combining both input geometries.

The resulting volume was then put through the Voxel Slicer to make a slice image stack, a selection of slices are shown below.

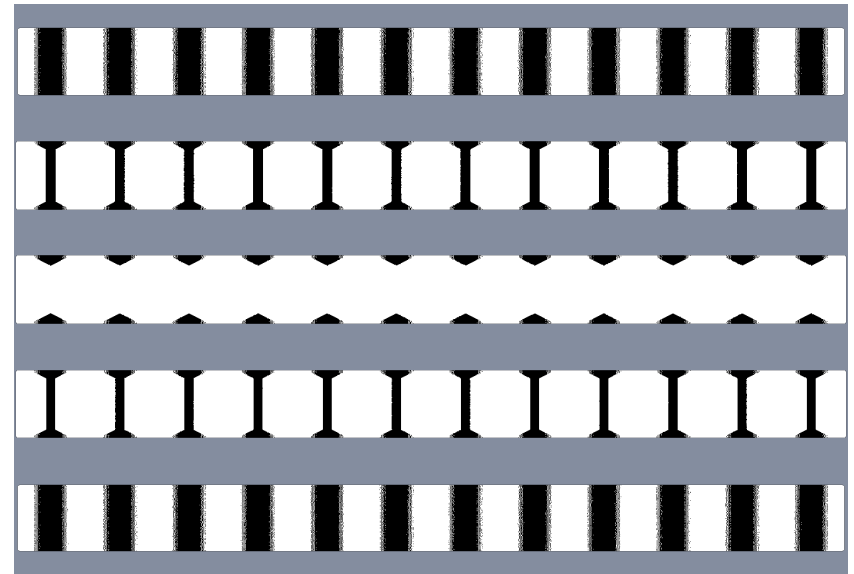


Figure 39. Series of selected slices from attribute VOP volume.

Discovery and Reflection

The image slices show that the colour of the volume tapers towards its centre, this is a massive issue as it means the strategy set up for using the Voxel Slicer doesn't give you full material control throughout the entire volume (this will be referred to as the tapering problem). This seems to be happening due to the way colour is surface-based and the inside of the geometry is empty prior to being transformed into a volume. It appears that as the colour is being projected from the outside in during the volume transformation, it is being lost fairly quickly. This is bad in this simple 5mm strip so has the potential to be much worse in larger and more complex 3D geometry. The tapering problem means we have nowhere near the amount of material control desired.

Further, while the VOP system does offer a lot of nice gradient control, it is a fairly unintuitive system for people with little to no Houdini experience. So the VOP system is not well suited to make an easy to use workflow.

Update Design Criteria

Produce a system that allows for full volumetric control to create gradients of materials for voxel printing.

Create an intuitive workflow that is simple to use and helps give a visual understanding of volumetric gradients.

Allows the sampling of geometry from other software and flexible enough to be used for any scenario requiring material gradients.

Works efficiently to produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

Any created system must avoid the tapering problem.

PHASE TWO - MASK FROM GEOMETRY

This experiment makes use of the mask from geometry tool, which takes a base geometry and an effector geometry and uses the shape and position of the effector geometry to create a gradient mask on the surface of the base geometry. The shape of the gradient is controlled by the shape of the effector geometry (this can be anything). The position of the gradient is controlled by the relative position in 3D space the two geometries have to one another. Finally, the gradients falloff is controlled by a simple curve control.

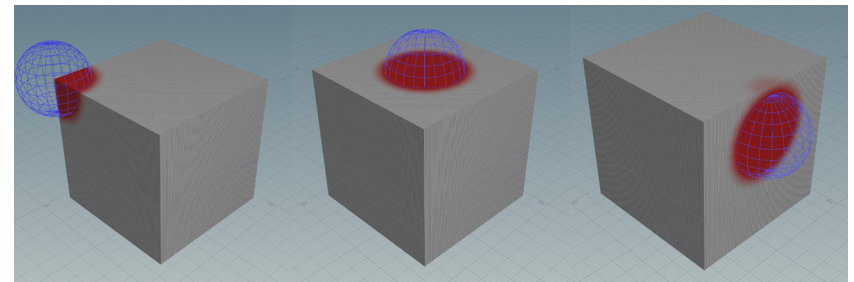


Figure 40. Demonstration of dragging around sphere in 3D space to control mask.

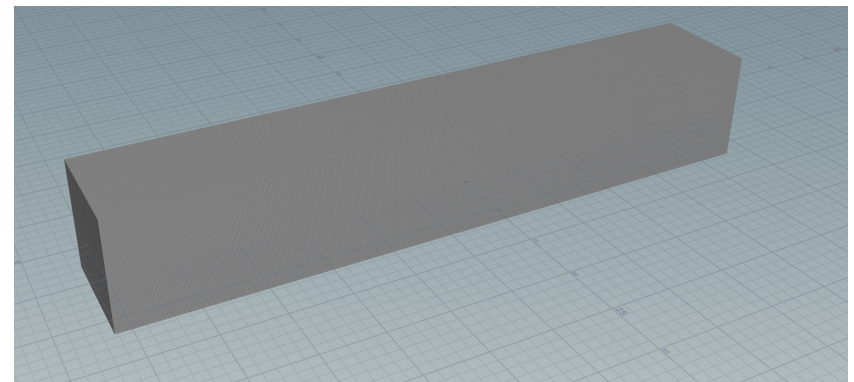


Figure 41a. Base input geometry.

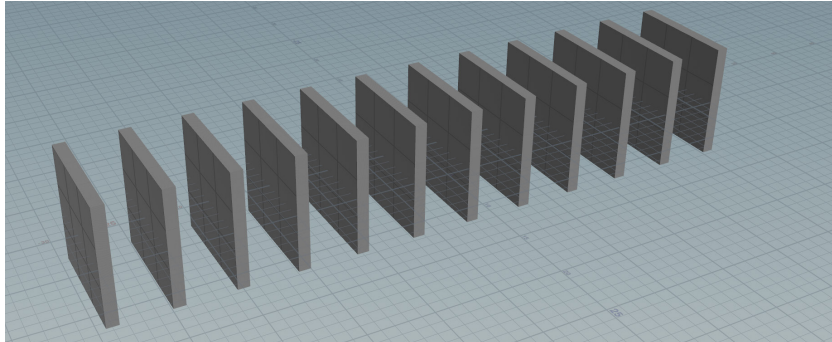


Figure 41b. Affector input geometry used to define mask on base geometry surface.

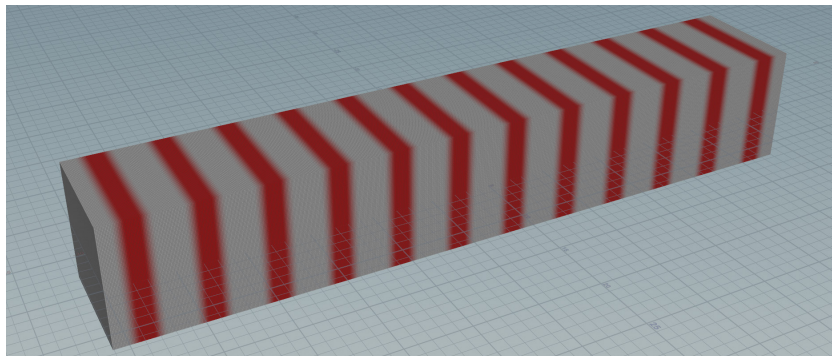


Figure 42. Resulting mask.

This mask can then be put used to control a colour gradient, to control the colour thus controlling the printed material post voxel printing.

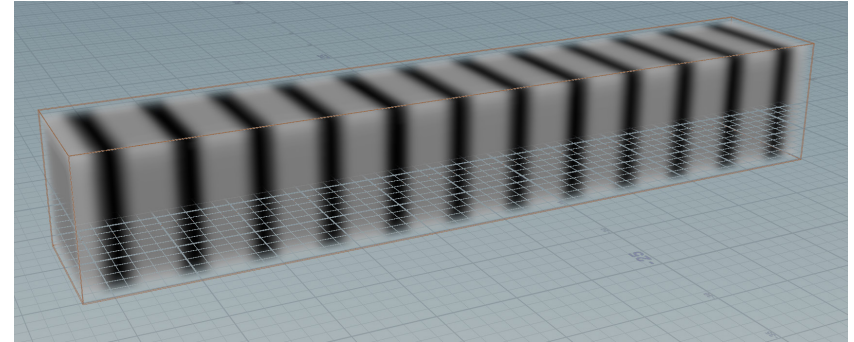


Figure 43. Volume resulting from masked geometry.

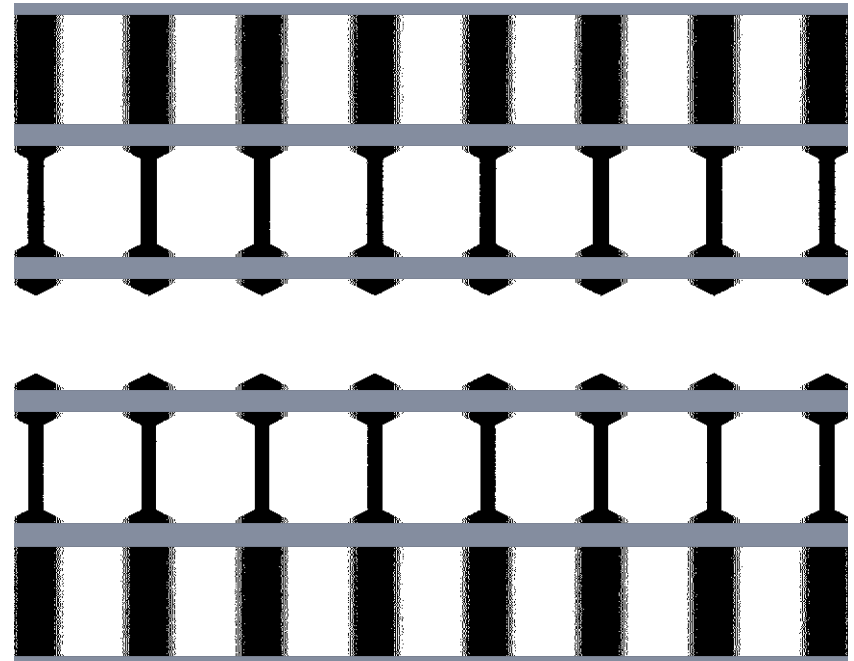


Figure 44. Series of selected slices from masked geometry volume, looking exactly the same as phase one.

Discovery/Reflection

This strategy still produces the same tapering problem as experiment one, this is due to the mask being surface-based again.

The surface-based nature of these strategies also means we get very little internal control, so cannot have volumes that are completely encompassed by another with a 3D gradient in all directions. So these surface-based strategies don't give us the full internal material control that voxel printing is capable of.

The gradient mix of materials being controlled by moving two pieces of geometry in 3D space is very tangible and intuitive feeling, allowing the control of material gradients simply by dragging around geometries in space. A strategy that utilises this idea more volumetrically with a simple falloff control would give us all the desired material control, while keeping it simple and intuitive to use. The shape of the mask is completely controlled by shape of input geometry, so can be modelled to be anything.

Update Design Criteria

Produce a system that allows for full volumetric control to create gradients of materials for voxel printing.

Create an intuitive workflow that is simple to use and helps give a visual understanding of volumetric gradients. This workflow should utilise the physical movement of geometries in space with a simple falloff control.

Allows the sampling of geometry from other software and flexible enough to be used for any scenario requiring material gradients.

Works efficiently to produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

Any created system must avoid the tapering problem.

PHASE THREE – DENSITY FALLOFF VOLUME

In this experiment a volume with a density gradient was utilised. This density attribute was then translated into a colour attribute, giving a colour gradient (needed to produce gradient materials with the voxel slicer). Density is the base attribute for the volumes we use in Houdini for voxel printing, it can be thought of as the density of a fog or smoke, becoming more opaque the denser it is. In terms of individual voxels in a volume the density can be thought of as referring to the opacity of the voxels, 1 being fully opaque and 0 being fully transparent.

This strategy used a series of rectangular cubes as input geometry, turning them into a volume and controlling the density of the volume using a ramp curve control. This curve control allows the creation of a density gradient, where these volumes are fully dense in their centre and this density trails off towards their edges (this is really hard to visualise within Houdini).

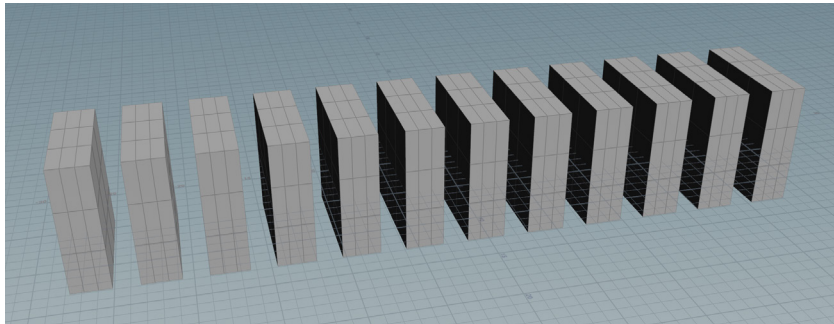


Figure 45. Input geometry for density falloff volume.

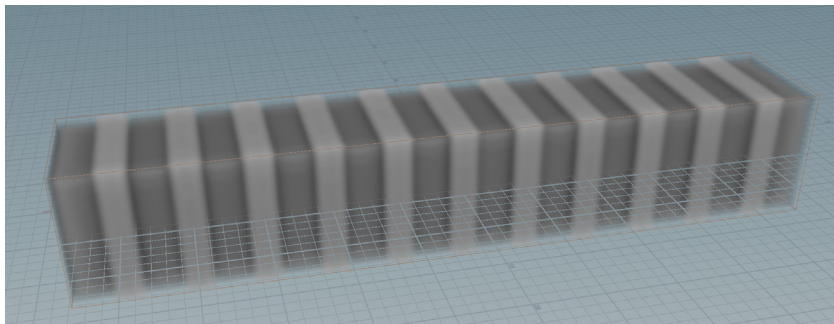


Figure 46. The volume produced from input. The darker areas are volumes where there is a density falloff, the lighter areas have a solid density.

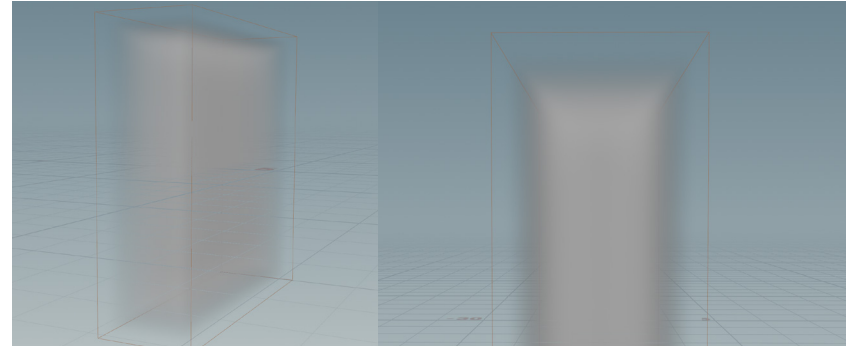


Figure 47. Demonstrating the volume falloff. You can see it is denser in the middle and the density tapers off towards the outside.

Once the volume is produced, a trick was used that allows for one volume attribute to be changed into another. The convert VDB tool was used on the density attribute, then the rename tool was used to rename density to Cd (the attribute for colour). This combination translates the density attribute to colour, giving us colour gradients (see figure 48).

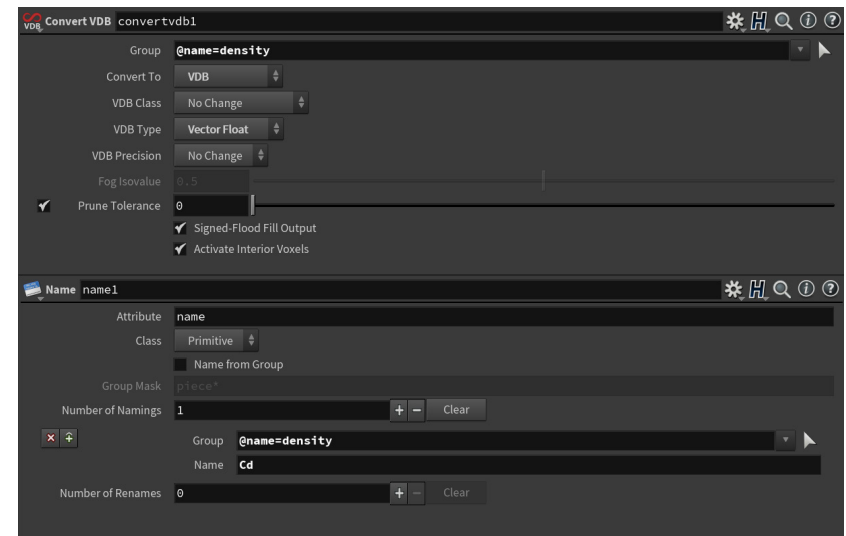


Figure 48. The pair of tools that allow for density attribute to be renamed and used as colour.

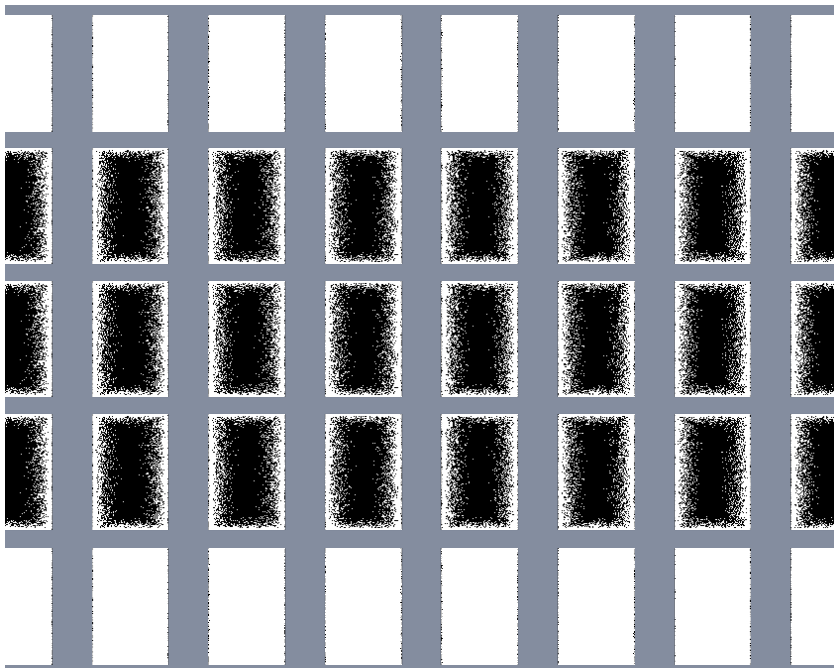


Figure 49. Selected image slices from volume density falloff.

Discovery/Reflection

This technique did fix the tapering problem, the colour gradient went through the entire volume so was on all the image slices, there are gaps in the output slices but this can be fixed by removing gaps from the input geometry.

Unlike the two previous techniques this, was volumetric so allowed for full volumetric falloff in all directions, so would allow for a fully encapsulated volume to blend into the outside volume.

Here I learned about how to use translate volume attributes and use their properties for other attributes, this is a handy trick.

The density falloff control to shape the gradient never quite gave the desired level of control. It made for really sharp falloff and not very smooth gradients.

This technique also introduced a lot of noise into the colour gradients, meaning that material would be placed where it isn't wanted, this will only get worse at larger scales. So it doesn't really allow for the material control desired.

Finally, this method is somewhat convoluted and doesn't visually show how the material gradients are working, since the majority of the technique uses volumes which are difficult to visualise. So this method doesn't give the desired intuitive workflow.

PHASE FOUR – POINT CLOUD + VDB FROM POLYGONS

In this experiment I utilised a strategy using point clouds and colour attribute transferral. I discovered that I could use a volume to create a point cloud using this simple code:

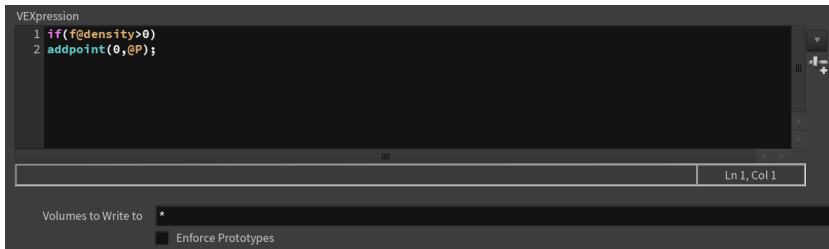


Figure 50. Code to create point cloud from volume.

This adds a point to the centre of every voxel in the given volume. The resulting point cloud could then be coloured. I made a base geometry point cloud coloured white and a set of thin effector point clouds coloured black. The attribute transfer tool was used to transfer the colour from the black effector points to the white base points. In the attribute transfer it is possible to set the blend width, which controls a falloff between the two colours giving us a colour gradient.

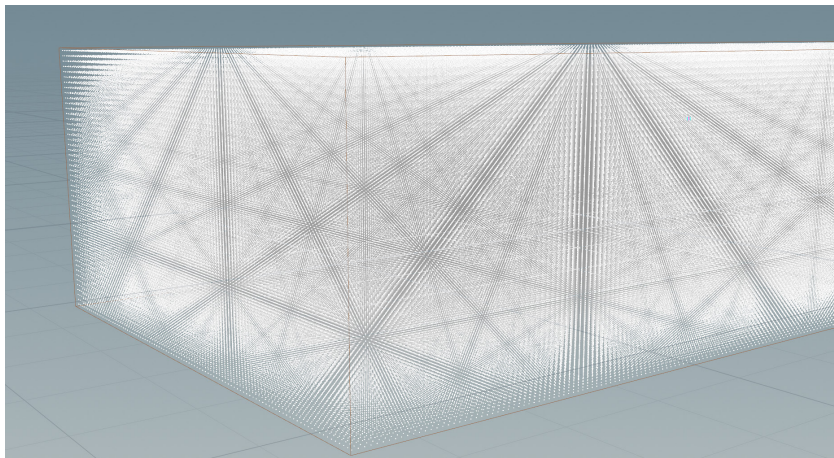


Figure 51. Demonstration of point cloud.

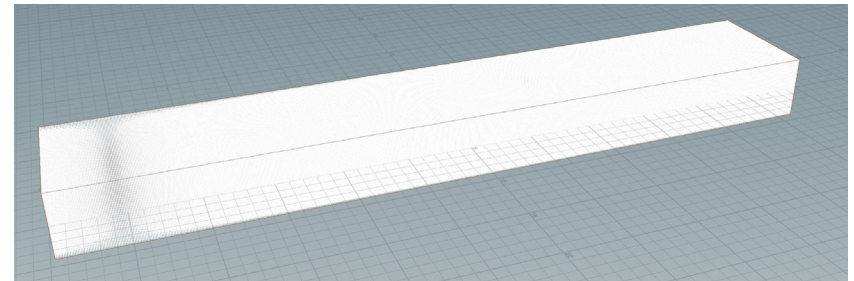


Figure 52a. Input point cloud one.

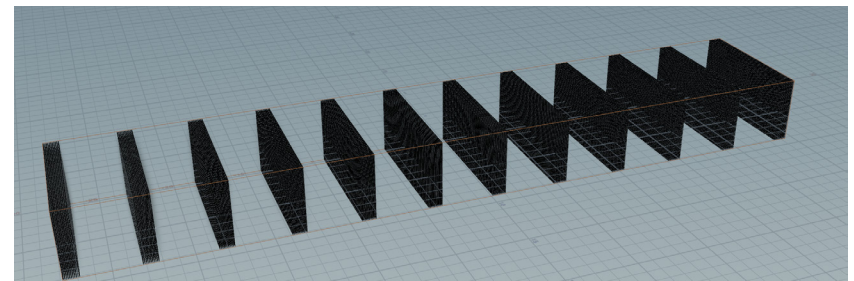


Figure 52b. Input point cloud two.

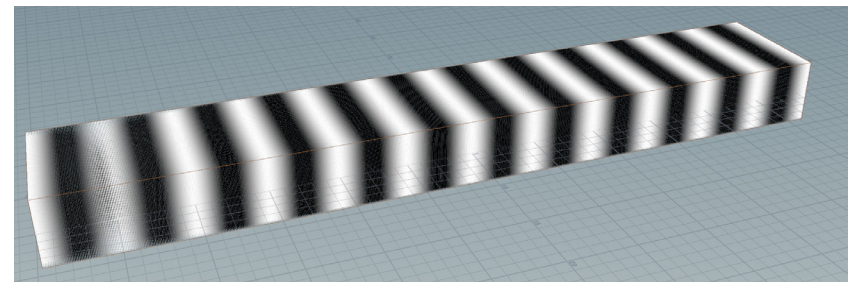


Figure 52c. Resulting point cloud mix.

With the resulting point cloud, I made a small box (which is the size of the distance between the points or the voxel size set when creating point clouds) and use a copy to points to copy that box to every point. The boxes automatically inherit the points colour.

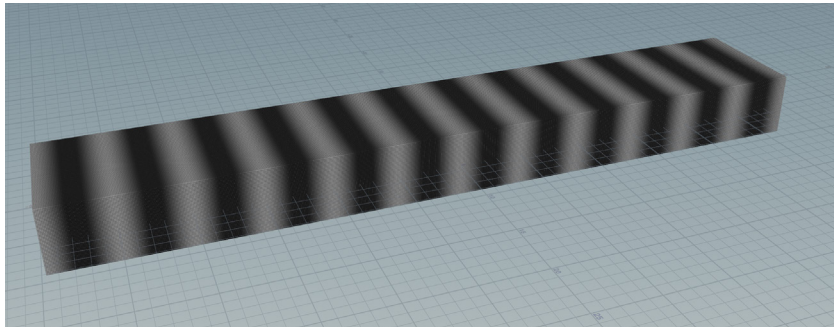


Figure 53a. Boxes copies to mixed point cloud.

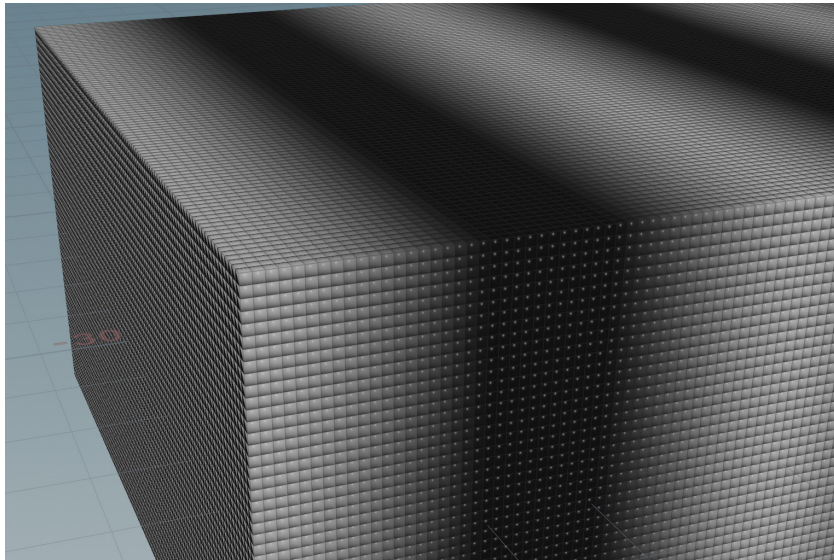


Figure 53b. Close up of boxes.

The resulting geometry was put through the VDB from polygons tool, transforming it into a volume that can be sliced.

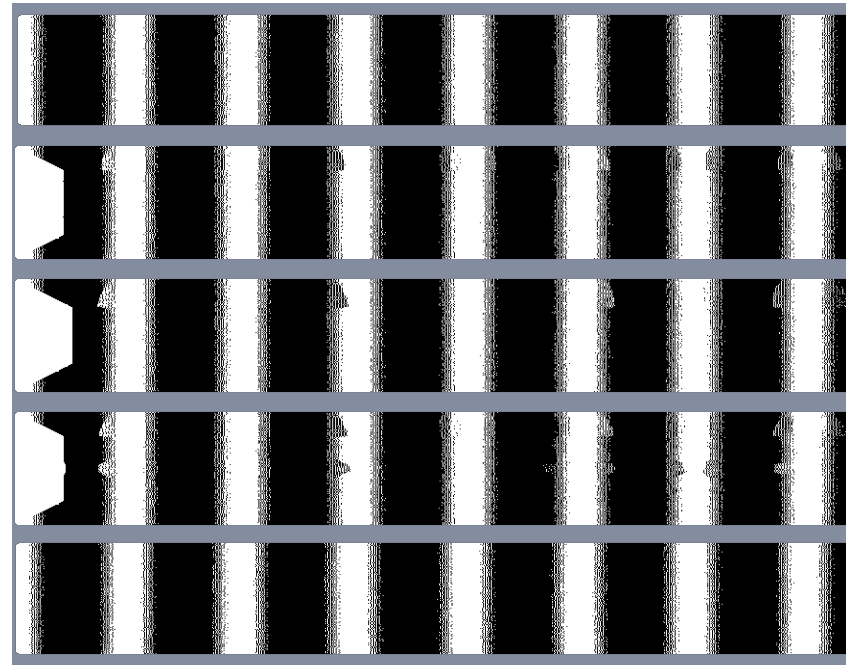


Figure 54. Selected slices from phase four.

Discovery/Reflection

The point clouds are great for visualising the volumetric gradients, and give a clear visual understanding of how the volumes are blending.

The attribute transfer tool with point clouds is fantastic to give all the desired control, users can blend materials using just moving geometries relative position and using the blend width. Attribute transfer with point clouds created full volumetric gradients.

Copying a small box to points and using that to create a volume is fairly brute force. It does work to make a volume but is very slow and inefficient.

There is some tapering and weird noise in the voxel slices, this could potentially be fixed by increasing the divisions on the box copied to points, however doing so even a small amount makes this system so slow and prone to crashes that it's unworkable.

Update Design Criteria

Produce a system that allows for full volumetric control to create gradients of materials for voxel printing.

Create an intuitive workflow that is simple to use and helps give a visual understanding of volumetric gradients. This workflow should utilise the physical movement of geometries in space with a simple falloff control.

Allows the sampling of geometry from other software and flexible enough to be used for any scenario requiring material gradients.

Works efficiently to produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

Any created system must avoid the tapering problem.

A system that utilises point clouds and attribute transferral.

PHASE FIVE – POINT CLOUD + VDB FROM PARTICLES

After seeing my work with point clouds a friend who has done a lot of work with particles in Houdini suggest I try using the VDB from Particles tool instead, this produces a series spherical volumes centred on the points given. Similar to the last set-up this uses point clouds, however here I discovered the points from volume tool, which produces a point cloud from input geometry. Points from geometry is a much easier and faster way to produce point clouds, and was used here. This point cloud is fed into the VDB from Particles tool.

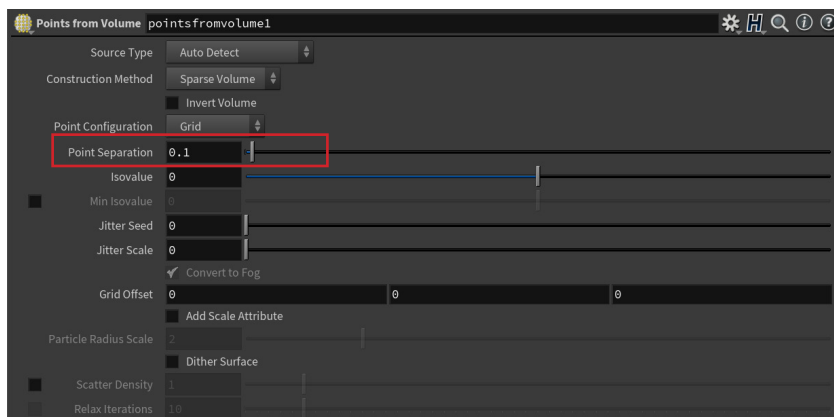


Figure 55. Points from volume tool interface, the only setting that needs to be adjusted is the point separation.

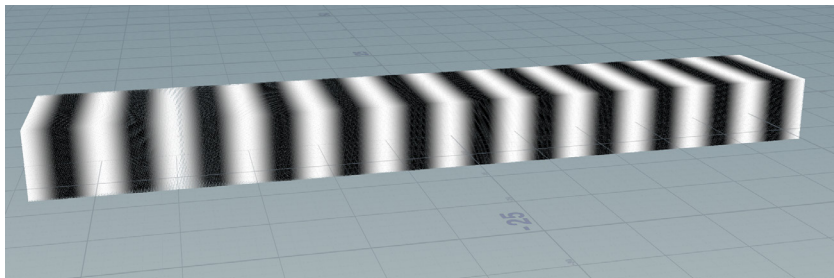


Figure 56. Point cloud used for VDB from particles.

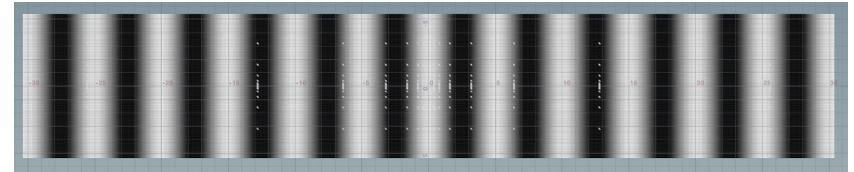


Figure 57. Volume slice showing noise, this is throughout the volume.

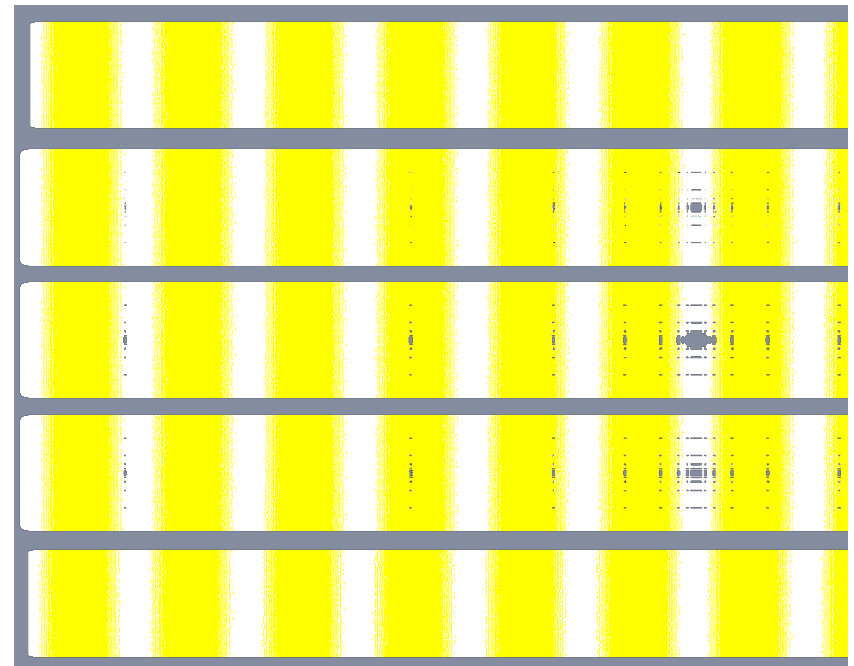


Figure 58. Selection of slices from VDB from particles volume.

Discovery/Reflection

The points from volume tool is much easier way to make point clouds. It also runs much more efficiently than my previous method (in small scale tests it usually takes around 1/5th of the time).

This strategy was difficult to get the settings right for, there is only a small margin on the point radius scale where the interior of the volume won't be empty, so it would be difficult to use for a variety of different point cloud sizes.

The volume slice above shows, this nearly produces the full desired volume, however there are always noise in the interior that leaves empty sections. So it doesn't give the desired material control.

When fed into the voxel slicer it produces a strange problem where the black sections turn yellow. It also produces an empty band of voxels around the outside which have sections of random colour. Finally, it rounds off the edges of the input shape (this is probably due to the way it uses spherical volumes) all meaning this strategy of forming volumes is problematic and doesn't give us the desired result.

PHASE SIX – POINT CLOUD + PYRO RASTERIZATION

This final experiment utilises a point cloud forming a volume using a combination of the pyro source tool and the volume rasterize attributes tool. This experiment used the same method to create point clouds as experiment five. A base geometry and an effector geometry run through points from volume, given their respective colour and then attribute transfer to blend the colour from the effector point onto the base points.

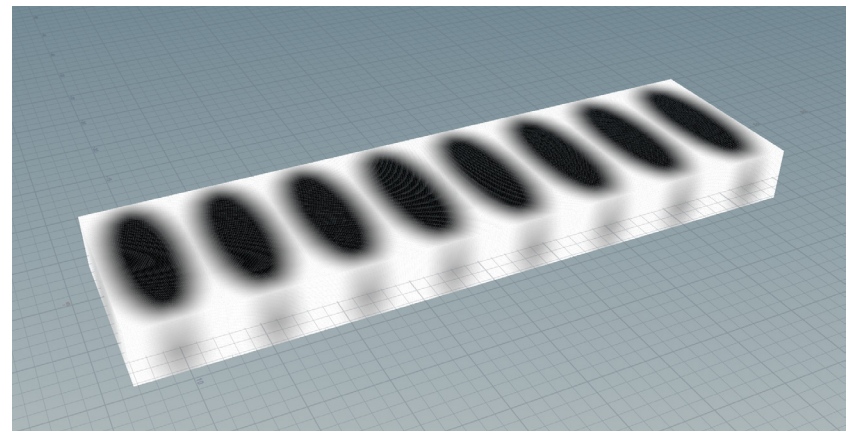


Figure 59. Point cloud. Made with a stretched out sphere and a cube, blended and repeated.

This gradient point cloud is then fed into the pyro source tool, which prepares the points to become a volume and adds a density attribute. The result is fed into the volume rasterize attributes tool, we then tell it what attributes we want within our volume and it transforms our point cloud with those attributes.

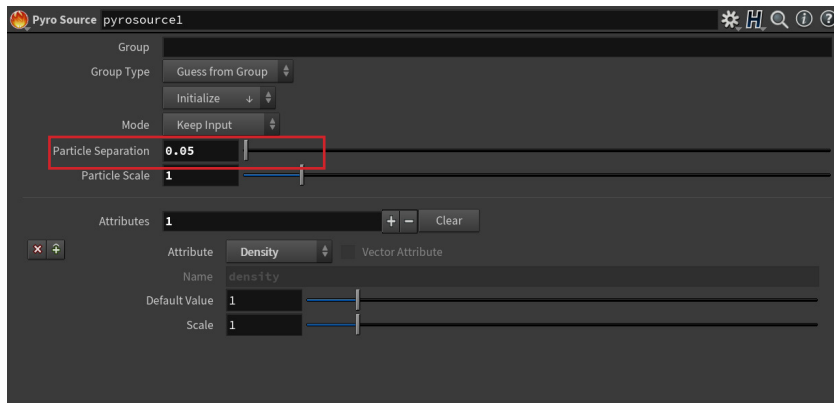


Figure 60. Pyro source, prepares point cloud for becoming volume adding density attribute. Make sure that particle separation matches point separation in points from volume.

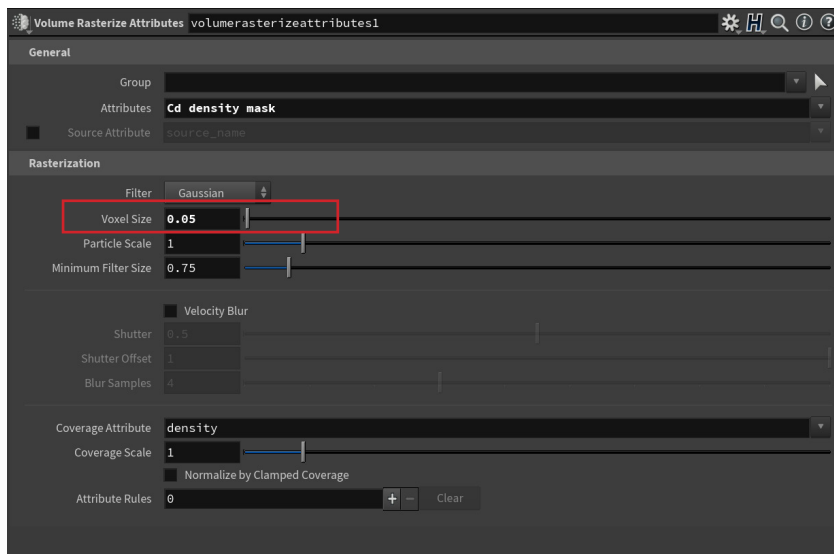


Figure 61. Volume rasterize attributes, takes a series of point and given attributes to form a volume. Make sure voxel size matches particle separation of pyro source.

For these volumes I am not using the 'A' attribute (alpha) as I discovered that when a volume is given to the Voxel Slicer that has both density and 'A' it produces slices that are all magenta and yellow (see below). To fix this I use the density attribute as the 'A' attribute and rename just before it is put into the voxel slicer, this fixes the colour issues.

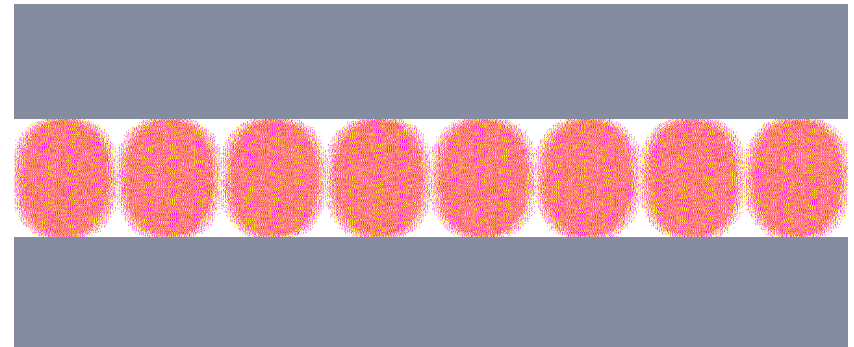


Figure 62a. PNG slice of volume with 'A' attribute, showing the issue of slices being displayed as yellow and magenta.

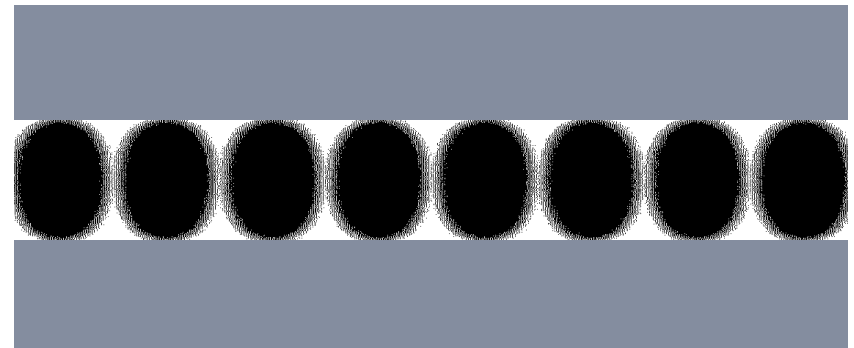


Figure 62b. PNG slice from same volume without 'A' attribute showing up black and white as it should.

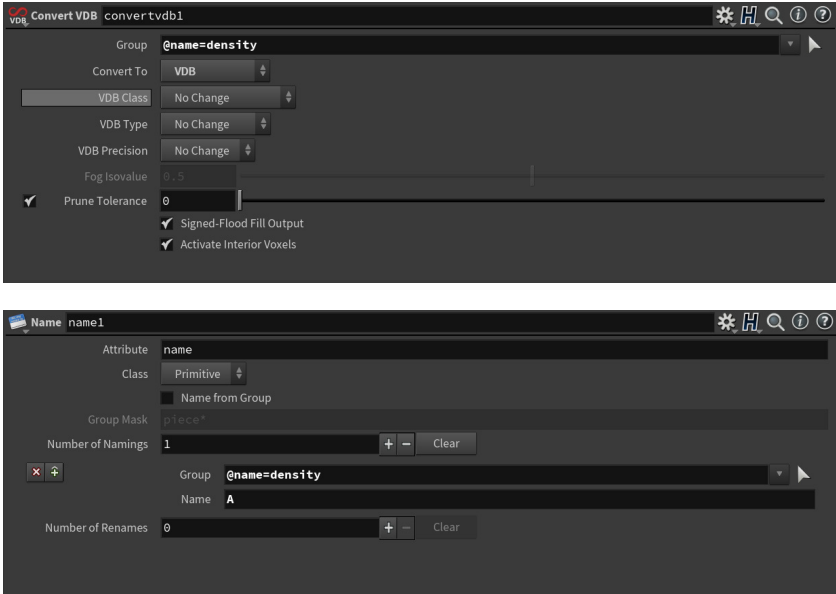


Figure 63. Demonstrating the process of renaming attributes learned in phase three. Here the density attribute is renamed to the A attribute needed to be sampled by the Voxel Slicer.

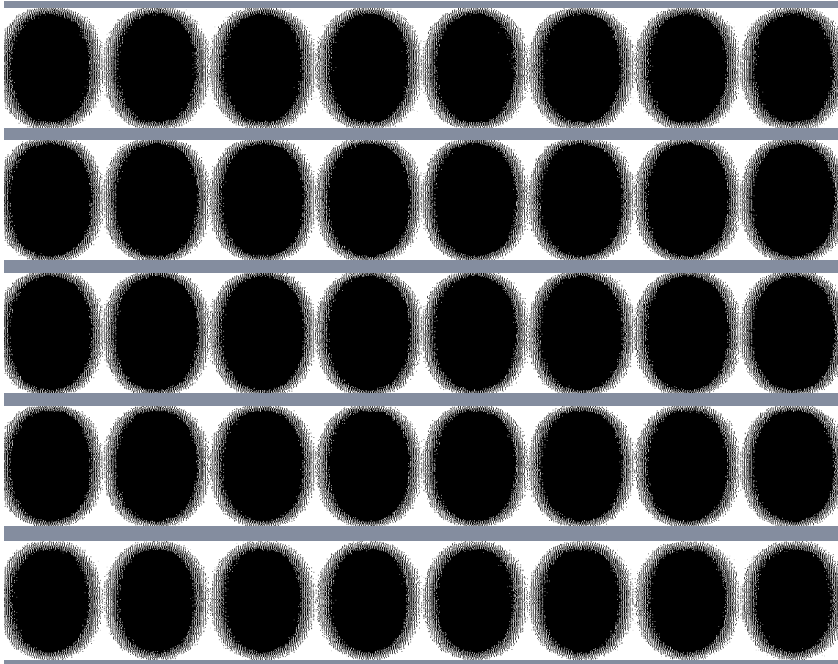


Figure 64. Showing that the volume slices are consistent the whole way through, so this method gives full control of volumetric gradients.

Discovery/Reflection

This final experiment provides a workflow that fulfils all of the design criteria. It is an efficient and easy to use workflow that allows for full desired control to create full volumetric gradients. (This will be further discussed in the final design and conclusion chapters of this study).

MRI MANIPULATION TOOL

Izzy Robb, another MDI student researching strategies of voxel printing medical imaging data, approached me and asked if I could find a way to allow her to better manipulate medical datasets. Izzy was interested in the value of medical data as an object, and wanted a way to cut 3-dimensional forms from medical dataset volumes. The resulting volume then being sliced for voxel printing.

Prior to this research digital manipulation of medical imaging datasets was limited to just 3DSlicer and Photoshop. 3DSlicer is an open source software for medical imaging (Fedrov et al., 2022) with this software medical datasets, whether they come as a volume or a stack of images, can be opened as a volume to be manipulated.

These medical datasets tend to be greyscale, with the greyscale value corresponding to the density of the scanned parts of the body. 3DSlicer allows for these datasets to be coloured by mapping a coloured gradient to the greyscale gradient of the original dataset (hence the greyscale values are replaced with corresponding colour values). 3DSlicer can then be used to cut out a section, however it is limited to only cutting out cuboid sections. The final volume is then output as a stack of image slices.

Photoshop is then used simply to crop and resize the stack of images to match the resolution of the printer. Finally, the images are dithered with Photoshop so that they only contain the colours that correspond to the J850s materials (Morris, 2020).

This workflow limited the manipulation available on medical datasets just to colouring, trimming and resizing. In order to cut a more complex 3-dimensional form using this workflow would require the manual cropping of hundreds to thousands of image slices individually, so is not a workable solution.

So we needed a tool that would allow medical image stacks to be sampled as a 3D volume that can then be cut with complex 3D forms. The following will be a selective list of the major milestones of the development of this tool.

Format of Experiments

Screenshot of the resulting point cloud in 3D space

This gives a visual understanding of the volumetric medical dataset in 3D space.

Selection of voxel slice PNG images from the output stack

The images of the layer slices once the volume has gone through the Voxel Slicer. Since the pixel colour corresponds directly to a printed voxel material, these slices can be used to assess the efficacy of each experiment. These will be used where applicable.

Description of tools used

Briefly describe the workflow.

Analysis

Reflective paragraph outlining the insights gained from each experiment.

Other

Other images used where applicable to illustrate key points about the workflows.

Initial Design Criteria

Ties into current medical data printing workflows, so can sample a stack of image slices from 3DSlicer to create a volume for manipulation.

Limited required user inputs that a non-Houdini user can follow with simple instructions.

Flexible and reusable allowing any image stack to be sampled and cut by any given geometry.

Produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

PHASE ONE – SAMPLING IMAGE STACK SET-UP

This workflow begins with a 2D plane (sampler grid), we use the points of this plane to copy the image slice colour data to. Users enter the number of slices, X-resolution, Y-resolution and DPI of their image slices, the sampler grid is then generated to the right size and resolution for their image stack.

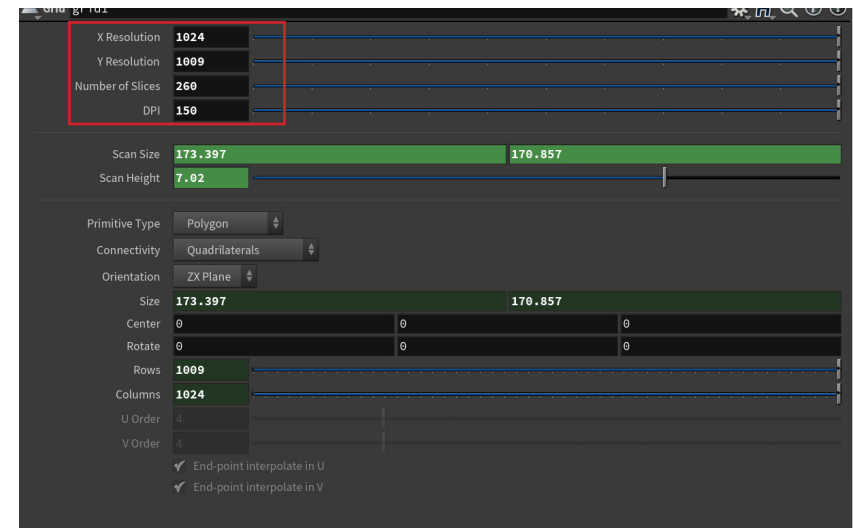


Figure 65a. Sampler Grid user inputs

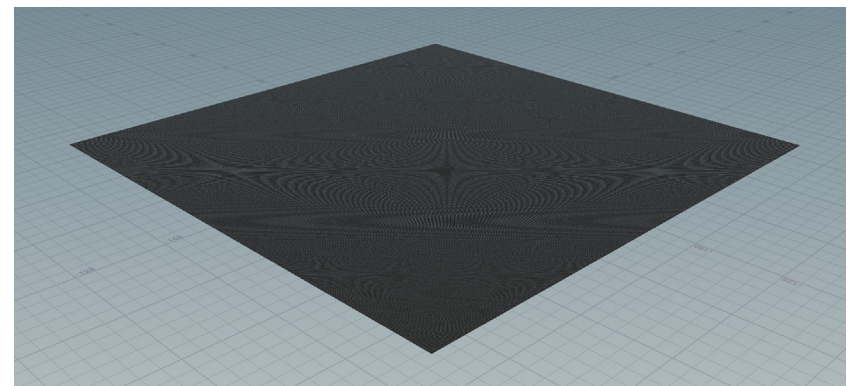


Figure 65b. Resulting sampler grid points.

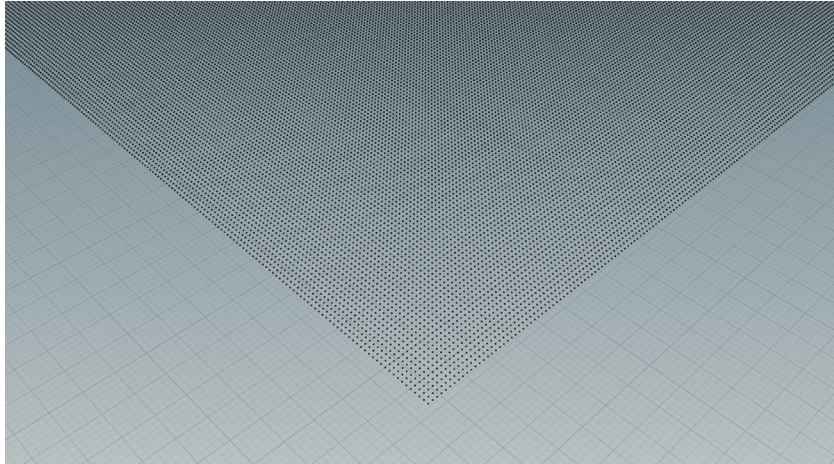


Figure 65c. Resulting sampler grid points close up. There is one point for every pixel in the dataset images.

A pair of attribute from map nodes are used to sample the image slices, one for colour, one for alpha. Users find the first image in their stack with the file directory in these nodes, then replace the number in its filename with:

```
`detail("../Loopmeta1/", "ivalu", 0)`
```

This is a detail function and tells the loop which image in the stack to sample based on the loop iteration that's running.

The colour and alpha information are then copied to the sampler grid, and the transparent parts of the image are removed (pixels from the stack image that have zero alpha). This essentially removes that transparent background of the images where we don't want voxels to be printed.

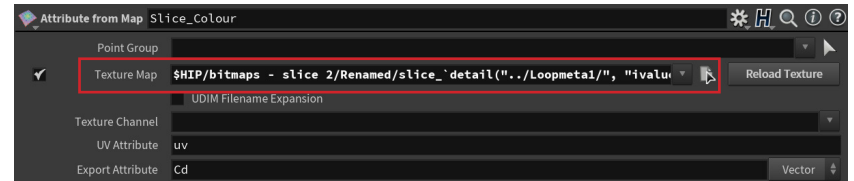


Figure 66a. File directory used to link an image from the dataset stack. Then the image number is replaced with the detail function in order to run the loop and import the full dataset. The colour of the selected image is copied to the sampler grid and displayed in the viewport.

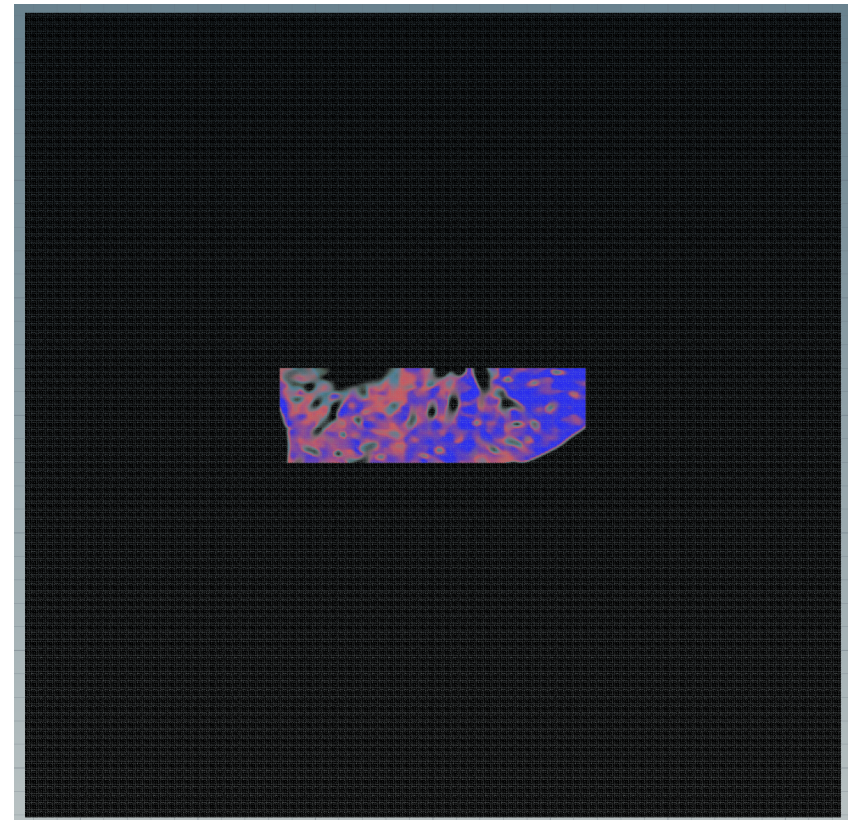


Figure 66b. Result of setting the colour side of the sampler grid.

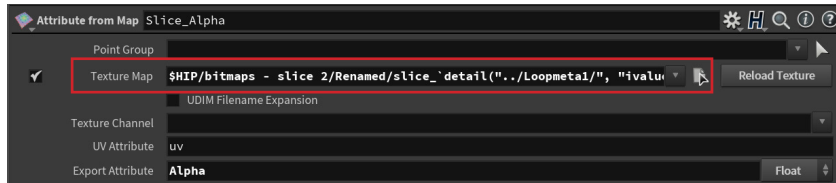


Figure 67a. File directory used to link an image from the dataset stack. Then the image number is replaced with the detail function. This is reading the image alpha, the alpha is copied to the sampler grid and displayed in the viewport as a greyscale image.

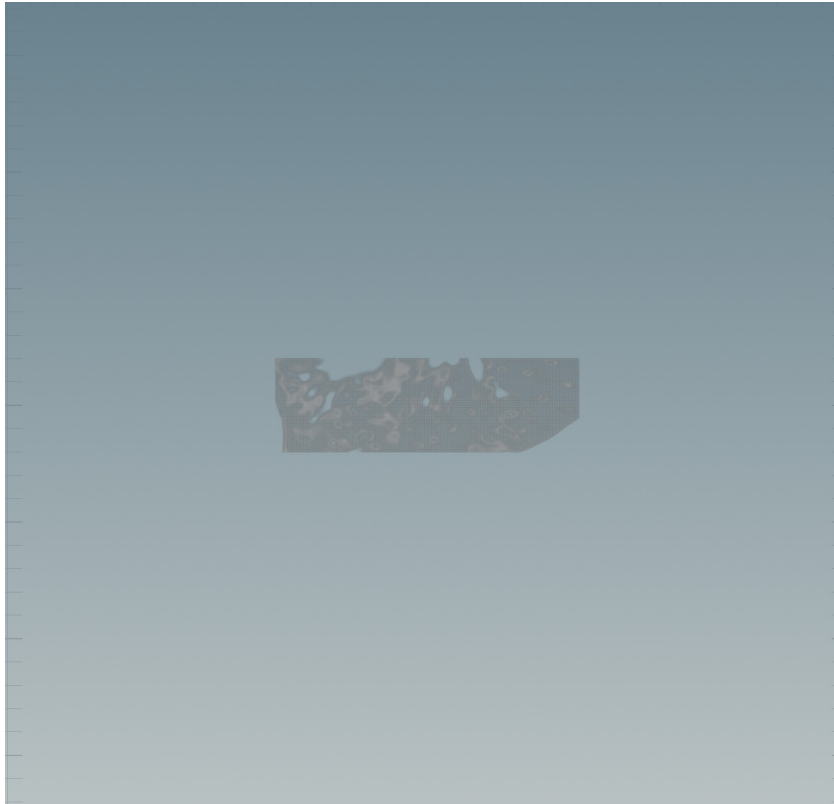


Figure 67b. Result of setting the alpha side of the sampler grid.

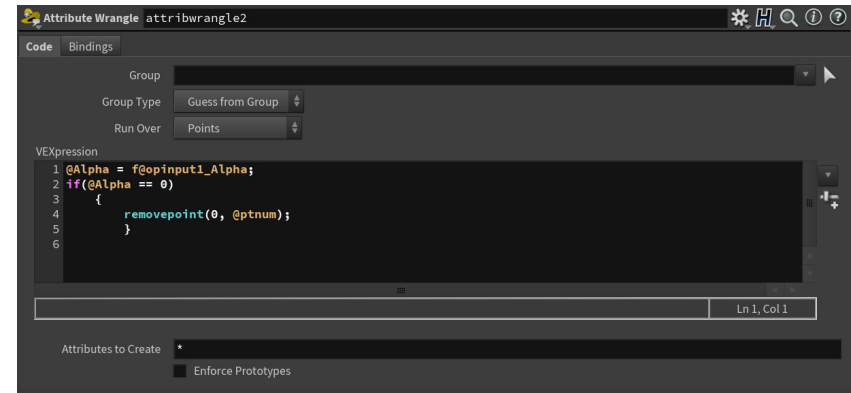


Figure 68. This code uses the alpha input to remove the points with 0 alpha from the image (so the transparent background) and removes the black background points.

This system is then run through a 'for loop', which repeats a set of instructions for a given set of iterations (defined by user input number of slices). For each image slice in the stack this loop repeats the above steps, moving the sampler grid up 0.027mm (the J850s layer height) between subsequent layers. This results in a 3D point cloud of the image stack dataset.

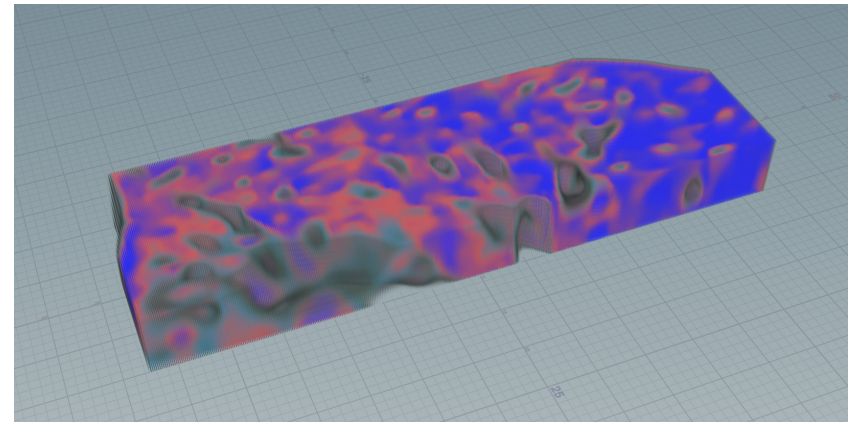


Figure 69. The resulting point cloud produced from the for loop importing the whole dataset.

PHASE TWO – PRODUCING A VOLUME

During this phase I explored how to take the point cloud that the loop was generating and translate it into a volume so that it could be sampled by the Voxel Slicer to produce PNG images for voxel printing.

To do this I made a cube with the same X and Y size as a single pixel of the dataset images and a Z height of 0.027mm, the size of one print layer and the gap between our point cloud layers. Making them this exact size means no data would be lost in the transition to a volume. The cube was copied to every point in the point cloud, inheriting the point colour.

Discovery/Reflection

Although the for loop takes a while to run, it works consistently and seems like a really effective way to generate a volumetric point cloud.

This works using only a few user inputs, the information on the starting grid and the images into the attribute from map node. So it is an effective way to procedurally sample a dataset, without needing any Houdini expertise.

Currently this point cloud isn't an output that can be sampled by the Voxel Slicer, need to find a way to translate this point cloud into a volume to do so.

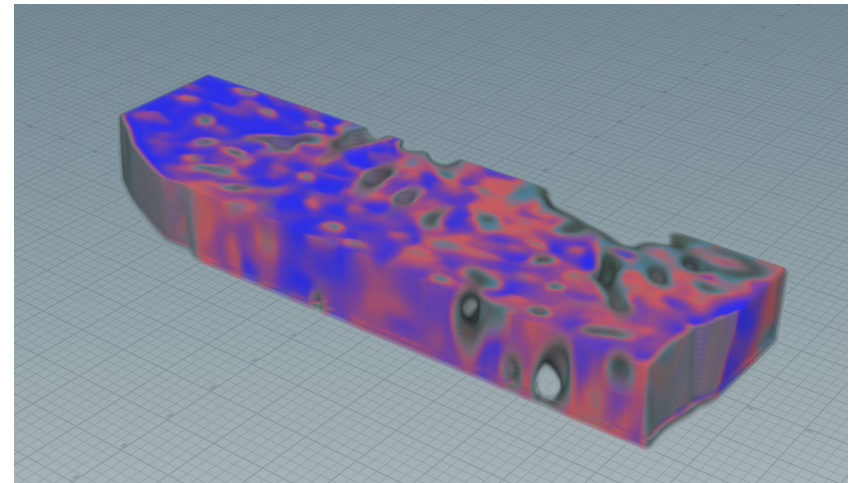


Figure 70. Pointcloud generated from dataset in phase 1.

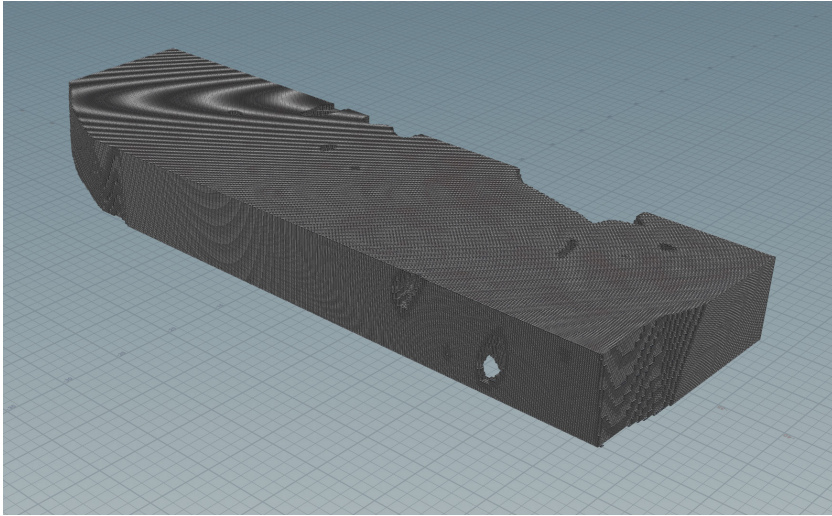


Figure 71a. Cubes copied to every point in the pointcloud.

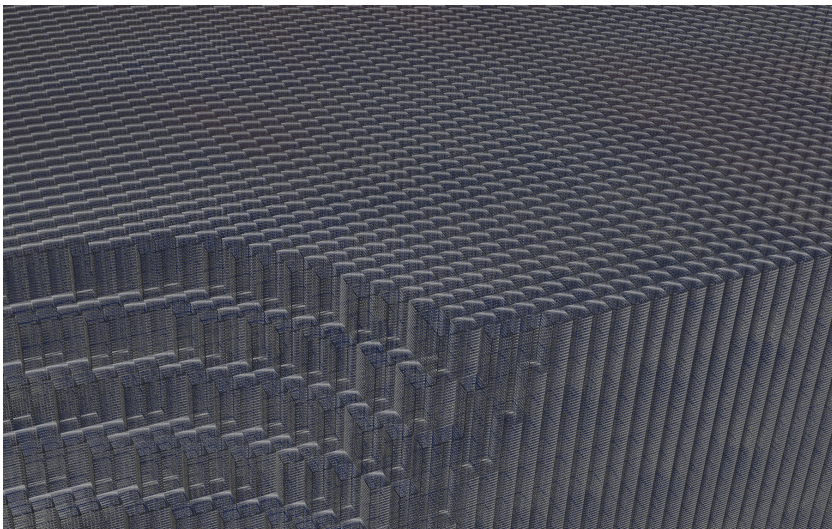


Figure 71b. Close up of copied cubes. You can barely see the colour since there are so many, however each of these cubes inherit the colour of the point to which they are copied.

The resulting stack of cubes was run through the VDB from polygons node, translating it into a volume to be sampled by the Voxel Slicer.

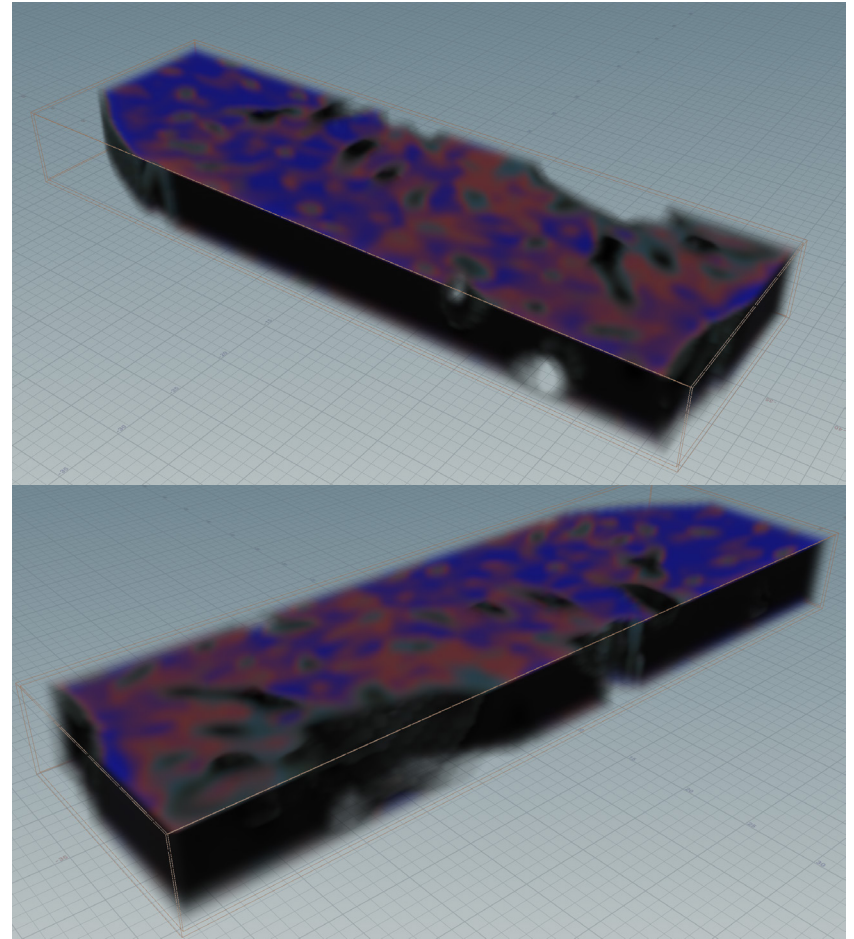


Figure 72. Volume produced.

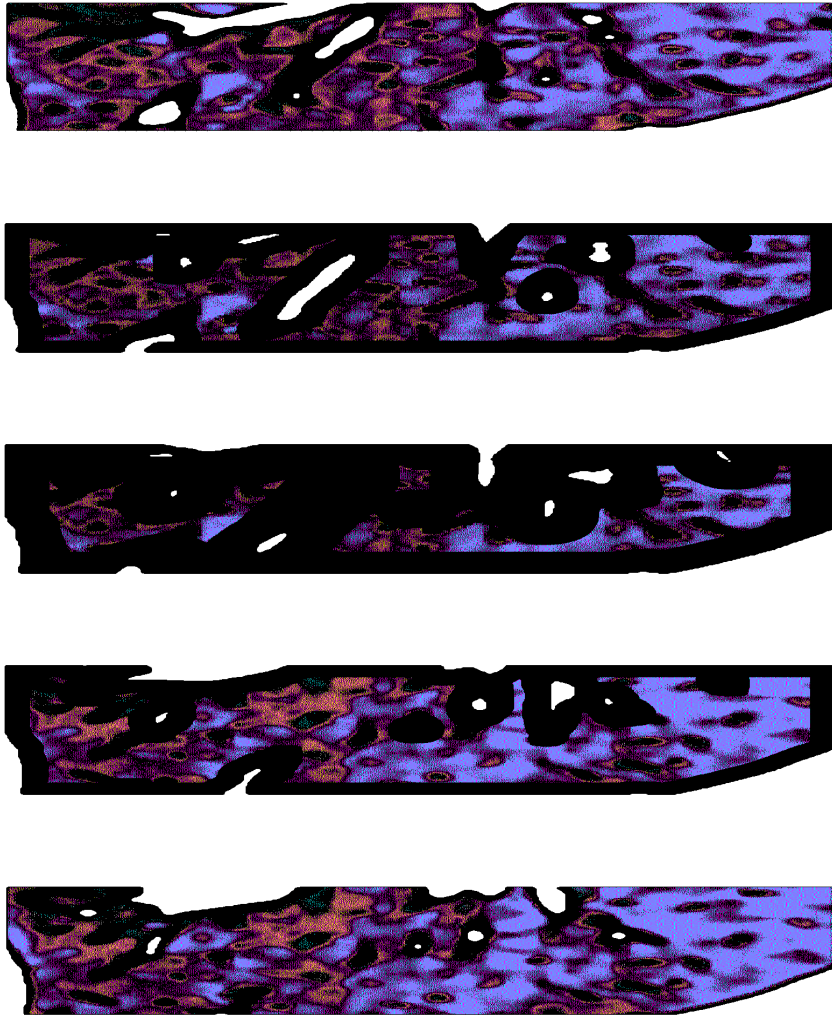


Figure 73. Slices from the Voxel Slicer. Same slices selected as figure74.

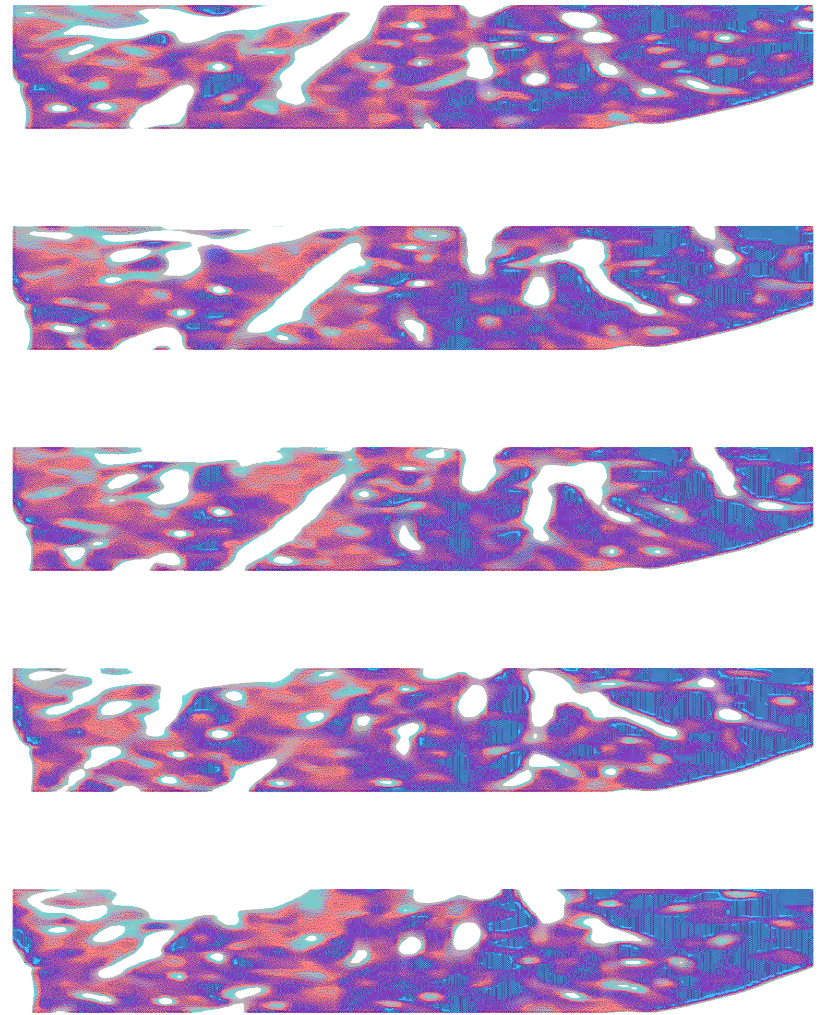


Figure 74. Slices dithered using photoshop method.

You can see from the selected slices above that the voxel PNG slices coming from the Voxel Slicer are quite different to those from the same dataset using the Photoshop dithering method. The Voxel Slicer images have a lot of large black areas around the edges of the holes in the volume, some of this is even filling in the holes that are clearly there in the original and Photoshop slices. This black banding extends towards the centre of the volume, this suggests these volumes are being affected by the tapering problem discussed in the previous section.

Discovery/Reflection

The method of copy cubes to the points in the point cloud and using those to make a volume is very slow and computationally intensive, it seems best to consider other options for making volumes from point clouds.

All of the black banding seen in the voxel slices is problematic because it is removing the data from the input dataset, not giving the desired result. This is either a problem with how the volumes are being made or an issue with the Voxel Slicer itself.

PHASE THREE – CUTTING THE VOLUME

This phase was the first attempt at cutting the volume using another imported geometry. Here an 3D object file (obj) of a fork was added into the tool, sized and position so it sat within our dataset volume, then transformed into a volume itself. The resulting fork volume and dataset volume were combined using a combine VDB node, this made a volume from the areas they intersected.

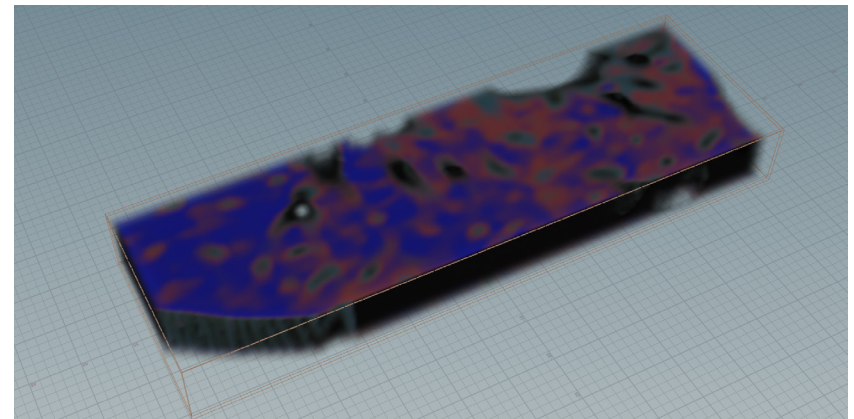


Figure 75. Dataset volume.

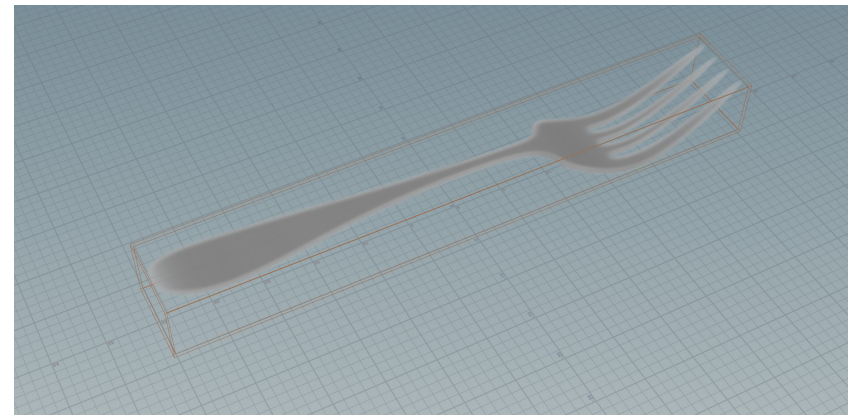


Figure 76. Fork volume.

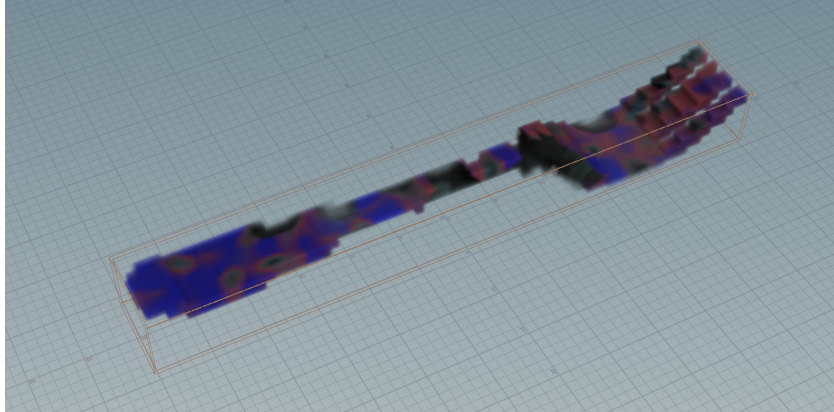


Figure 77a. Combined volume.

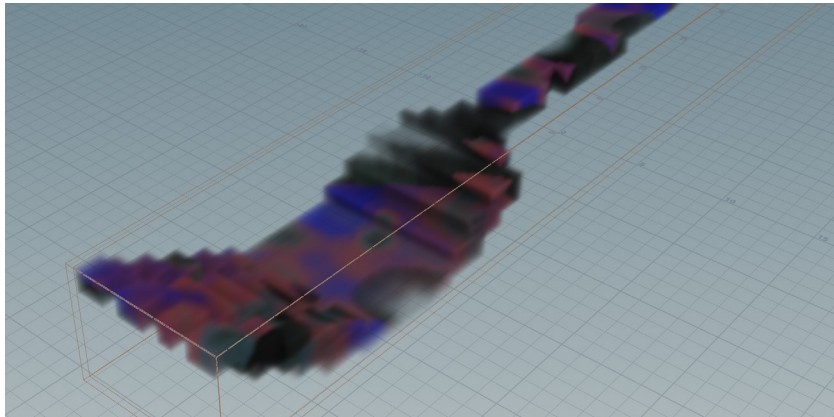


Figure 77b. Combined volume, close-up.

Discovery/Reflection

The resulting cut volume was really rough, though it allowed us to cut the volume as we desired to, when we attempted to slice this file and put it through the Grabcad print software it gave geometry that was full of holes and basically unprintable. So this method doesn't give us the desired output for voxel print slicing.

It appears that this strategy for producing volumes from the dataset point cloud is point cloud is problematic and I needed to devise a new strategy for producing volumes from point clouds.

PHASE FOUR – PYRO RASTERIZATION METHOD

This phase coincided with my discovery that a combination of the pyro source and volume rasterize attributes nodes worked incredibly well for producing volumes from point clouds (discussed during material gradient phase 6 section). Recall from previously we need to just use the density, colour and mask attributes, and we rename density to A (alpha) as it is fed into the slicer. I set up the pyro rasterization workflow to create a volume from the dataset point cloud.

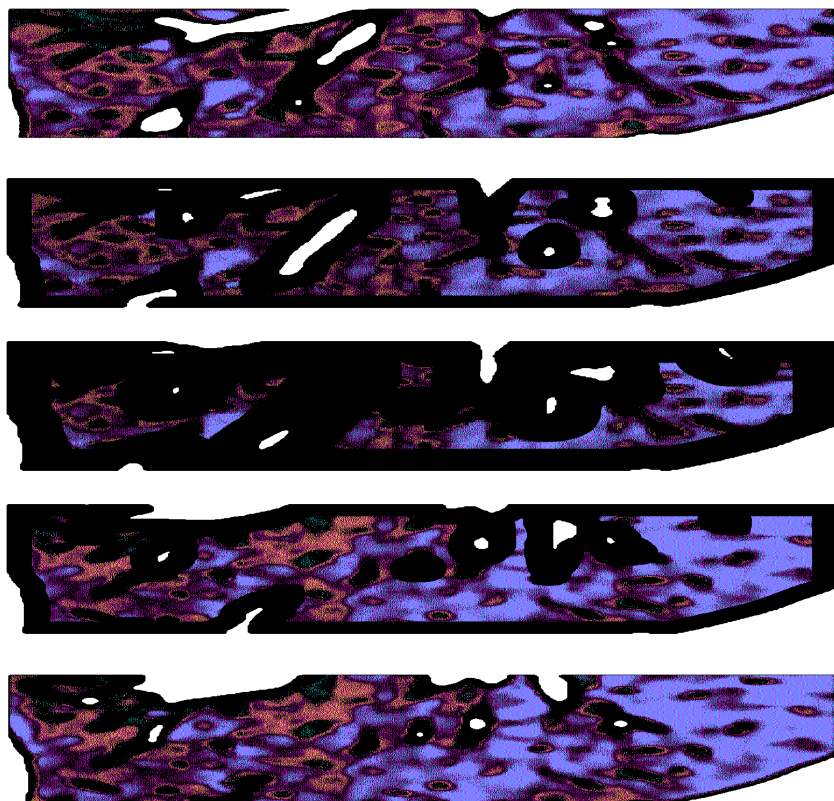


Figure 78. Slices from the volume produced in phase 2.

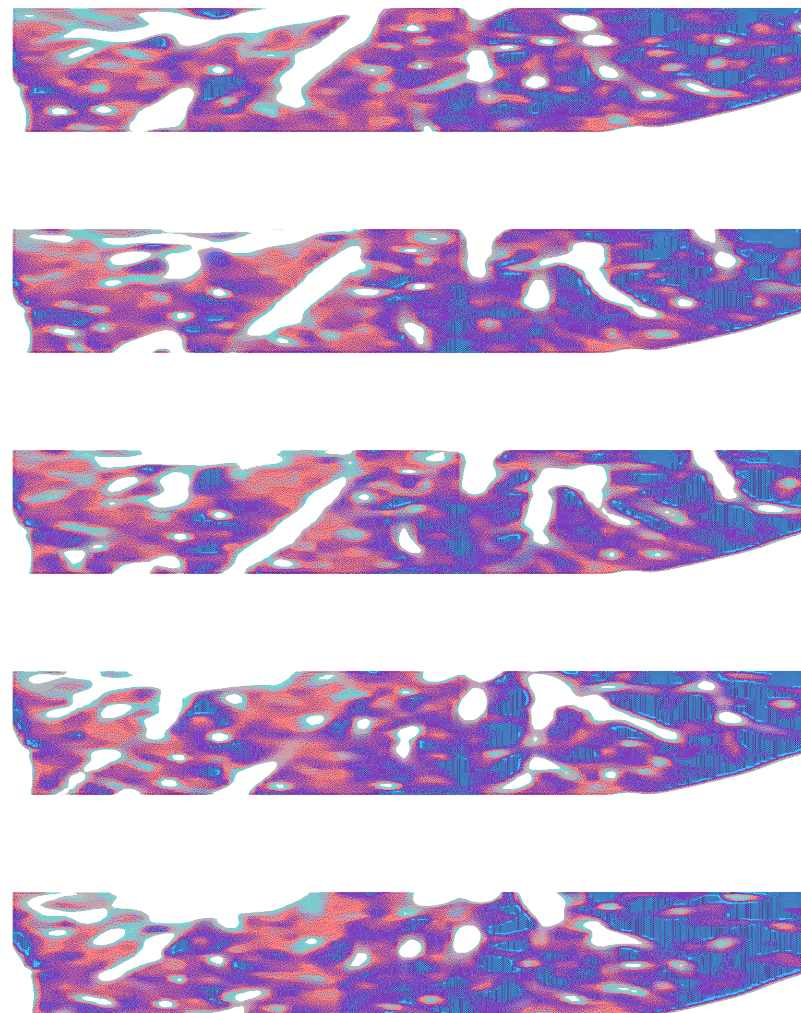
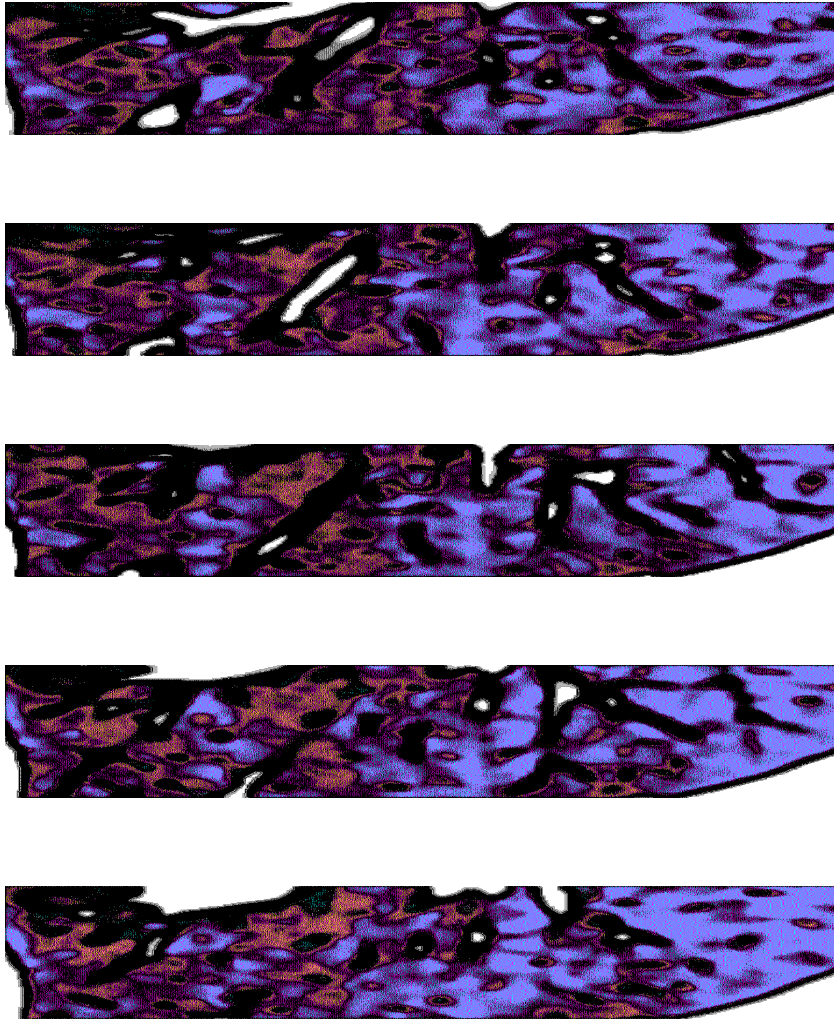


Figure 79. Slices dithered using photoshop method.



In the slices we are still getting a lot of black as compared to the Photoshop method, however we are not seeing the tapering problem the same as in the phase two slices, where the black outer bands expand through most of the volume in the centre.

Discovery/Reflection

The pyro rasterization method is much more efficient to create a volume from the dataset point cloud, the final volume is also more consistent and doesn't display the tapering problem.

The volume still has significantly more black areas than the Photoshop method, this could either be due to the Voxel Slicer using a slightly different process or there could still be problems in the volume.

Figure 80. Slices from the Voxel slicer using the pyro rasterisation method.

PHASE FIVE – ALPHA ADJUSTMENT

During this phase I discovered that the dataset point cloud had a lot of points that were very close to having a zero alpha value, but are just above zero. Our current workflow removes the points with a zero alpha value, but appears to be leaving some which are basically transparent. These close to zero alpha points are made black by default in Houdini so explain why we were seeing so much extra black in the voxel slices where there should be holes in the dataset. I added a point alpha adjust using a wrangle:

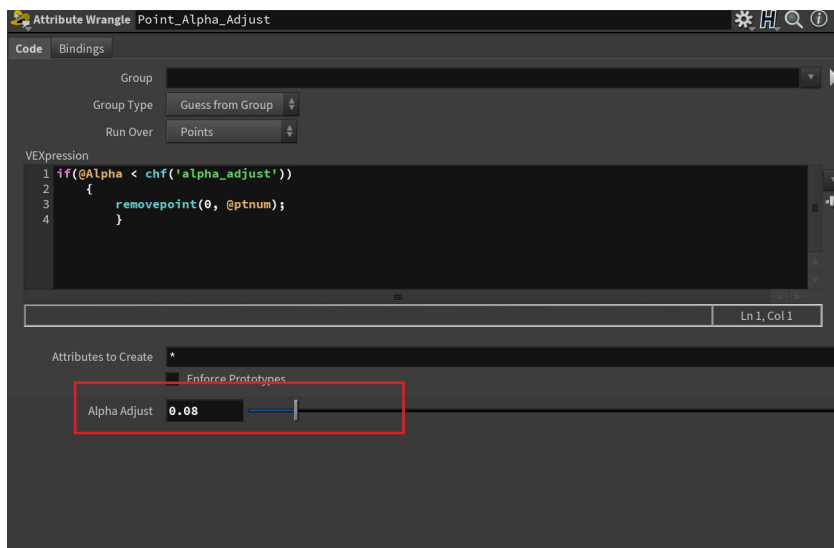


Figure 81. Alpha adjust slider. Users adjust this value to alter the alpha threshold for points that are removed. These are points that have an alpha value just above zero and aren't part of the dataset and need to be removed. As this is adjusted the point cloud visually updates so the user adjusts until they are happy with the resulting point cloud volume (it can also be increased to decimate the dataset if that is the desired result).

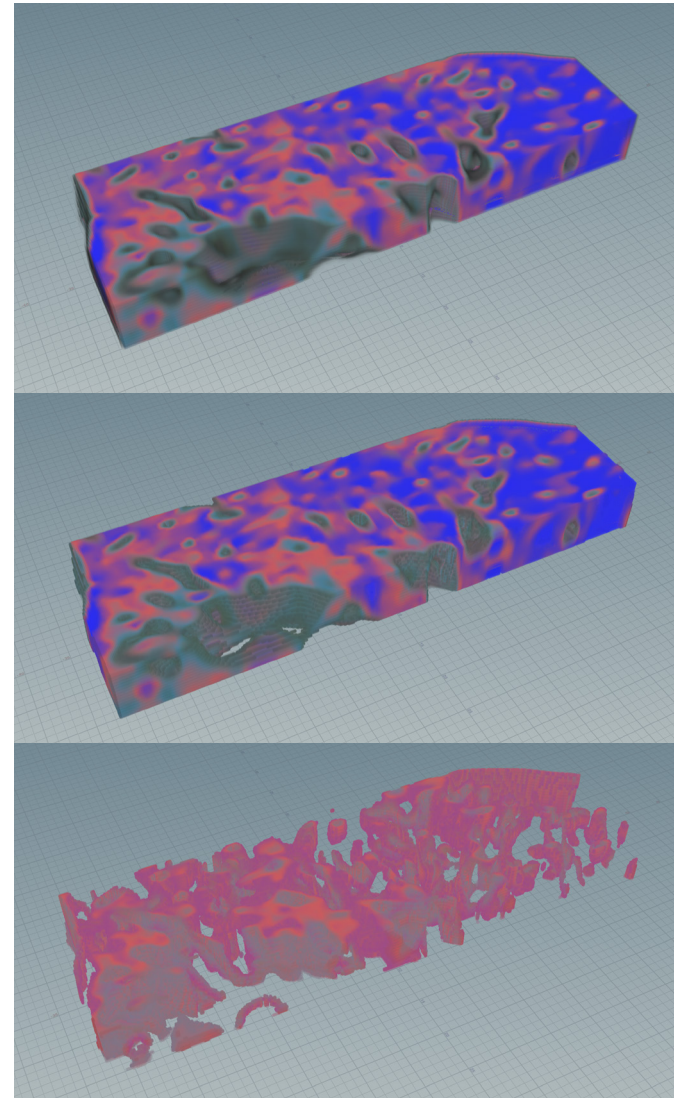


Figure 81. Demonstrating alpha adjust. Top not adjusted, middle adjusted correctly & bottom adjusted too far so removing too much of the dataset.

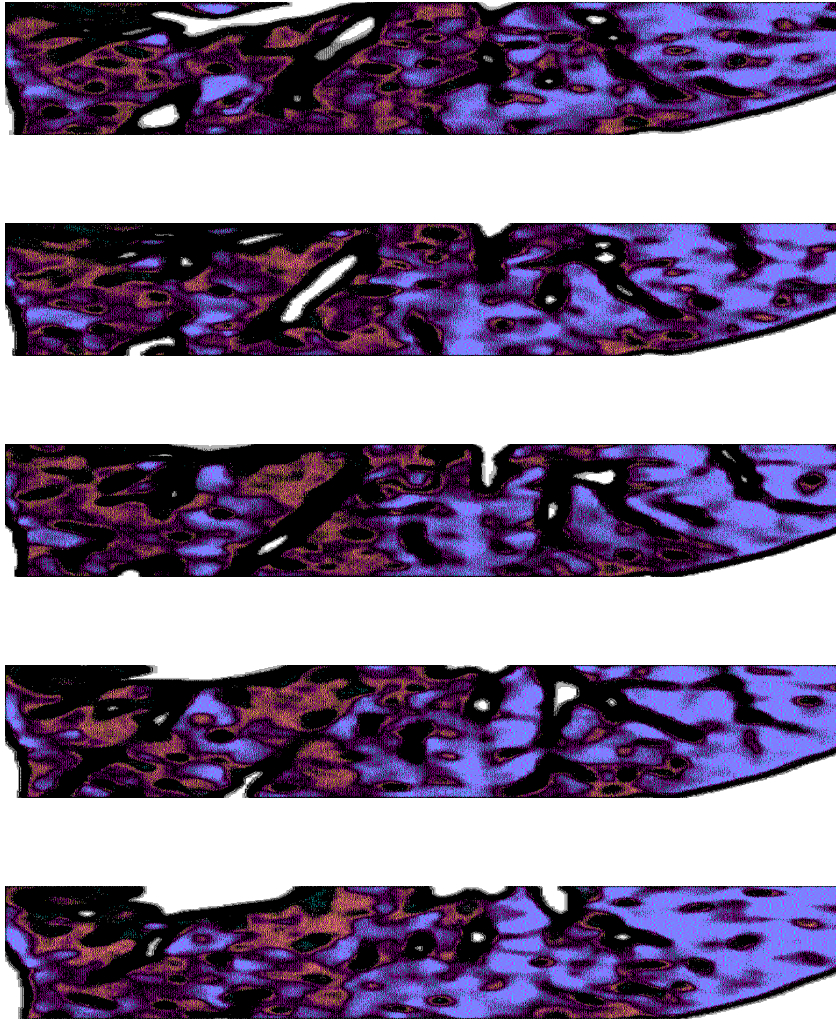


Figure 82. Slices from the Voxel slicer using the pyro rasterisation method.

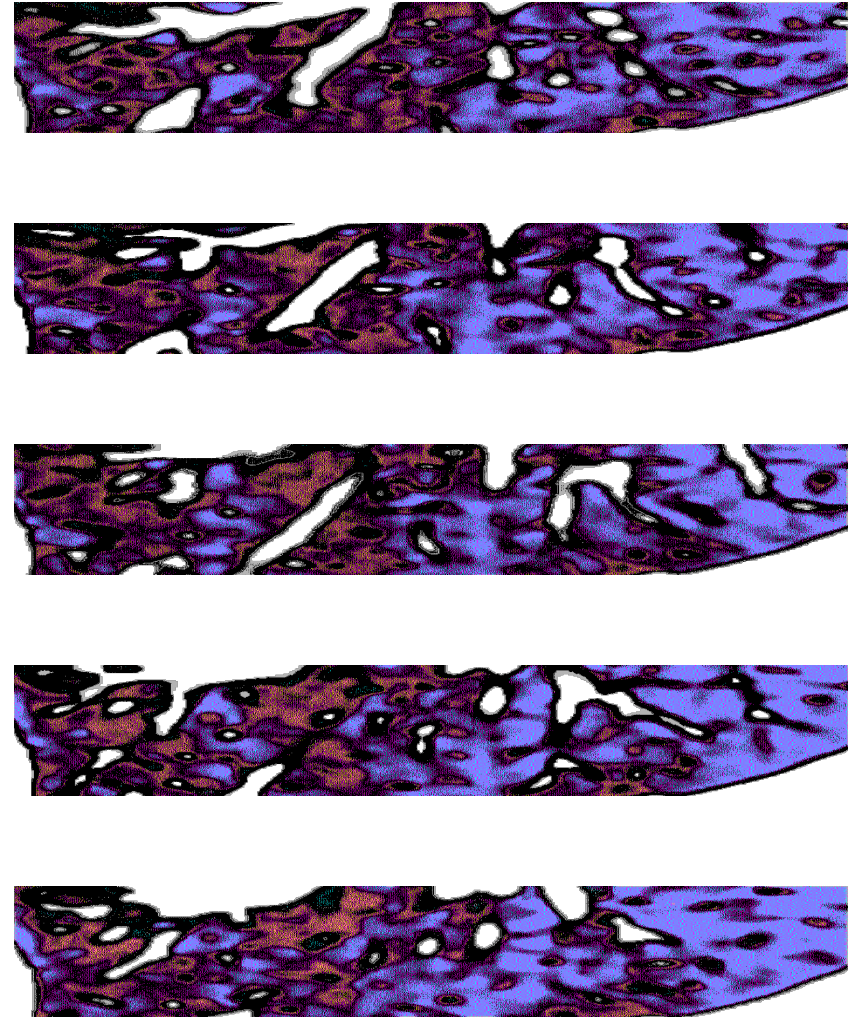


Figure 83. Slices from from pyro rasterisation method that have been alpha adjusted.

The slices show that there is a significant reduction in black areas where there should be holes in the dataset.

Discovery/Reflection

The alpha adjust can be used to fix the problems we have been having with the Voxel Slicer files up to this point. This allows for the dataset to be adjusted to meet the desired outcome. This is a user controlled slider as different datasets will need different levels of adjustment, it is up to user discretion as to how much.

While there is still a lot more black in these slices this is likely due to how the slicer deals with clear material, clear material is placed where there are colourless voxels in the input volume, not where there are grey voxels. It seems many of the grey pixels of the dataset seem to be set to black instead of grey for clear. Where the Photoshop method would make these grey since it will just match pixels to the closest colour value. So we see much more grey/clear areas in the Photoshop method and much more black in the Voxel slicer method.

At this stage Izzy expressed the desire to cut out quite sparse medical datasets and fill the background of the final cut objects with clear material.

Update Design Criteria

Ties into current medical data printing workflows, so can sample a stack of image slices from 3DSlicer to create a volume for manipulation.

Limited required user inputs that a non-Houdini user can follow with simple instructions.

Flexible and reusable allowing any image stack to be sampled and cut by any given geometry.

Produce a 3D volume that has all the data needed to be sampled by the Voxel Slicer to produce a stack of voxel print PNG images.

Ensure the system can fill the background of the output objects with Vero Clear.

PHASE SIX – FINAL CUT OUT VOLUME

During this final phase I was given a much more sparse dataset:

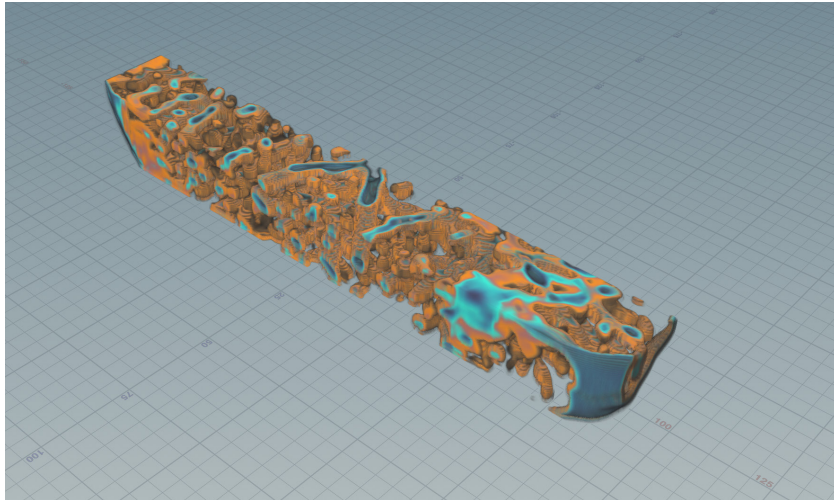


Figure 84. Sparse dataset point cloud.

The cutting geometry (here a fork) is input and transformed into a point cloud. Then the colour and alpha attributes from the dataset point cloud are transferred to the fork points.

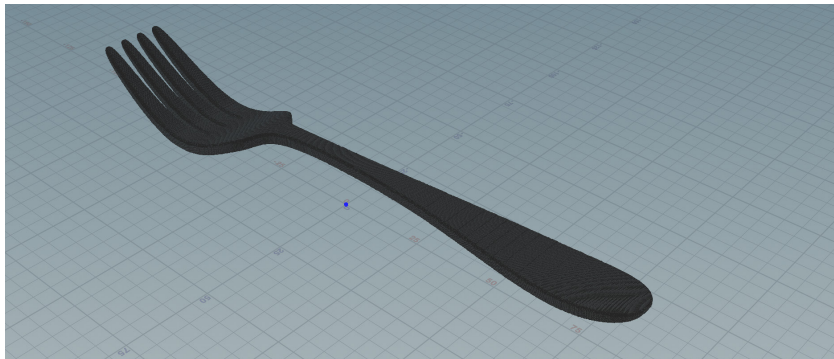


Figure 85. Cutting geometry point cloud.

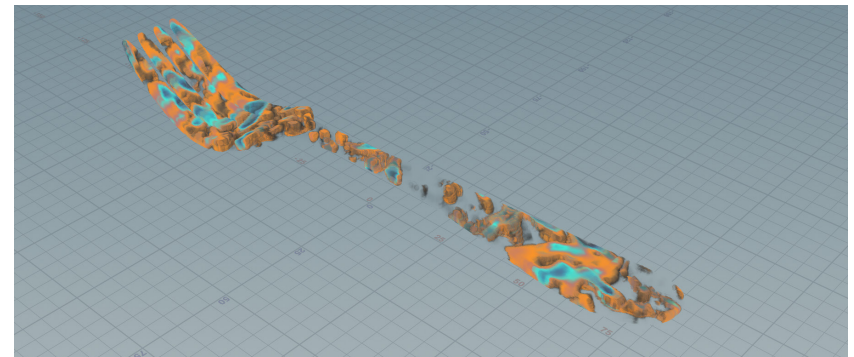


Figure 86. Colour and alpha attribute transfer from dataset to cutting volume.

The result is fed into the alpha adjust, which removes the unnecessary transparent points, making the point cloud more efficient for transformation into a volume.

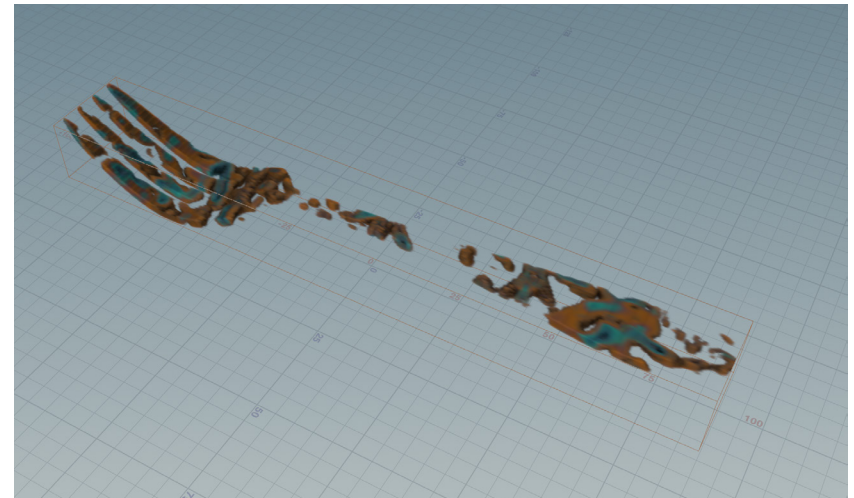


Figure 87. Colour volume from the resulting point cloud.

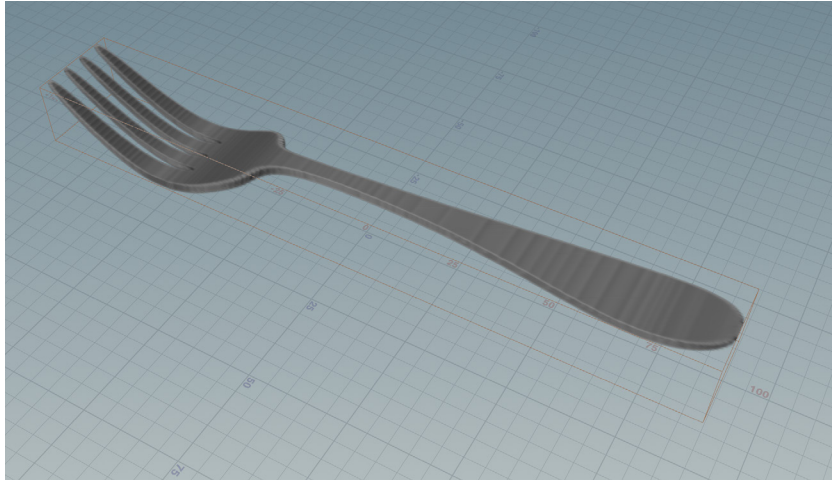


Figure 88. Colourless volume made from cutting geometry.

The two volumes we just made above (figure 87 & 88) are required for printing a cut dataset with a transparent background. The colourless volume made from the cutting geometry (fork) creates a transparent base so will print clear material where there are gaps in the colour volume. Both of these volumes are saved and imported into the voxel slicer file, the colour plugs into the left and the clear background into the right.

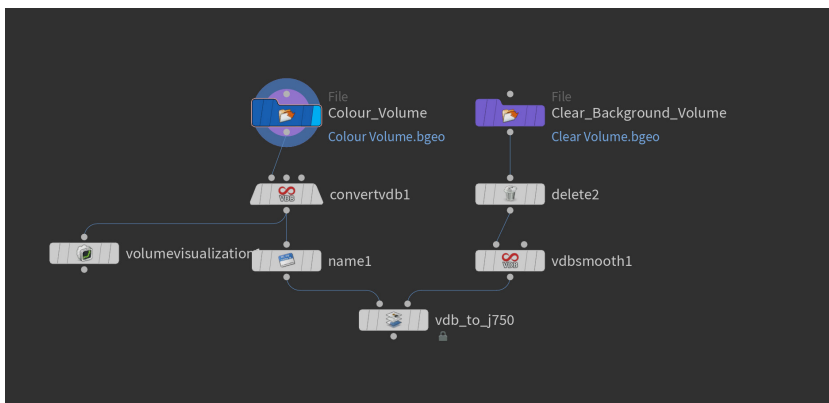


Figure 89. Voxel Slicer controls.

The final outcome is a set of slice files that contain the cut dataset within the transparent body of the cutting object.



Figure 90. Final slices of cut dataset in with clear background (the grey pixels are clear material). Due to the shape there is no slice that features the whole fork.

Discovery/Reflection

The final outcome of this development produced a tool that fulfilled all of the design criteria. It allowed Izzy with very little Houdini experience to create a set of objects containing complex medical datasets. (This will be further discussed in chapters 4 & 5 of this study).

3D PRINTING AND PROCEDURAL SOFT ROBOTICS

Part one of this section will document a selection of small scale voxel print test files. These tests were conducted to gain an understanding of the properties of gradient blended materials. Here I wanted to understand what gradient mixes of rigid Vero and soft Agilus effects elasticity and flexibility, or how reducing the density by printing air voids might affect the softness of printed objects.

Format of Experiments

Aim

The aim of each group of experiments will be outlined.

Relevant Settings & Measurements

This will outline the specific measurements/set-up of experiment as a means of comparison.

Selected Voxel Slice Image/Volume Slice

As a means to compare digital model with physical result.

Digital Model in 3D

As a means to compare digital model with physical result.

Photographs

Photographs of physical prints.

Discovery

Findings of the experiments.

Part two of this section will outline a procedural system that is set up to output a soft robotic grippers for automated fruit picking.

The goal of this system was not to produce the most impressive and effective soft robotic gripper ever conceived, rather the purpose of this system is twofold:

First, to give a contextual example as to how the previously outlined workflow for digitally controlling and voxel printing gradient materials can be utilised.

Second, to demonstrate how endlessly adjustable procedural systems can streamline the design of a diverse set of models. This endless adjustability means procedural systems are very adaptable, so one system can be used to design the solution to many different problems, hence this single system allows for the design of grippers for a variety of fruit.

Format of Section

This procedural system will be explained through a series of diagrams, looking at the user parameters and illustrating how they influence the generated geometry of the soft robotic gripper. Discussion and analysis of this system will be featured in the final design and conclusion sections of this study.

Design Criteria for Procedural System

Utilise gradient materials, demonstrating the gradient material workflow developed in this study.

Flexible enough that it allows for minor adjustments for rapid iteration prototyping and major adjustments so one system can be used to make grippers for multiple fruits.

Streamline the workflow to produce complex voxel printable models.

Procedurally generated from a set of controllable input parameters allowing for a diverse the design of a diverse range of grippers without requiring any 3D modelling.

GRADIENT TESTS

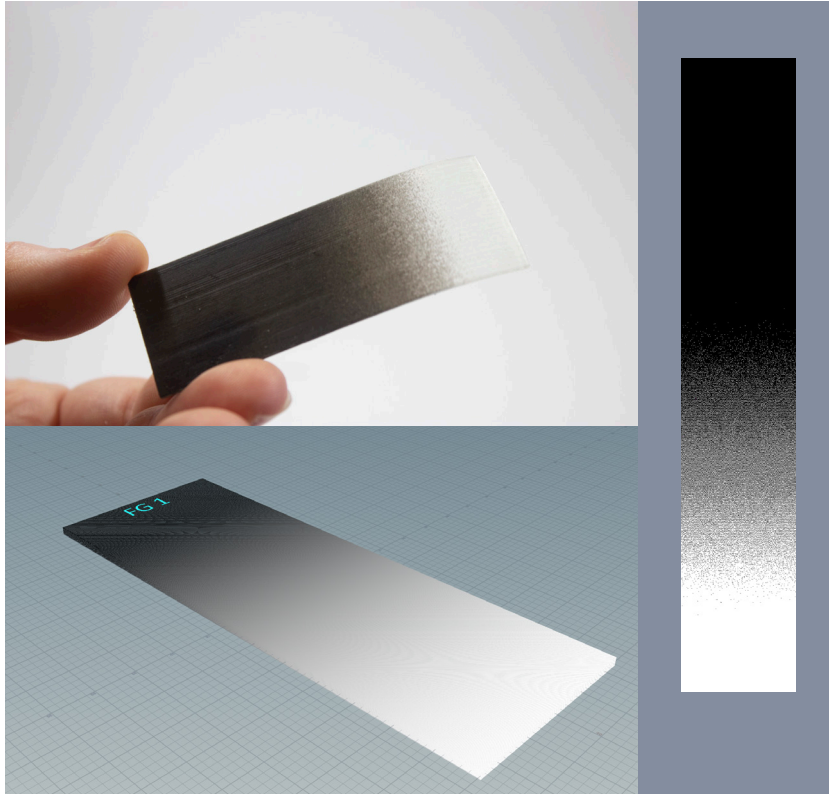


Figure 91. Floyd Steinberg gradient test 1.

Floyd Steinberg 1

Base

70mm x 25mm x 1mm

Effector Size

10mm x 25mm x 1mm

Effector Placement

100% overlap with base geometry.

Blend width

65

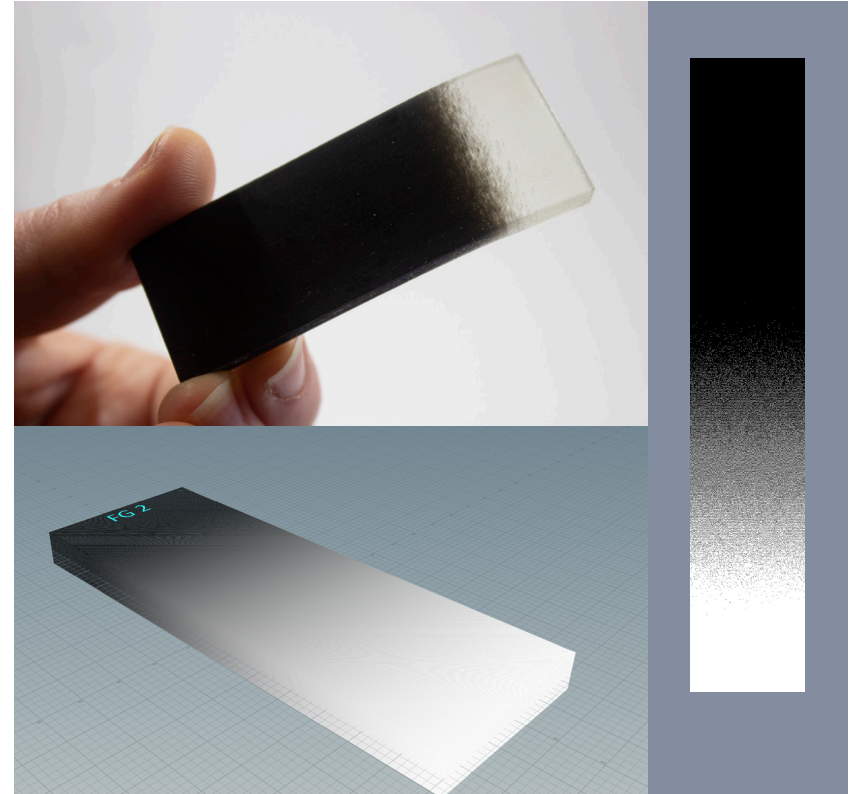


Figure 92. Floyd Steinberg gradient test 2.

Floyd Steinberg 2

Base

70mm x 25mm x 5mm

Effector Size

10mm x 25mm x 5mm

Effector Placement

100% overlap with base geometry.

Blend width

65

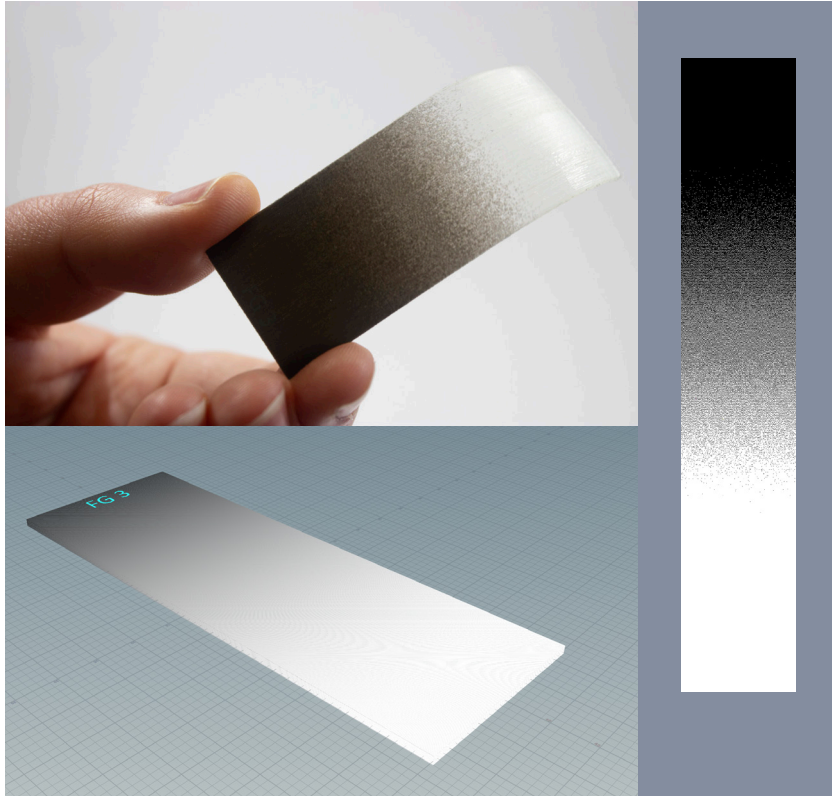


Figure 93. Floyd Steinberg gradient test 3.

Floyd Steinberg 3

Base

70mm x 25mm x 1mm

Effector Size

0.5mm x 25mm x 1mm

Effector Placement

10mm outside base geometry.

Blend width

75

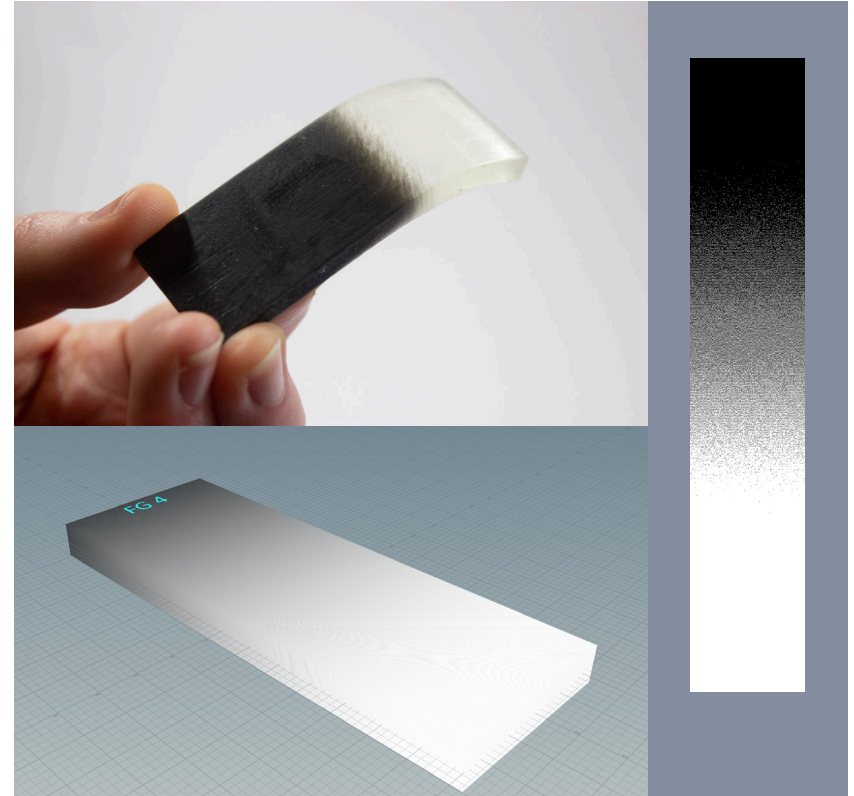


Figure 94. Floyd Steinberg gradient test 4.

Floyd Steinberg 4

Base

70mm x 25mm x 5mm

Effector Size

0.5mm x 25mm x 5mm

Effector Placement

10mm outside base geometry.

Blend width

75

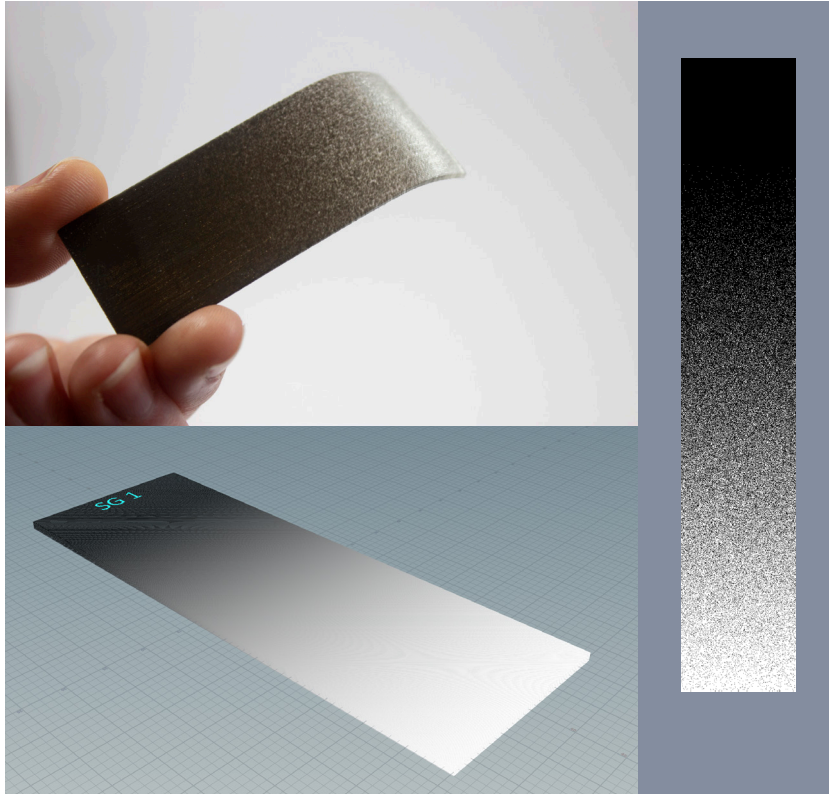


Figure 95. Stochastic gradient test 1.

Stochastic 1

Base

70mm x 25mm x 1mm

Effector Size

10mm x 25mm x 1mm

Effector Placement

100% overlap with base geometry.

Blend width

65

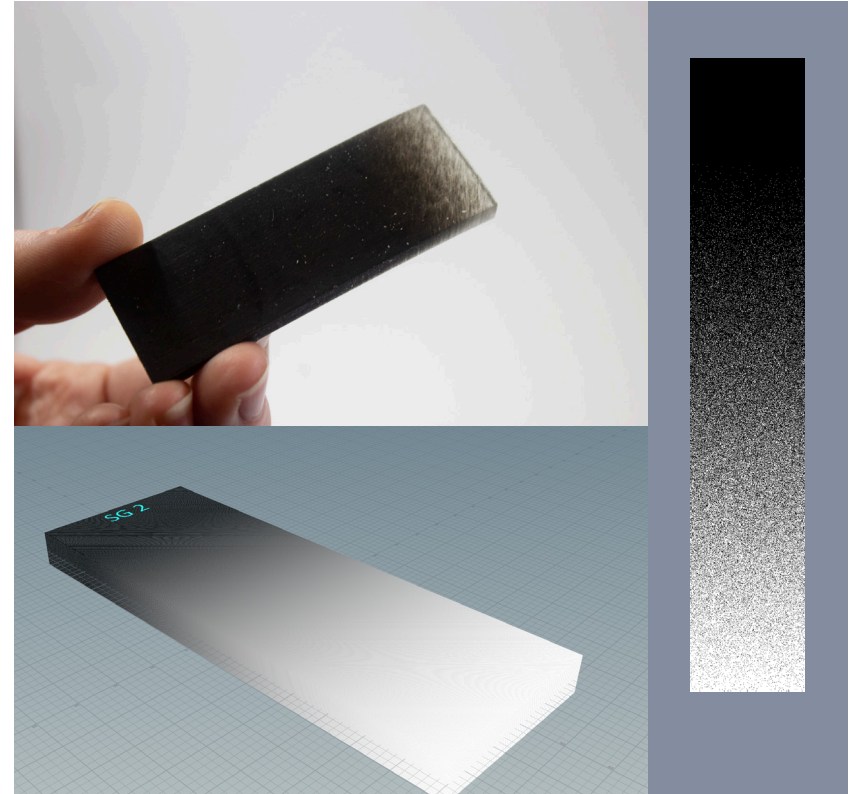


Figure 96. Stochastic gradient test 2.

Stochastic 2

Base

70mm x 25mm x 5mm

Effector Size

10mm x 25mm x 5mm

Effector Placement

100% overlap with base geometry.

Blend width

65

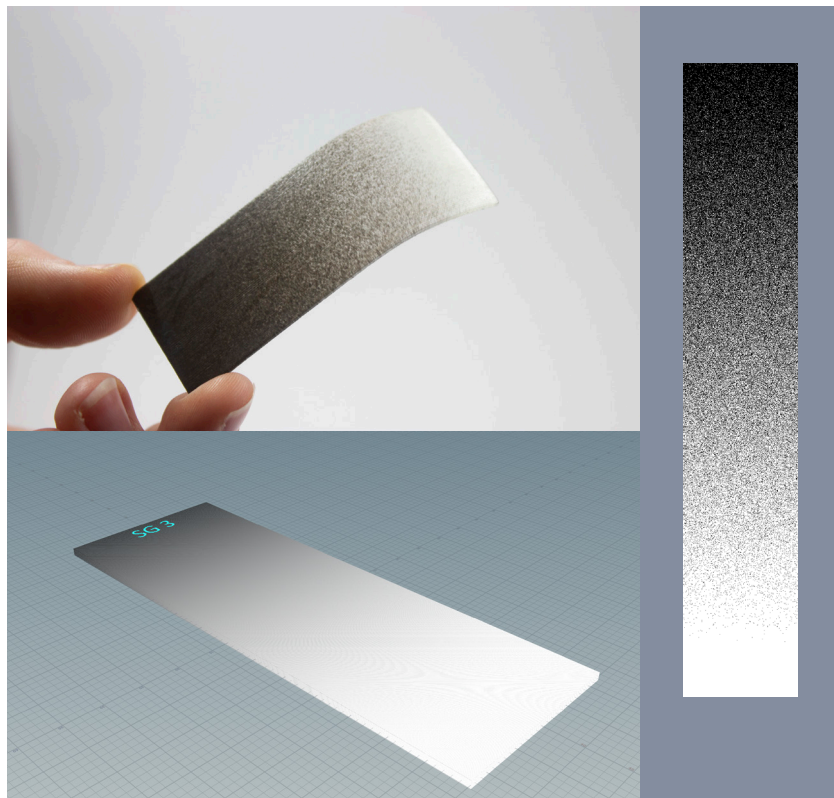


Figure 97. Stochastic gradient test 3.

Stochastic 3

Base

70mm x 25mm x 1mm

Effector Size

0.5mm x 25mm x 1mm

Effector Placement

10mm outside base geometry.

Blend width

75

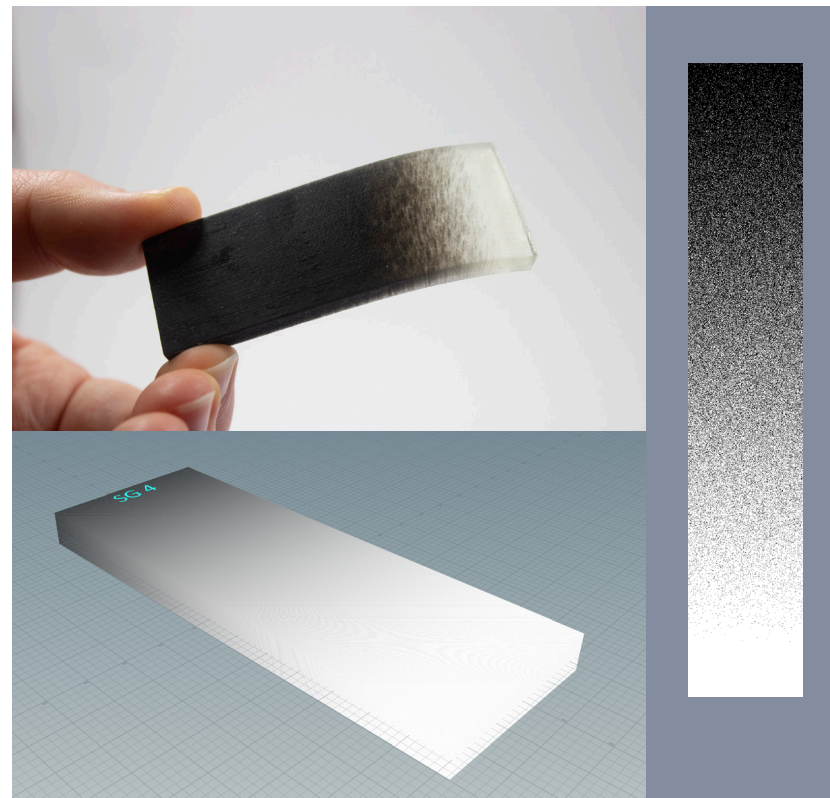


Figure 98. Stochastic gradient test 4.

Stochastic 4

Base

70mm x 25mm x 5mm

Effector Size

0.5mm x 25mm x 5mm

Effector Placement

10mm outside base geometry.

Blend width

75

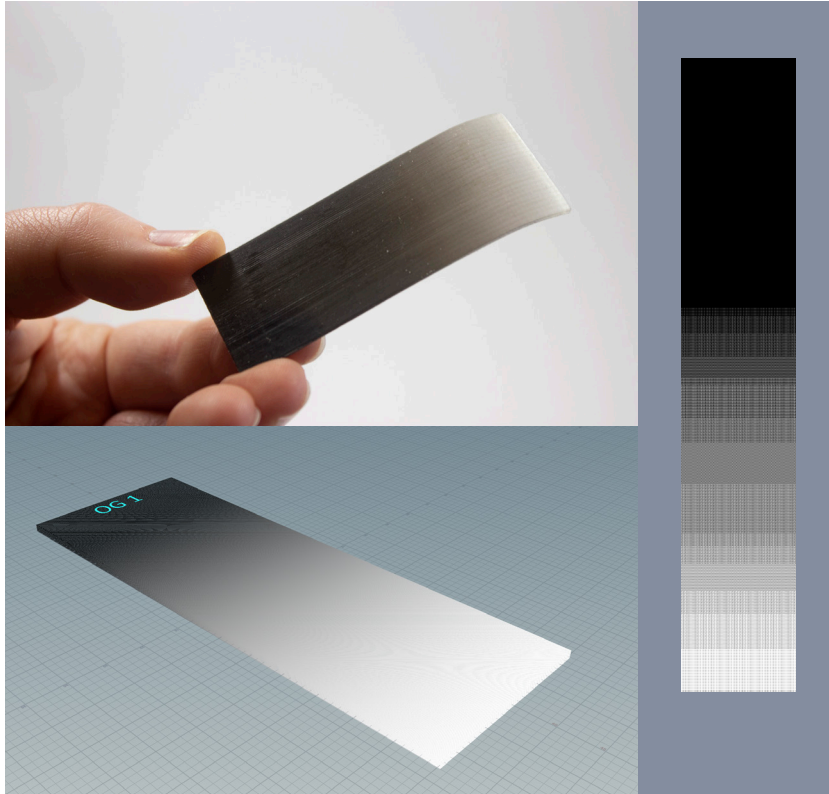


Figure 99. Ordered gradient test 1.

Ordered 1

Base

70mm x 25mm x 1mm

Effector Size

10mm x 25mm x 1mm

Effector Placement

100% overlap with base geometry.

Blend width

65

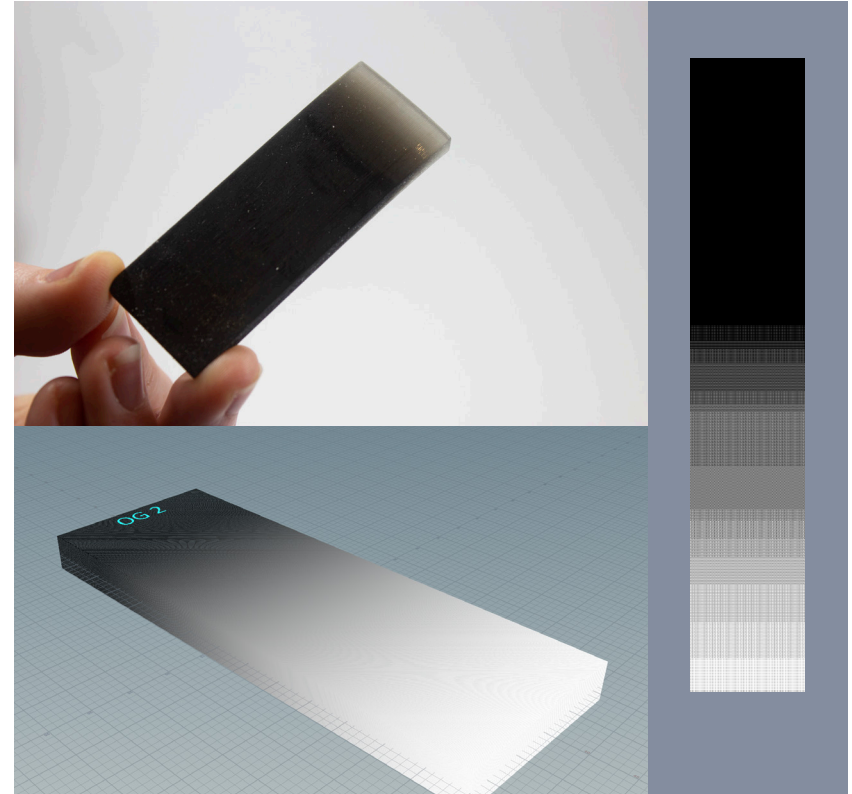


Figure 100. Ordered gradient test 2.

Ordered 2

Base

70mm x 25mm x 5mm

Effector Size

10mm x 25mm x 5mm

Effector Placement

100% overlap with base geometry.

Blend width

65

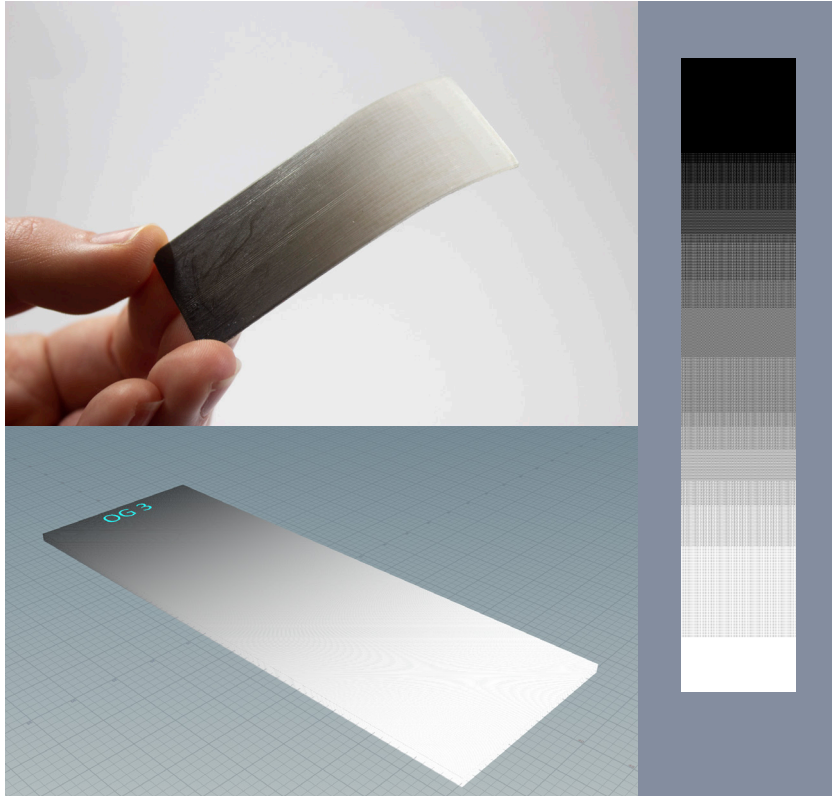


Figure 101. Ordered gradient test 3.

Ordered 3

Base

70mm x 25mm x 1mm

Effector Size

0.5mm x 25mm x 1mm

Effector Placement

10mm outside base geometry.

Blend width

75

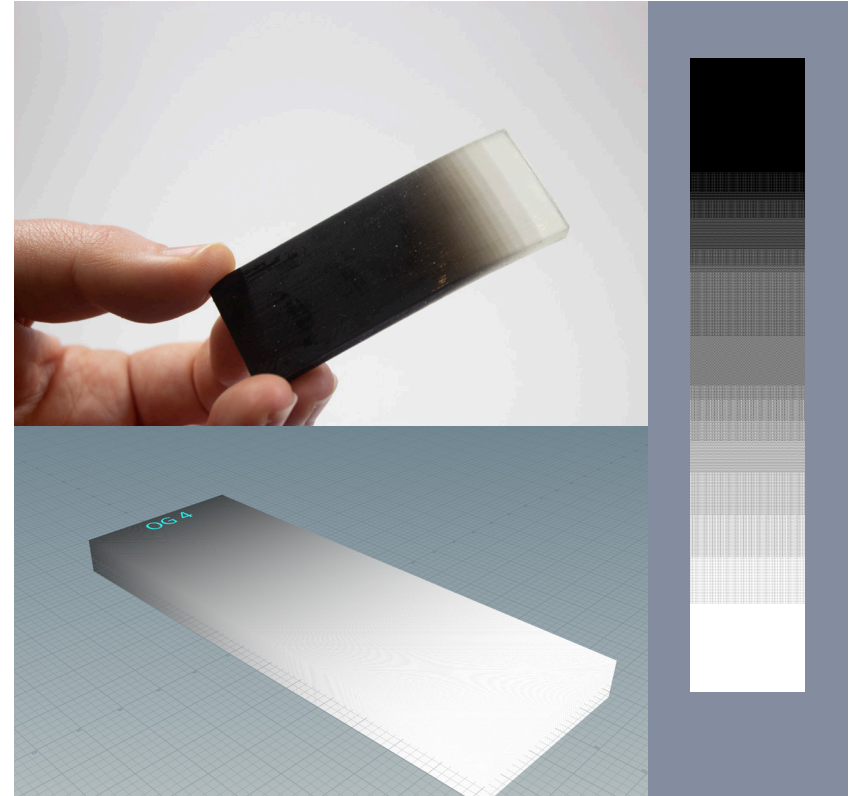


Figure 102. Ordered gradient test 4.

Ordered 4

Base

70mm x 25mm x 5mm

Effector Size

0.5mm x 25mm x 5mm

Effector Placement

10mm outside base geometry.

Blend width

75

Aims

To gain an understanding of the physical properties of printed gradients of material, comparing the on screen gradients to their results in flexibility and rigidity when printed.

To compare the different dithering styles available in the Voxel Slicer to see how they affected the PNG image slices produced and the physical properties of the printed outputs.

Discovery

The Vero tends to dominate the blends, prints become much darker and more rigid sooner than expected compared to the prints on screen counterparts. So the use of Vero should be pretty conservative to keep flexibility in parts with gradient materials.

Floyd Steinberg showed as being the style that allows for the most retention of flexibility, but it also shortens the material blend width the most. Ordered and Stochastic performed worse for keeping flexibility, with stochastic performing slightly worse. Ordered produces the smoothest gradients visually, the banding seen in the slices is less obvious in the printed result. The noise is very visually prominent in Stochastic and Floyd Steinberg prints, but perhaps this displays the voxel based nature of the prints better.

FOAM TESTS

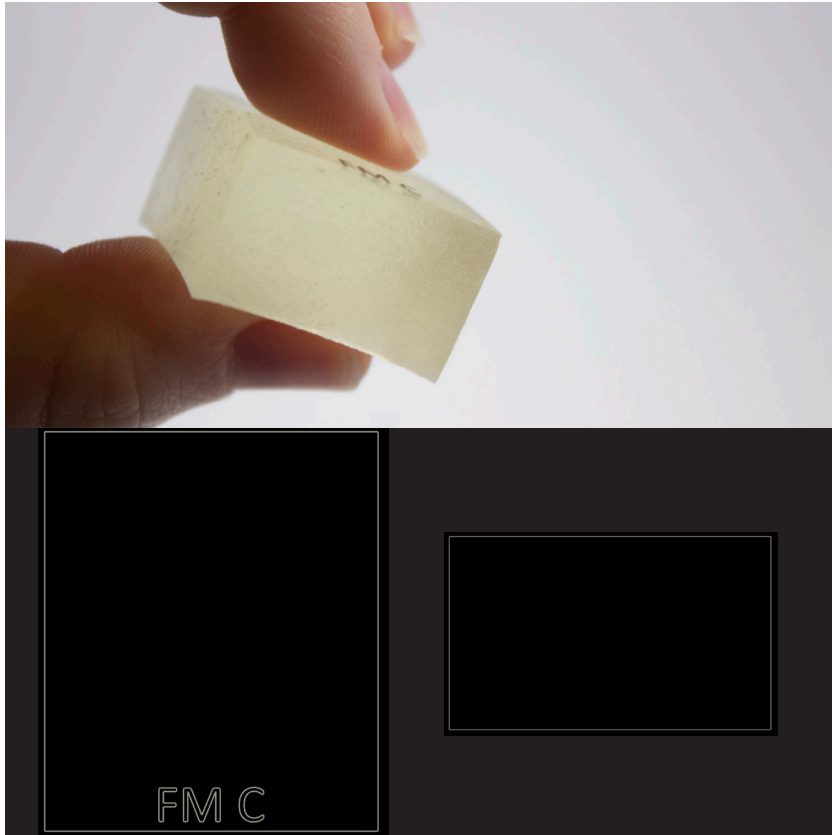


Figure 103. Agilus control sample.

Agilus Control

Size
25mm x 30mm x 15mm

Cell Height
NA

Cell Grid
NA

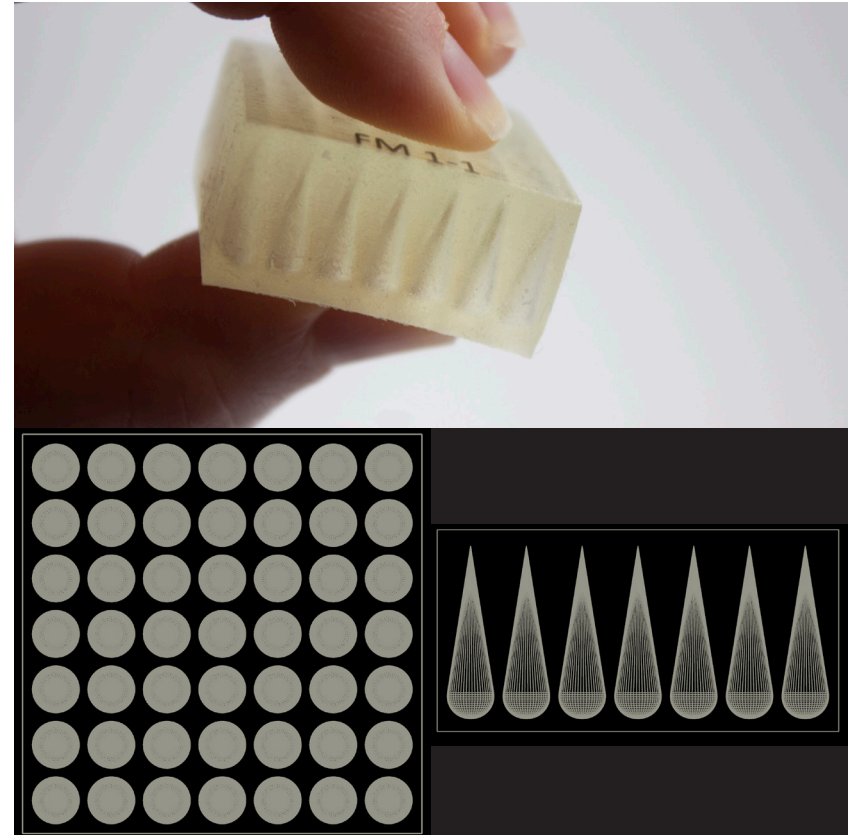


Figure 104. Foam test 1-1.

Foam 1-1

Size
30mm x 30mm x 15mm

Cell Height
13mm

Cell Grid
7 x 7

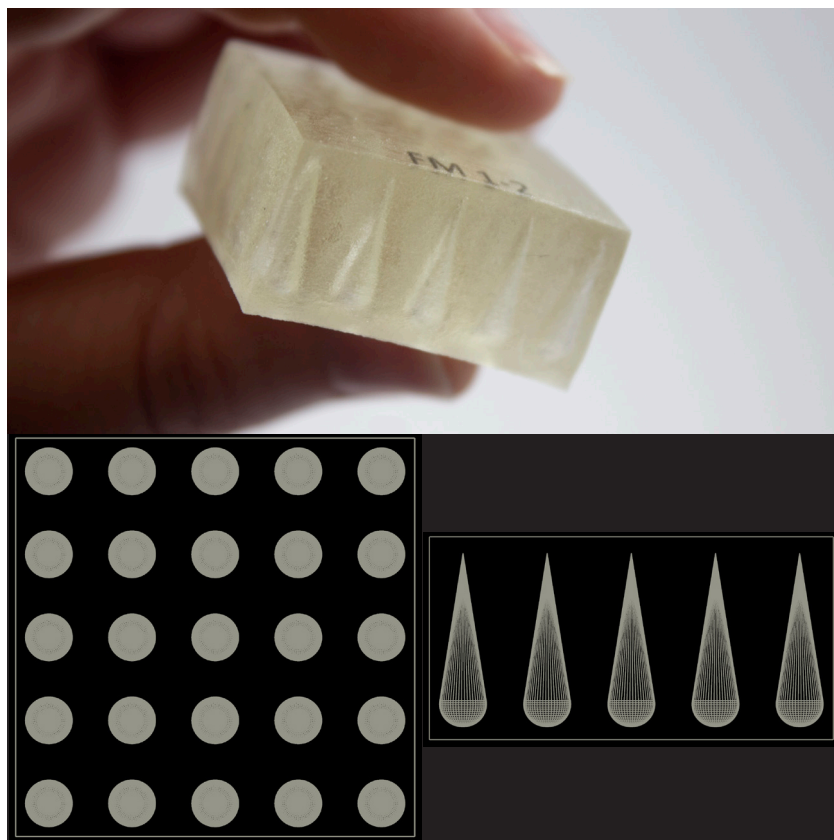


Figure 105. Foam test 1-2.

Foam 1-2

Size
30mm x 30mm x 15mm
Cell Height
13mm
Cell Grid
5 x 5

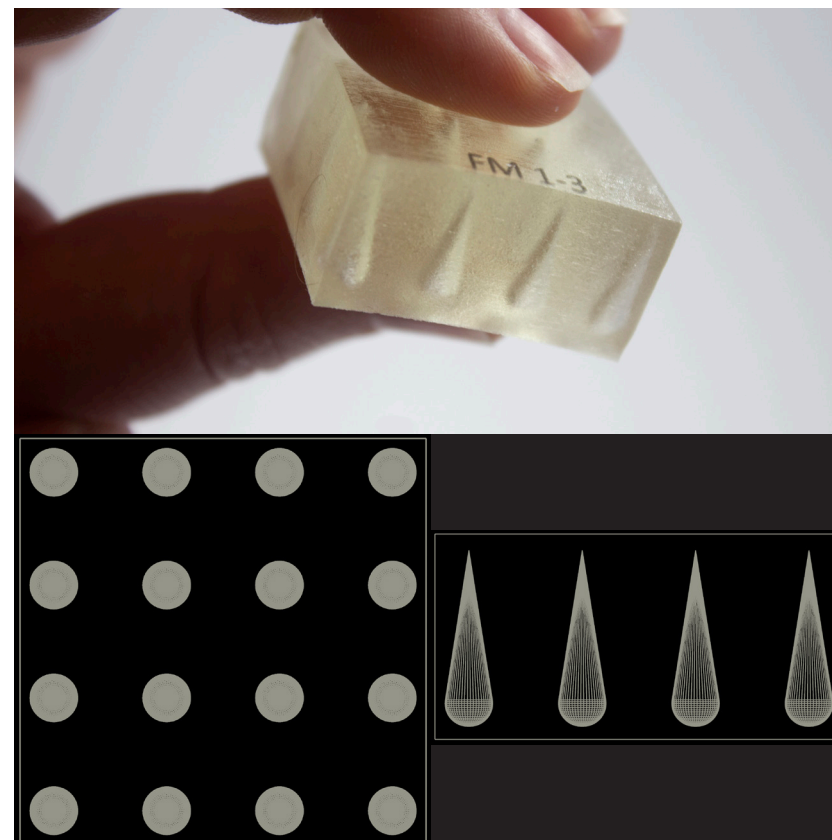


Figure 106. Foam test 1-3.

Foam 1-3

Size
30mm x 30mm x 15mm
Cell Height
13mm
Cell Grid
4 x 4

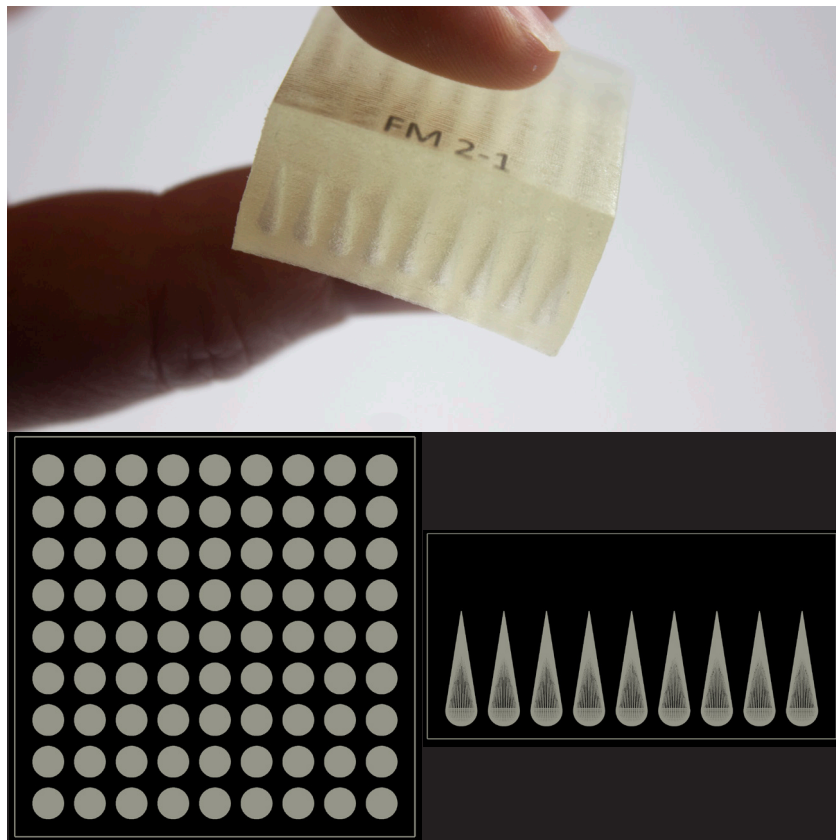


Figure 107. Foam test 2-1.

Foam 2-1

Size
30mm x 30mm x 15mm
Cell Height
8.5mm
Cell Grid
9 x 9

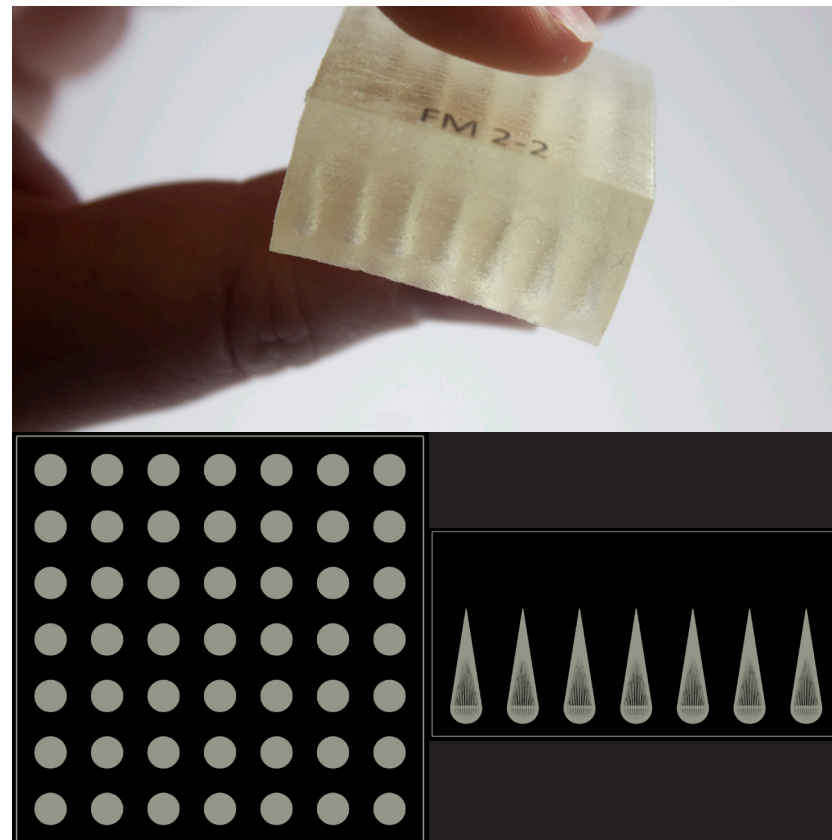


Figure 108. Foam test 2-2.

Foam 2-2

Size
30mm x 30mm x 15mm
Cell Height
8.5mm
Cell Grid
7 x 7

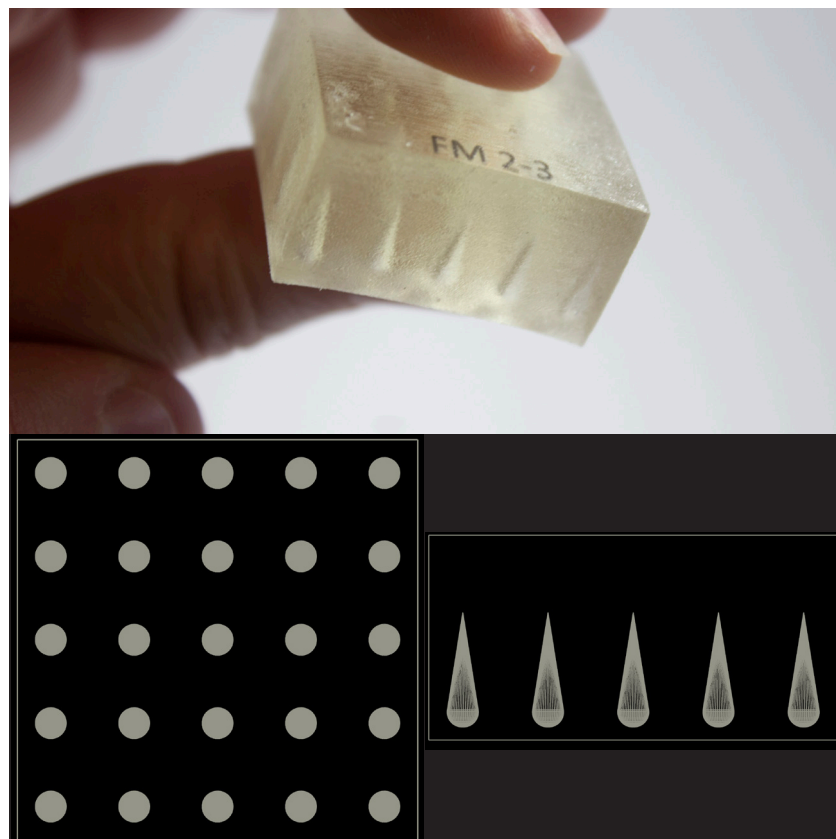


Figure 109. Foam test 2-3.

Foam 2-3

Size
30mm x 30mm x 15mm
Cell Height
8.5mm
Cell Grid
5 x 5

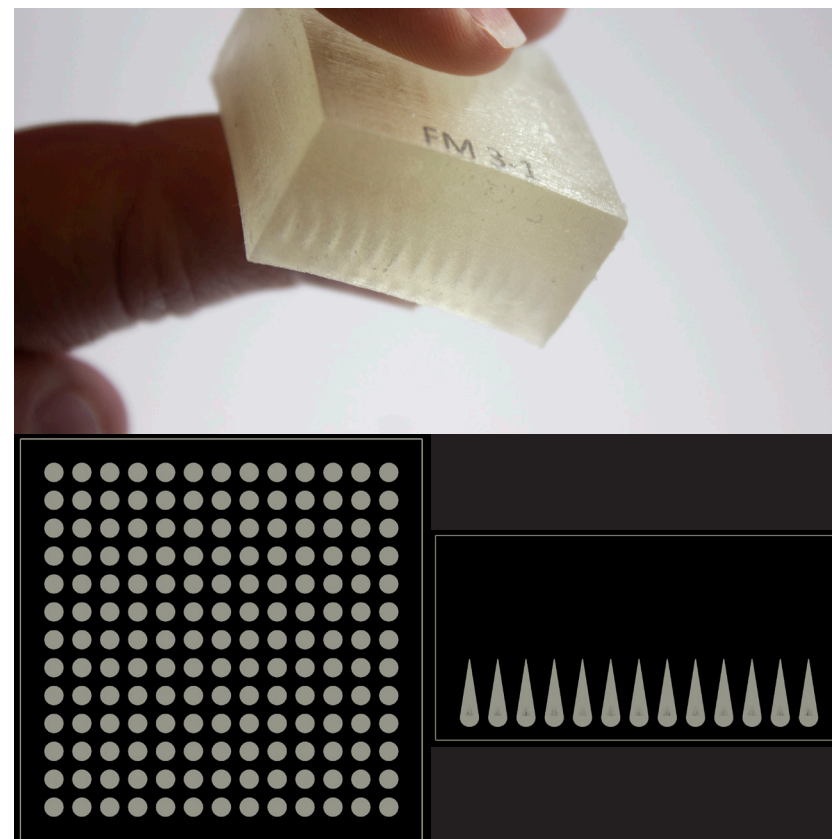


Figure 110. Foam test 3-1.

Foam 3-1

Size
30mm x 30mm x 15mm
Cell Height
5mm
Cell Grid
13 x

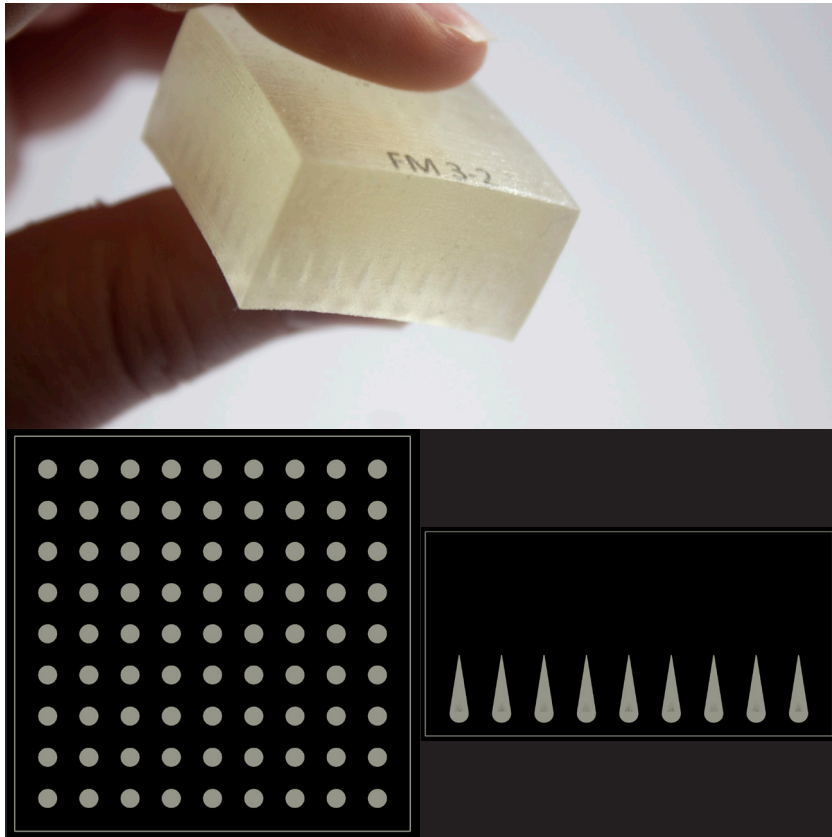


Figure 111. Foam test 3-2.

Foam 3-2

Size
30mm x 30mm x 15mm
Cell Height
5mm
Cell Grid
9 x 9

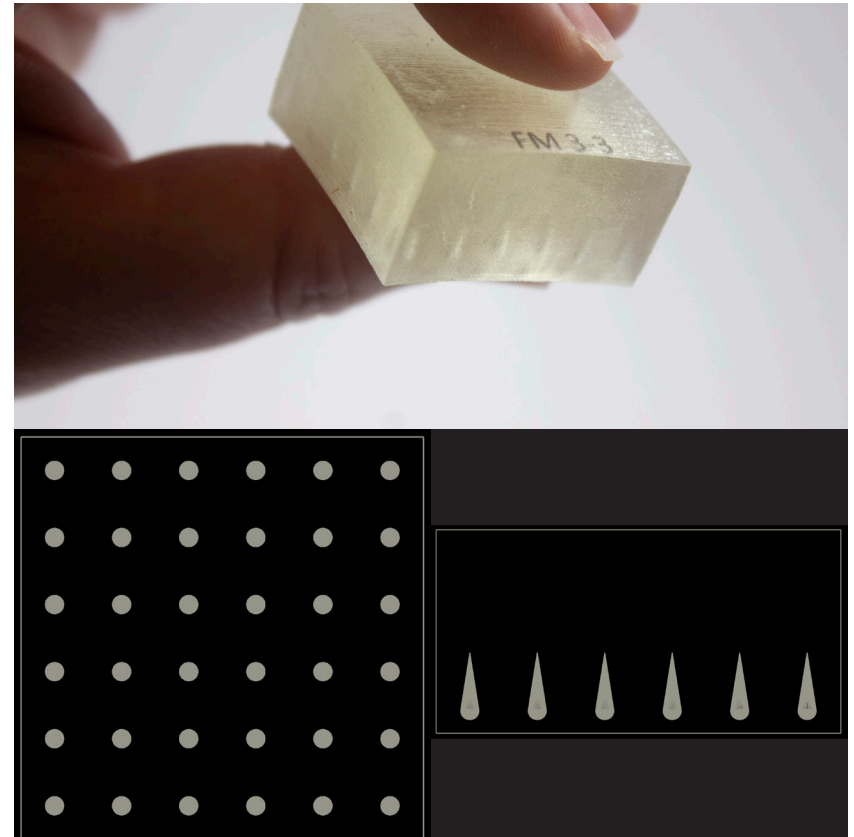


Figure 111. Foam test 3-3.

Foam 3-3

Size
30mm x 30mm x 15mm
Cell Height
5mm
Cell Grid
6 x 6

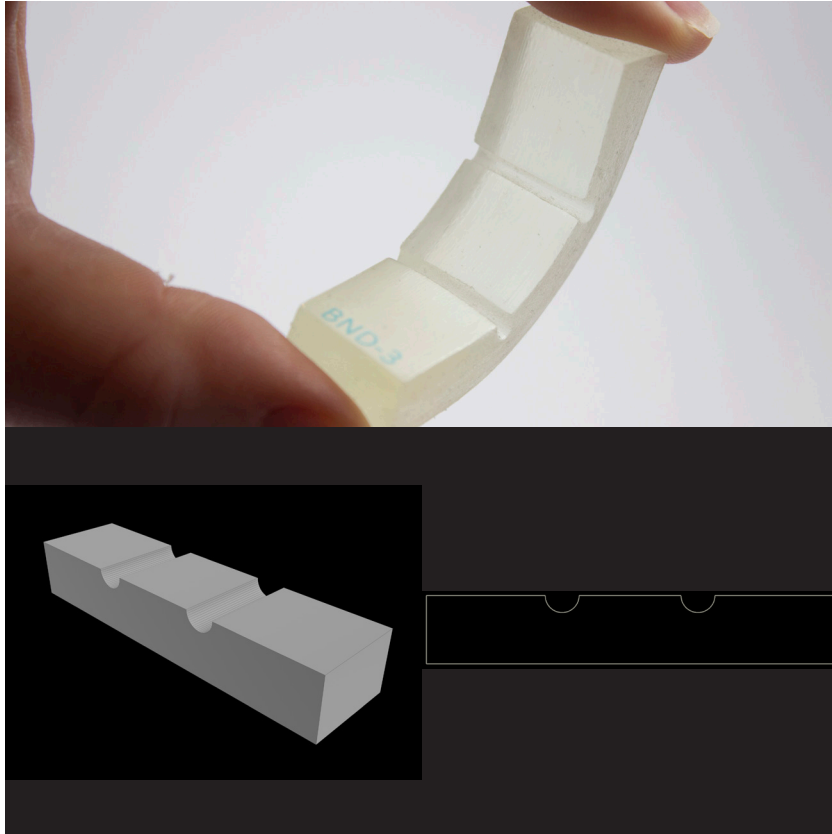


Figure 112. Bend test.

Bend Test

Size

60mm x 15mm x 10mm

Cut-outs

5mm across 2.5mm deep

Aims

To test using air voids to reduce the density of Agilus prints. This is to produce structures with foam like properties that soften the material so it is softer and has more give when force is applied.

The bend test was conducted to see if cuts in Agilus parts would cause controlled bending when lateral forces are applied to the ends.

Discovery

The Agilus foam tests had very little effect on the softness of Agilus prints when compared to the control. The most extreme of these tests strayed only very slightly out of recommended air void usage, so maybe to get any real effect we would need to push further. This would risk printing problems and collapses. During this testing we discovered that air voids prepared using voxel printing methods would result in an unexplained error when our technician tried to send the job to the J850, these tests had to be prepared using STL assemblies. So though the functionality is supposed to work, it is currently impossible to voxel print air voids, hence prints with both material gradients and air voids are currently not possible.

The bend test worked as intended, however was still pretty stiff. Based on other Agilus parts printed it is recommended that the thickness of bodies around bend points be 5mm or below.

TENDON TESTS

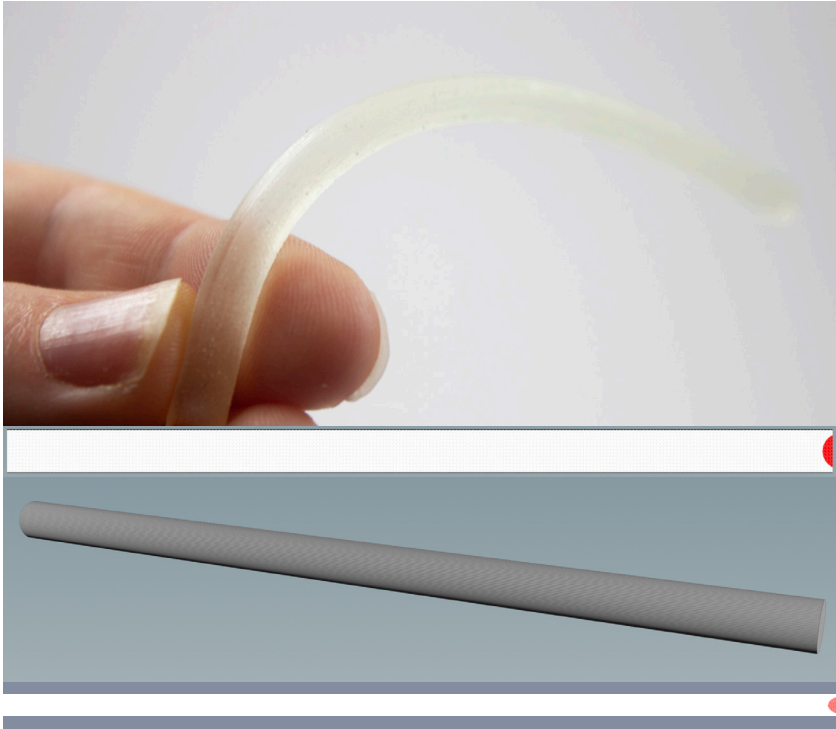


Figure 113. Tendon agilus control.

Agilus Control

- Diameter
5mm
- Length
100mm
- Sphere Size
NA
- Sphere Spacing
NA
- Blend Width
NA

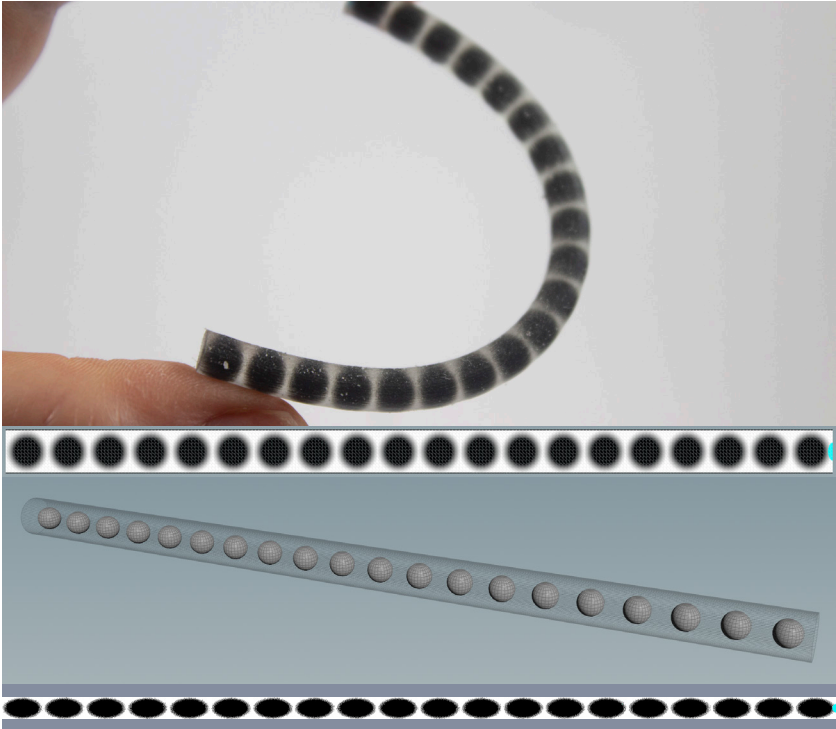


Figure 114. Tendon test 1.

Tendon Test 1

- Diameter
5mm
- Length
100mm
- Sphere Size
3mm
- Sphere Spacing
2mm
- Blend Width
1.25

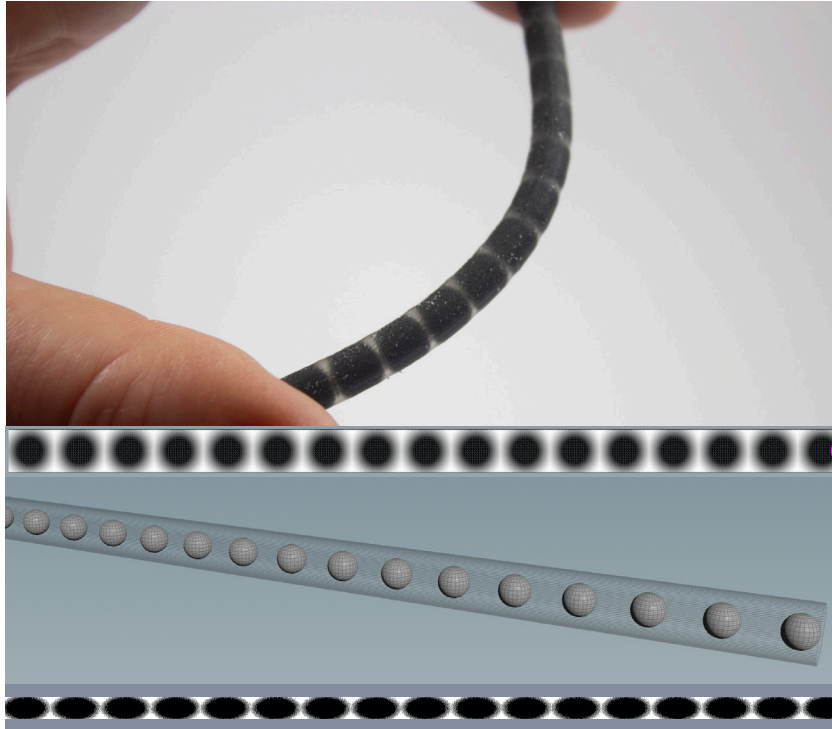


Figure 115. Tendon test 2.

Tendon Test 2

Diameter
5mm
Length
100mm
Sphere Size
3mm
Sphere Spacing
3mm
Blend Width
2.25

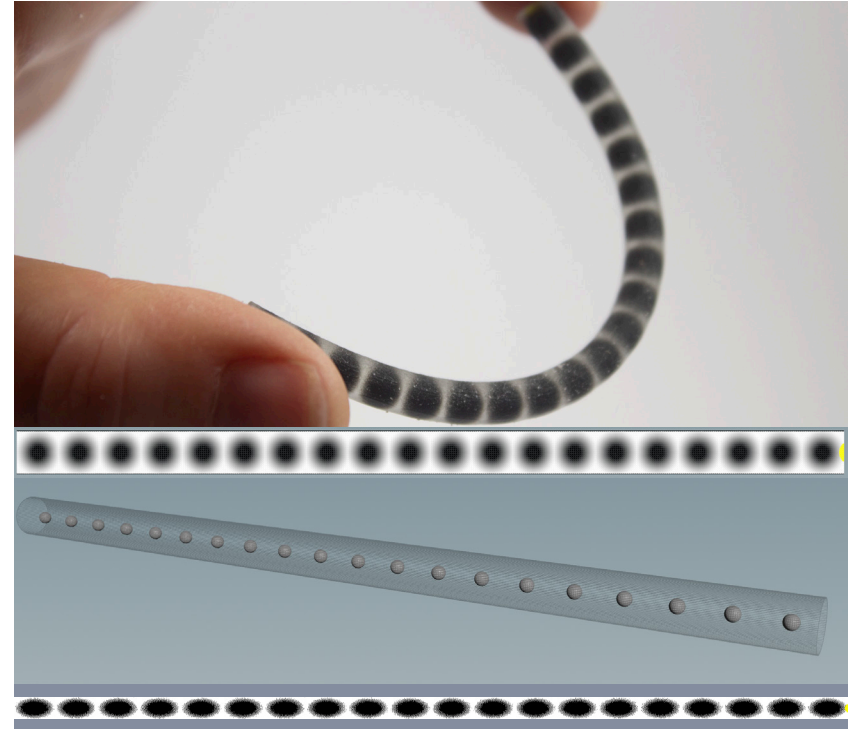


Figure 116. Tendon test 3.

Tendon Test 3

Diameter
5mm
Length
100mm
Sphere Size
1.5mm
Sphere Spacing
3.5mm
Blend Width
2.25

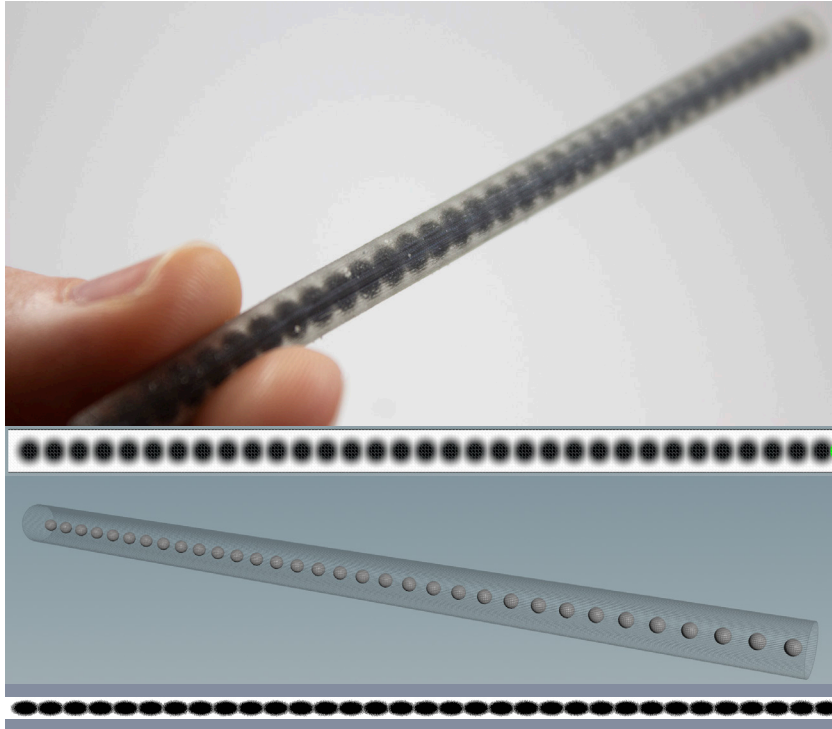


Figure 117. Tendon test 4.

Tendon Test 4

Diameter

5mm

Length

100mm

Sphere Size

1.5mm

Sphere Spacing

1.5mm

Blend Width

1.5

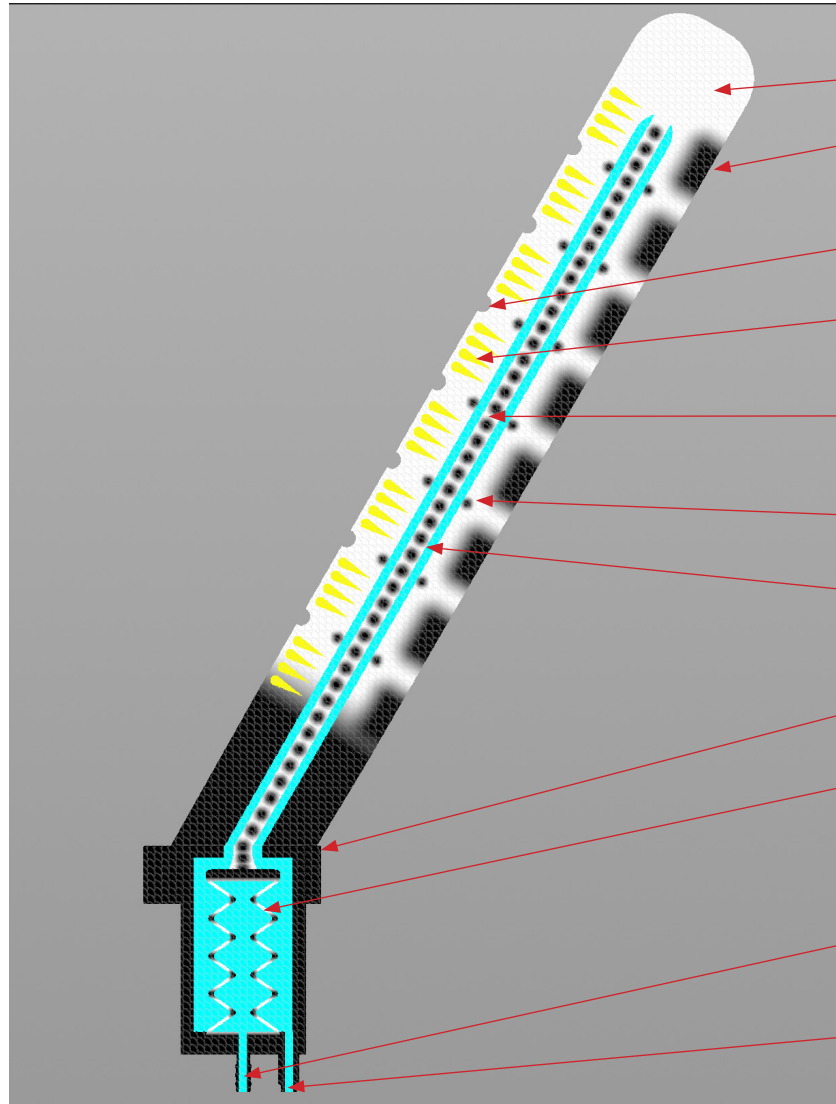
Aims

To test if blends of Agilus and Vero can be used to create structures that retain flexibility but reduce extension. The idea here is that reducing the amount of Agilus between spheres would reduce stretch in the lateral direction.

Discovery

This worked as intended, the best results came from tests 1 & 3. Tests 2 & 4 lost their flexibility as the gaps between Vero were reduced. Compared to the Agilus control which stretched 50mm, test 1 only stretched 10mm and test 3 only 5mm. So we see significant reductions in stretch while staying flexible.

PROCEDURAL SOFT ROBOT SYSTEM



Key

Agilus

Vero

Liquid

Air

Soft Agilus body.**Rigid Outer Shell sections**

Help the form to hold its structure and used to set controlled articulation points in the soft sections inbetween these.

Cut-outs

Used to set controlled articulation points as they act as bending zones in the soft body.

Air voids

Act as foam cells to soften the inner gripping side of the soft robot(material testing showed that these weren't effective).

Tendon

Pulled by the actuator to make the limb bend. The controlled articulation points control where and how the limb bends.

Small rings of rigid material

Placed at articulation points to stop the corners pinching.

Liquid printed in areas where internal voids are desired. This is drained post printing.**Rigid base**

Holds the limb in orientation and connects gripper to robotic apparatus.

Actuator

this is activated by vacuum, when applied the form shrinks and folds down, pulling on the tendon and forcing the limb to bend. This has small areas of rigid material on the corners intended to keep them from shrinking during actuation to keep the motion controlled and linear.

Center drain

This allows the liquid printed within the actuator to be drained post print. It also acts as the point of attachment of a pneumatic line to actuate the print.

Side drain

Allows the liquid throughout the print to drain post print. This is also used to get lubricant in the internal channel to stop any friction between the tendon and the walls of the internal chamber. A cap for this is printed too.

Figure 118. Soft robotic system cross section.

Here a series of diagrams will be used to explain all of the controls in the procedural system/
The first group here is the ring controls:

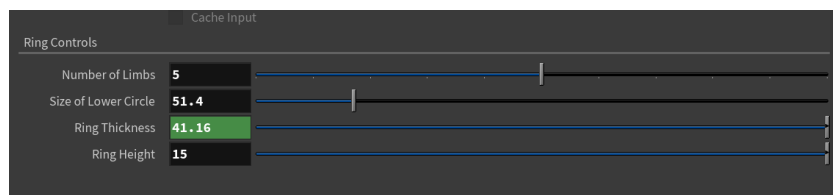


Figure 119. First group of procedural controls for soft robotics system.

Number of Limbs

Controls the number of limbs of the soft robot (figure 120 shows an output with three limbs).

Size of Lower Circle

Controls the size of the diameter of the lower circle (here seen in red) this should be smaller than the diameter of the fruit the picker will be used for.

Ring Thickness

This is procedurally set by the thickness of the limbs.

Ring Height

The y-height of the base ring.

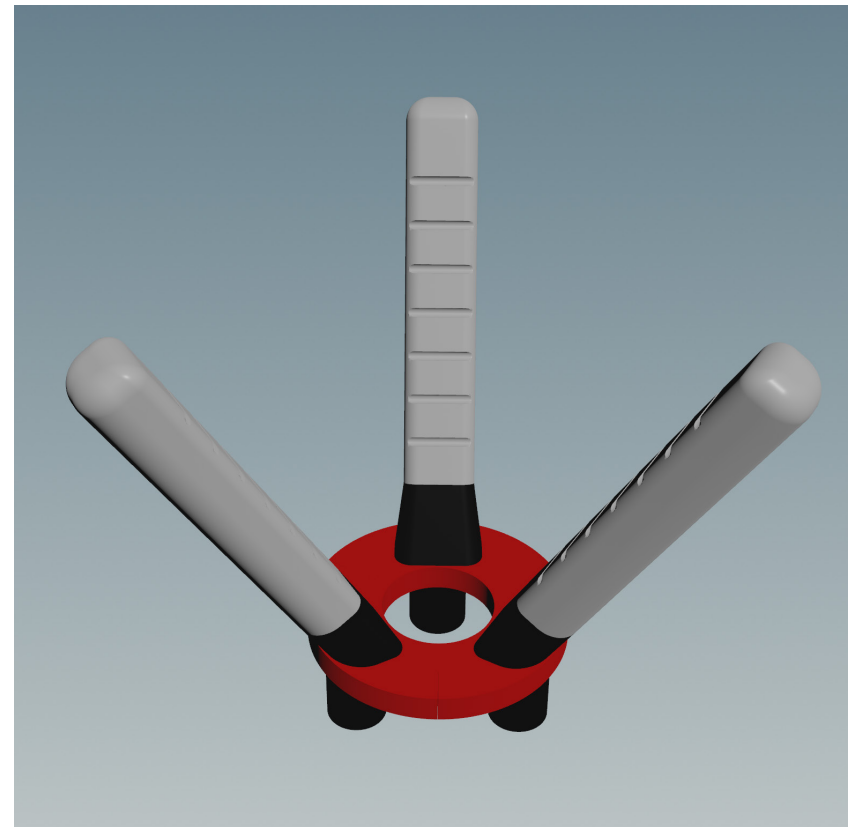


Figure 120. Soft robot model produced by system.

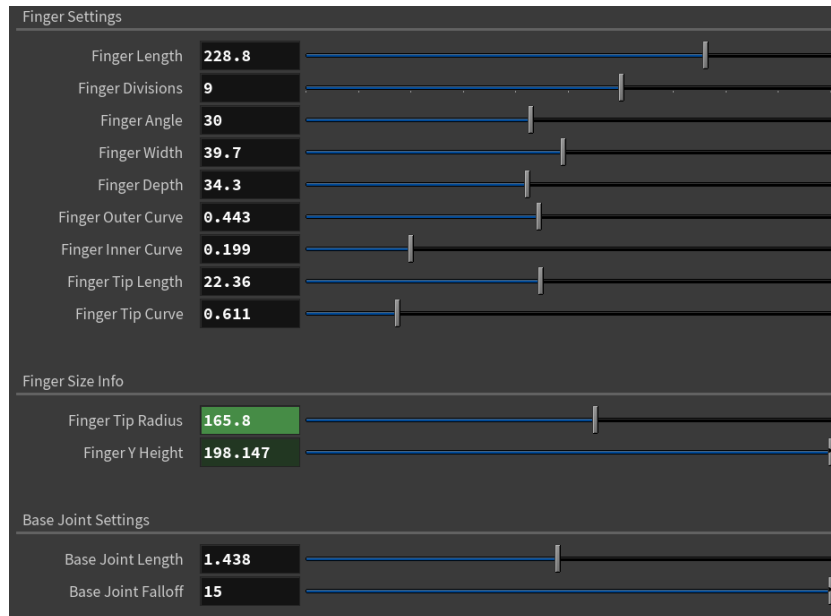


Figure 121. Finger settings for soft robotics system.

Finger Length

Length of the finger (indicated by red line).

Finger Divisions

Number of divisions, this controls how many outer shell and inner cut-outs there are. Users can use this to control the shape of bend on the fingers.

Finger Angle

Offset angle of the finger. Users control this to ensure the top of the fingers are larger than the desired fruit while the bottom is smaller (indicated here in blue).

Finger Depth

Sets the depth of the finger (indicated here in yellow).

Finger Width

Other direction to depth. Users use to control shape and width of finger.

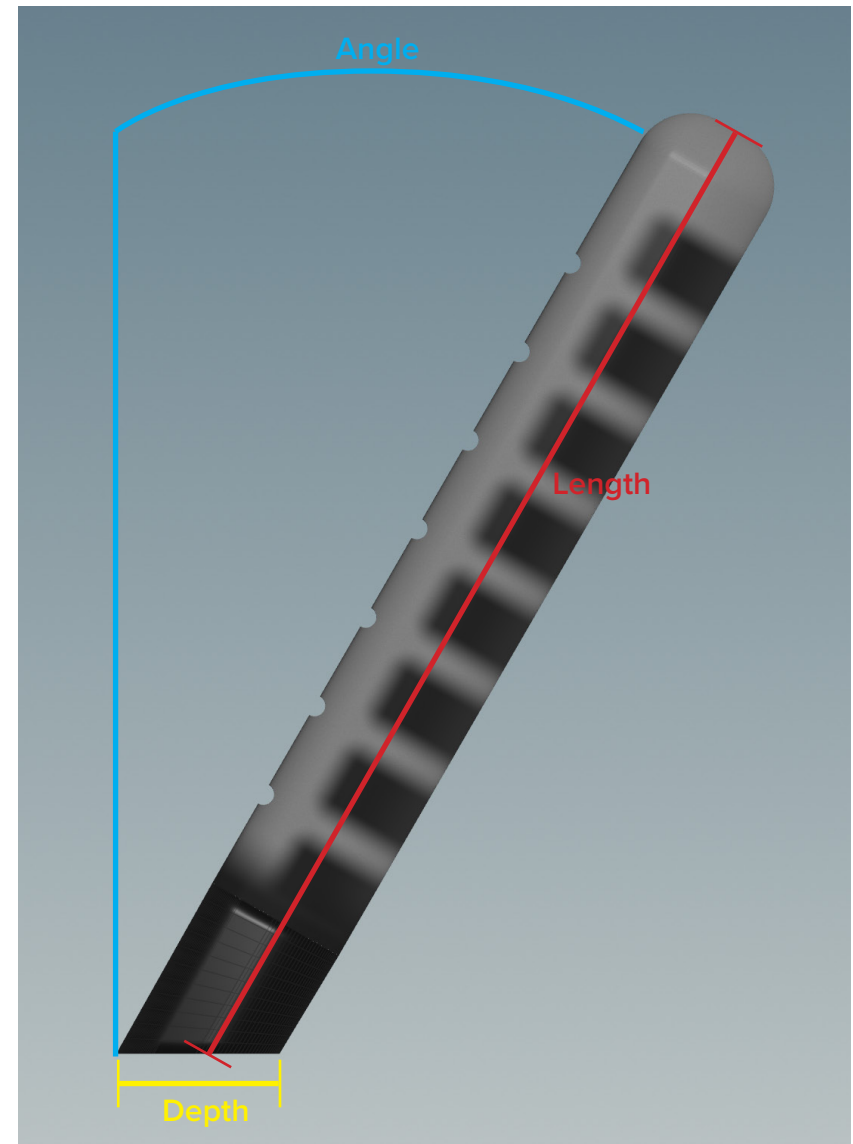


Figure 122. Output finger.

Finger Outer Curve

Curve control for outer corners of finger.

Finger Inner Curve

Curve control for inner corners of finger.

Finger Tip Length

Length of tip extended from finger.

Finger Tip Curve

Curve control for upper corners of finger.

Finger Tip Radius

This indicates the radius of a circle at the tips of the fingers. Users need to make this value bigger than the size of their desired fruit, and the lower circle needs to be smaller.

Base Joint Length

The length of the black rigid bottom section (seen in figure 122) this can be extended up the finger for added stability at the base.

Base Joint Falloff

Controls the gradient size of material transition from the rigid material at the base to the soft material of the finger.

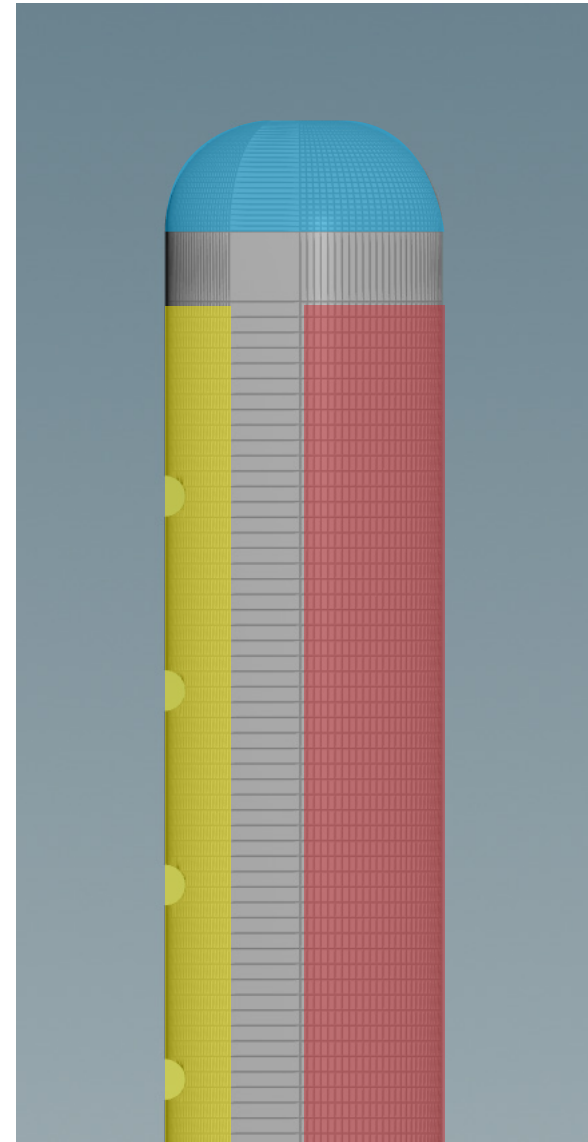


Figure 123. Finger curves.

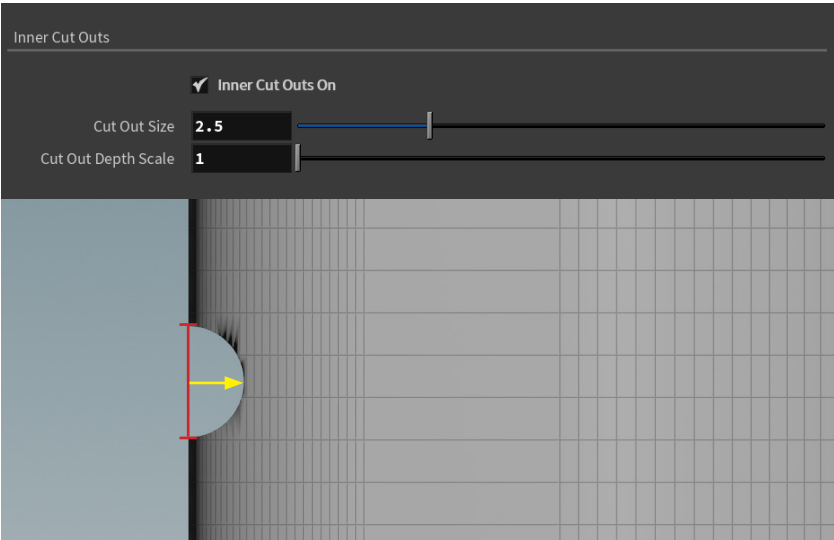


Figure 124. Inner Cuts.

Cut Out Size

Overall diameter size for tube that cuts geometry.

Cut Out Depth Scale

Used to scale cutting tube inwards to cut deeper into the geometry.

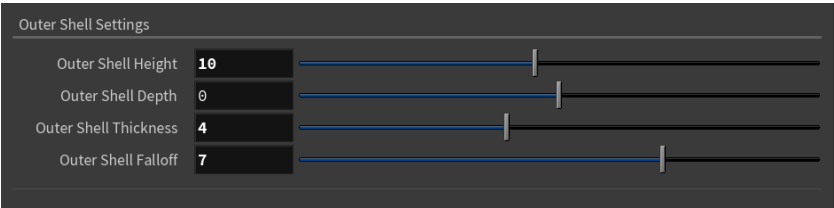


Figure 125. Outer shell settings.

Outer Shell Height

Height of each rigid section, to control how rigid each of the sections are overall.

Outer Shell Depth

This is used to inset the rigid section into the soft robotic body.

Outer Shell Thickness

The thickness of the rigid body. Controls how much of the internal body of the finger is made of rigid material.

Outer Shell Falloff

Controls the gradient distance between these rigid sections and the soft body.

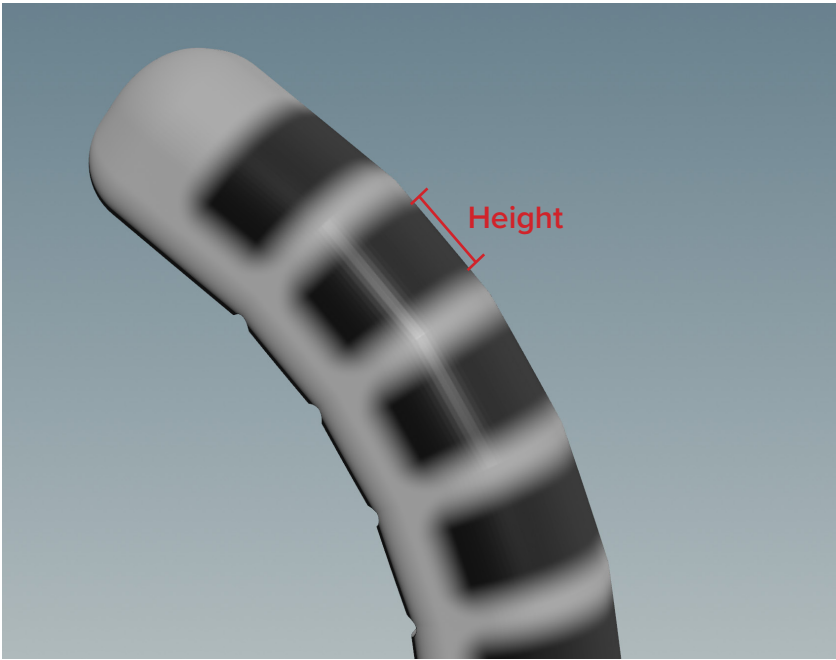


Figure 124. Outer shells blended into soft robotic finger.

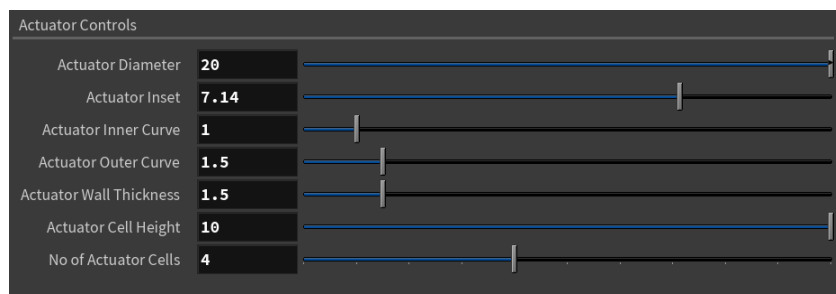


Figure 125. Soft robot actuator controls.

Actuator Diameter

Overall diameter of actuator.

Actuator Inset

Difference in diameter between outer curves and inner curves.

Actuator Outer Curve

Controls the radius on the outer curves.

Actuator Inner Curve

Controls the radius on the inner curves.

Actuator Wall Thickness

How thick the walls of the actuator are, this may need to be altered depending on the size.

Actuator Cell Height

The height of each individual cells of the actuator.

No of Actuator Cells

The number of cells that make up the actuator, this doesn't include the two ends.

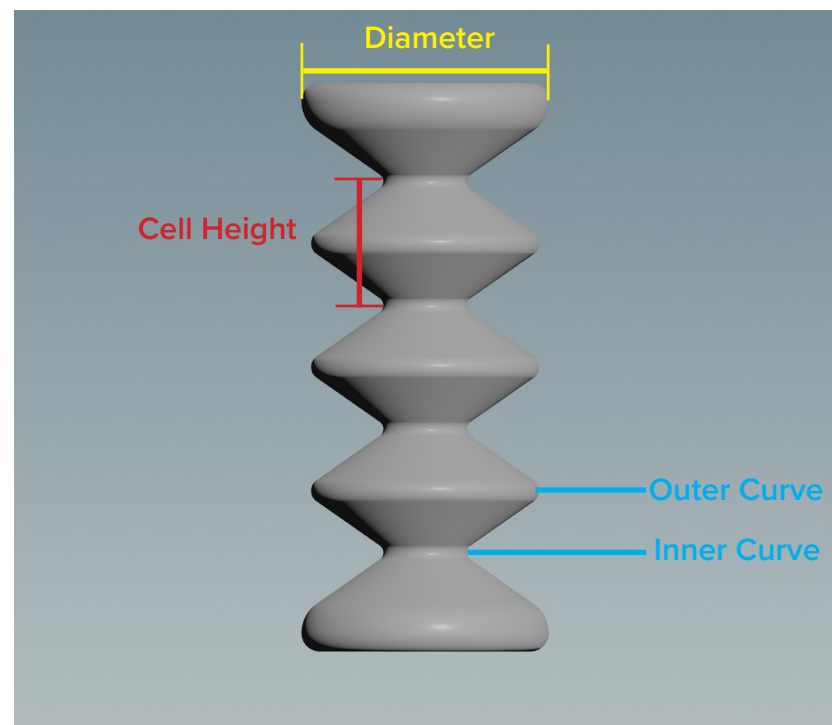


Figure 126. Soft robot actuator.

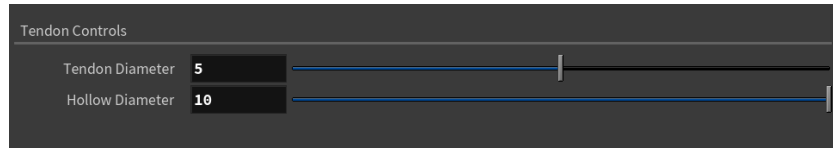


Figure 127. Tendon controls.

Tendon Diameter

Diameter of tendon (shown in red below).

Hollow Diameter

Controls the diameter of the hollow section around the tendon (the blue section below) this will be filled with a liquid during printing and drained out after.

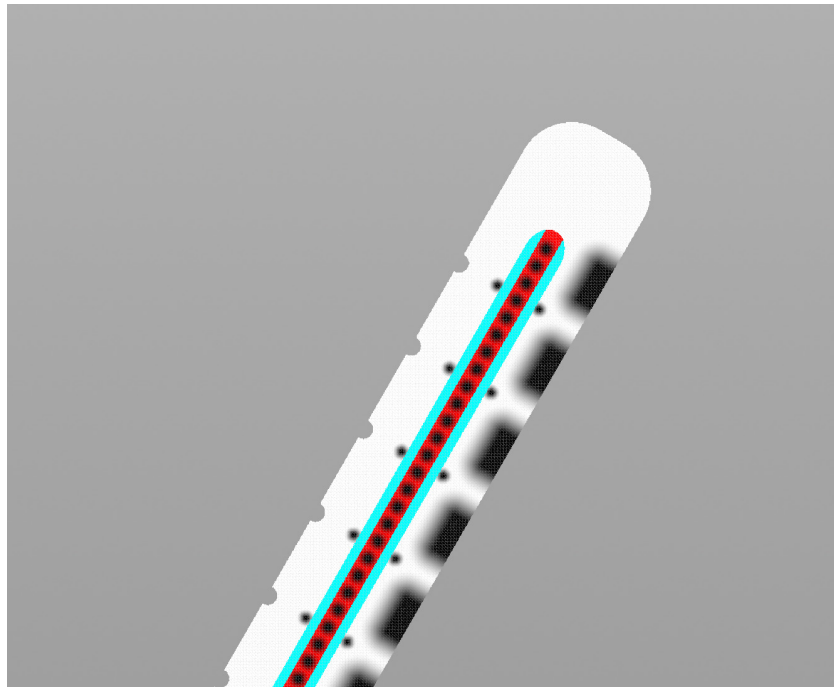


Figure 128. Cross section showing tendon and hollow.

A series of controls for creating the air voids were also included, however they will not be covered here since we discovered in material testing that this has little to no effect on the softness of Agilus bodies.

To use this system users can either use known average measurements for their desired fruit to set the gripper to the correct size. The alternative way is to use either simple geometry that is the size correct size, or use a 3D scan, with this geometry users can change the parameters of the gripper to make it the correct size (see figure 129).

Once the correct size is achieved the gripper can be tested using a simple animation control to see how it will bend around and grab the fruit (see figures 130-134).

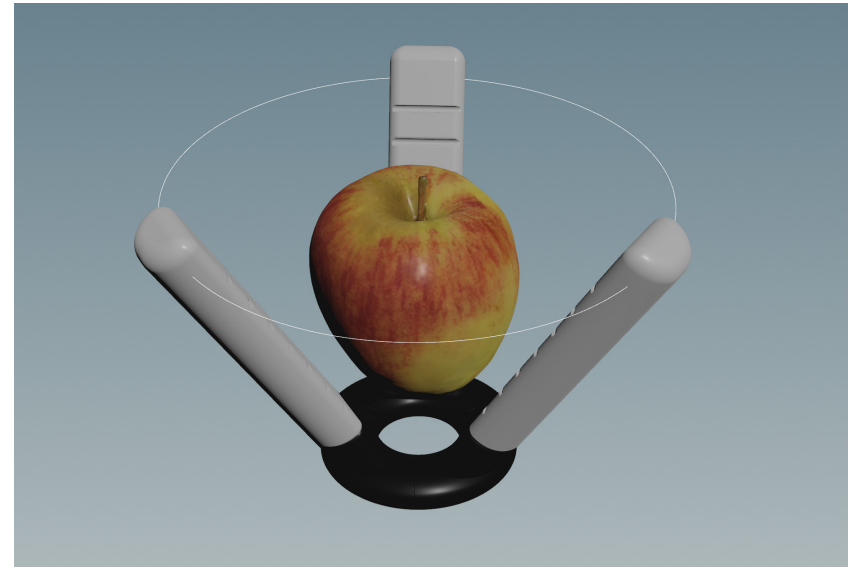


Figure 129. Fruit 3D scan being used for size reference for soft robotic gripper.

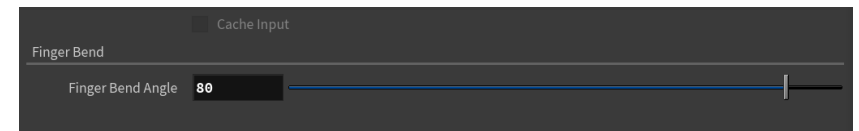
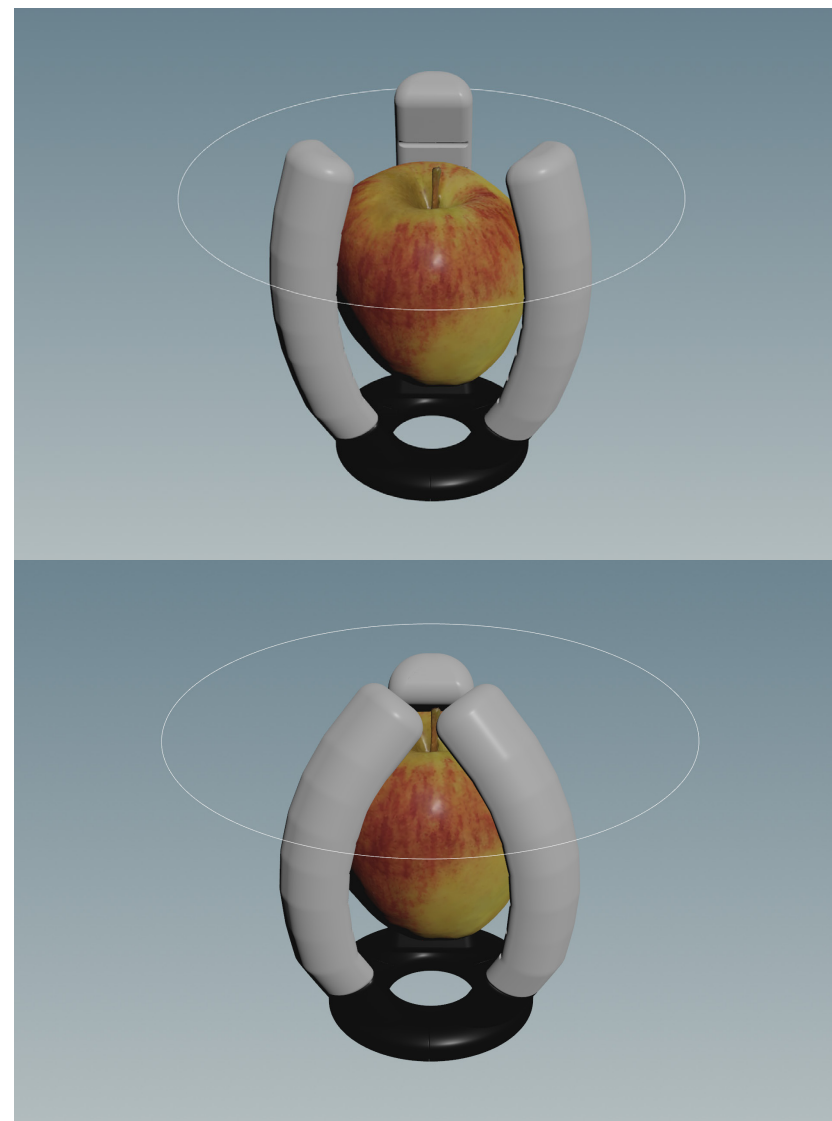
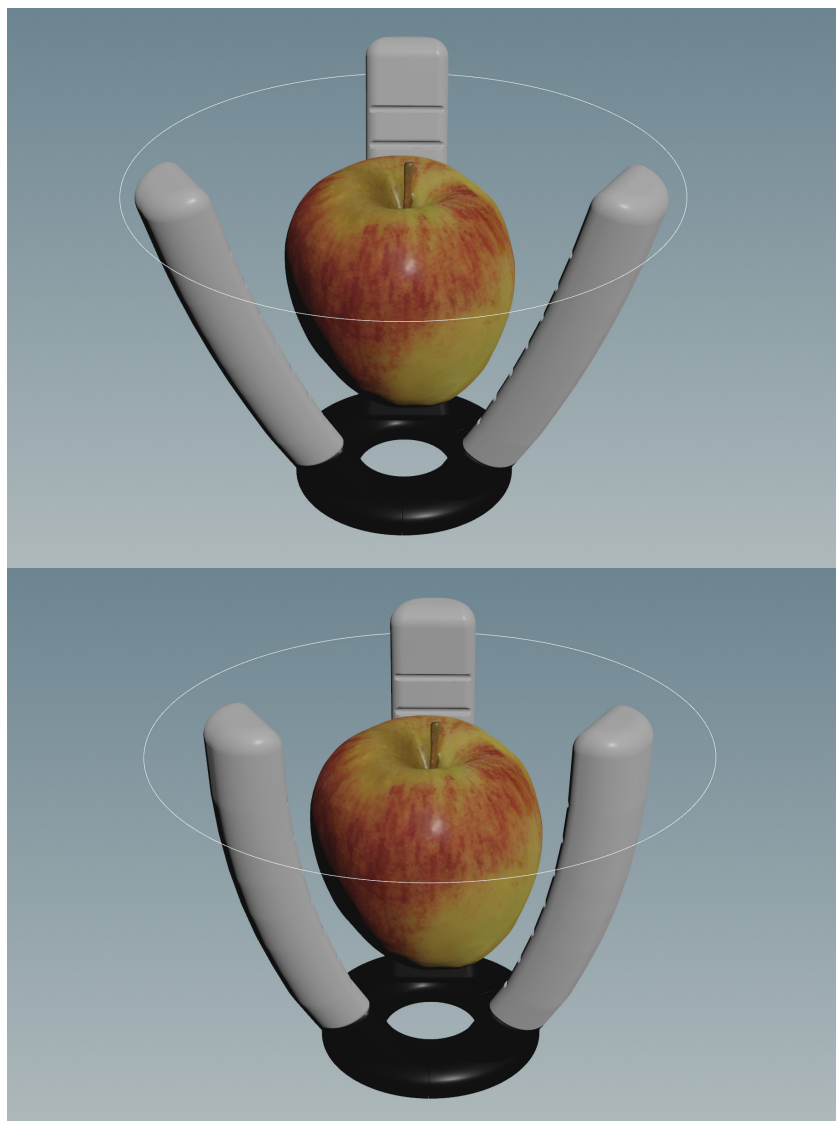


Figure 130. Animation slider to bend gripper around fruit.



Figures 131-134. Animated gripper grabbing fruit 3D scan.

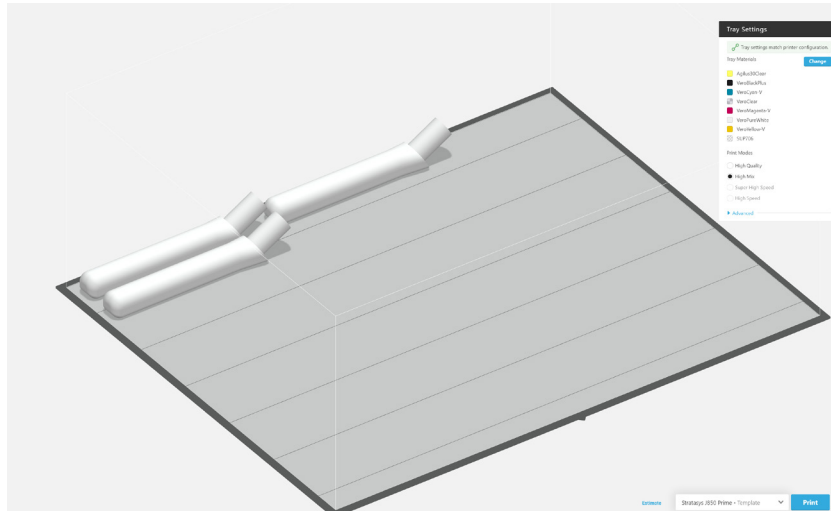


Figure 135. Individual finger voxel files in GrabCad print.

The system then optimises the orientation of the individual fingers for voxel printing and produces volumes ready for slicing. The fingers are printed individually, since this is optimal for printing. The base ring is customised to fit whatever robotic arm the gripper will be attached to, this is printed separately. In figure 135 above you can see gcvf files for individual fingers on the print bed of GrabCad Print ready for printing with the J850.

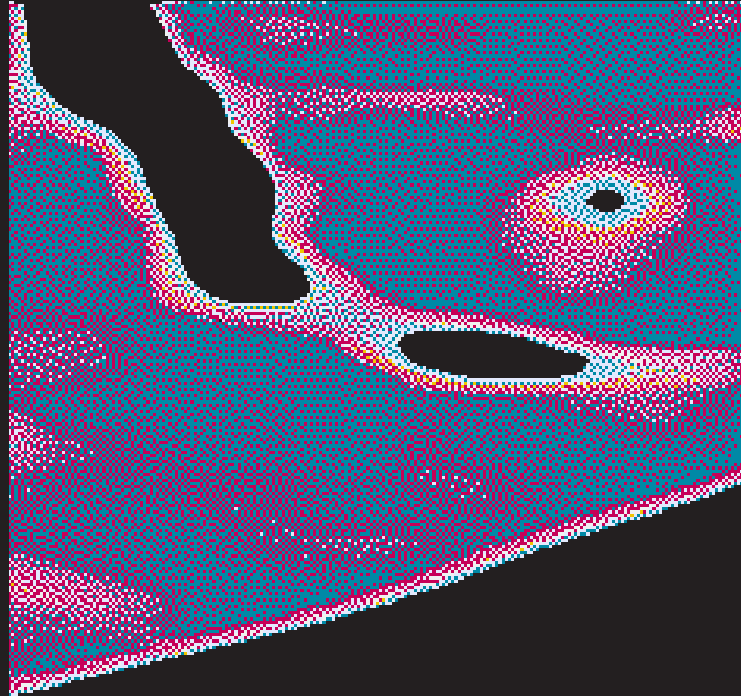


Figure 136. Section of a voxel print slice.

CHAPTER 4

DESIGN OUTPUT

MATERIAL GRADIENT WORKFLOW

Functionally graded materials are available through voxel printing, this goal of this workflow was to offer an easy and intuitive way to design with volumetric material gradients.

This system's ability to use any geometry produced from any software allows users the ability to model with whichever software they feel comfortable, allowing for quick and easy use of this tool. Further, if they save the geometry in file format such as OBJ Houdini will place those objects in the same coordinates as their base software.

The workflow of utilising multiple input geometries' relative position to one another makes the process of blending materials very intuitive for anyone with any 3D modelling experience, allowing for control of volumetric gradients by dragging that geometry around in 3D space. Using only input geometries shape, their relative position in 3D space and a simple falloff control keeps this process simple, while also offering all of the desired control to freely create material gradients. Point clouds are a very effective way to volumetrically transfer and blend material properties through blended transferral of colour, they also display these blends in a way that is easy to visually comprehend.

This gives users an intuitive toolset to control full volumetric gradients allowing users to take advantage of voxel printings capabilities for material blending. The resulting objects with gradient materials would be impossible to produce using other fabrication methods.

The efficacy of this workflow was demonstrated using Sophia Neill's shoe design made from a procedural system in Blender. All of the geometry used to create the material gradients came from this Blender system. During our collaboration on formulating the file for Sophia's voxel printed shoe, after a brief demonstration she was able to fully comprehend, use and explain to other people exactly how the system worked. The result of this collaboration affirms that this workflow is flexible, intuitive and easy to use (as of writing this has yet to be printed, but is planned to in the coming weeks).

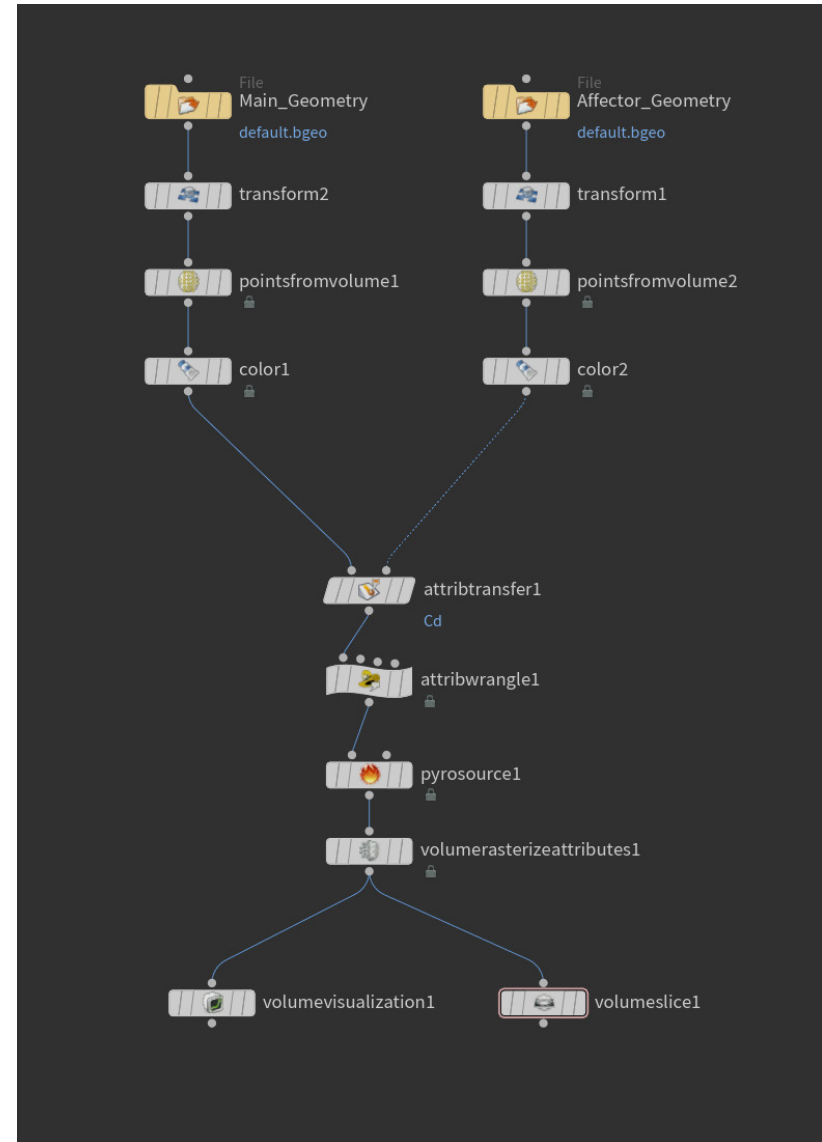


Figure 137. Full workflow to make material gradient volumes.

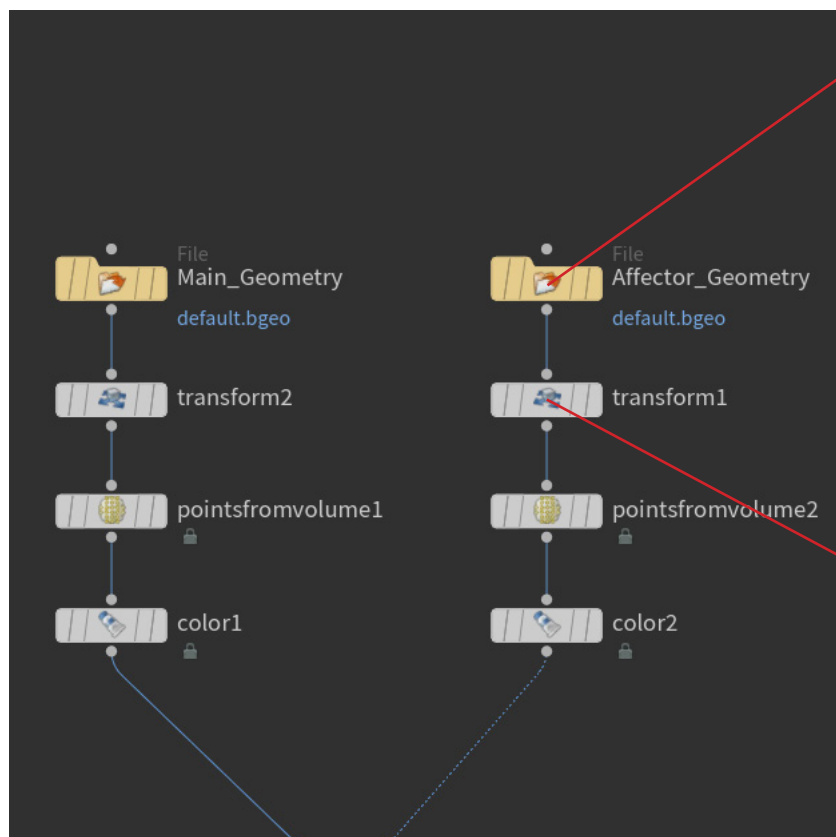


Figure 138a. Geometry inputs for material gradient workflow.

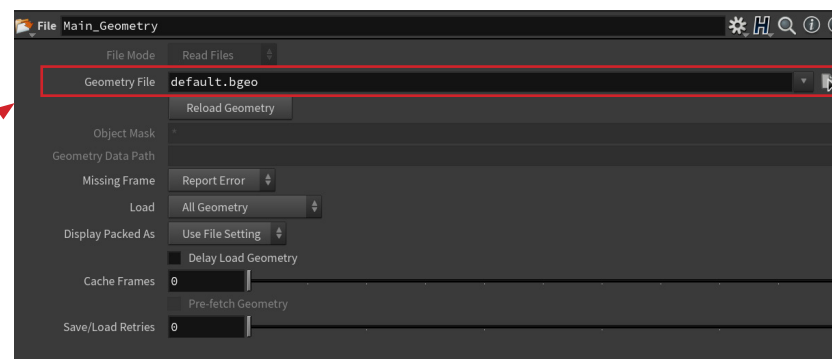


Figure 138b. Sampling geometry files in Houdini.

To create material gradients users first input their geometry using the file tools. Click the icon next to the geometry file and use the directory to find your files. Most geometry file types will work here but OBJs are suggested.

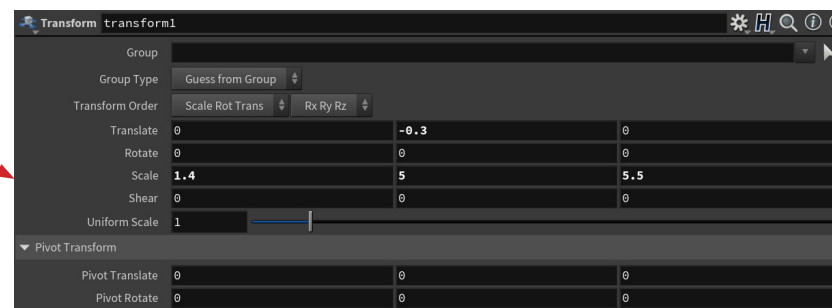


Figure 138c. Transformation of input geometries.

Use the transform tools to move geometry inputs around in 3D space to align relative to each other for creating material blends.

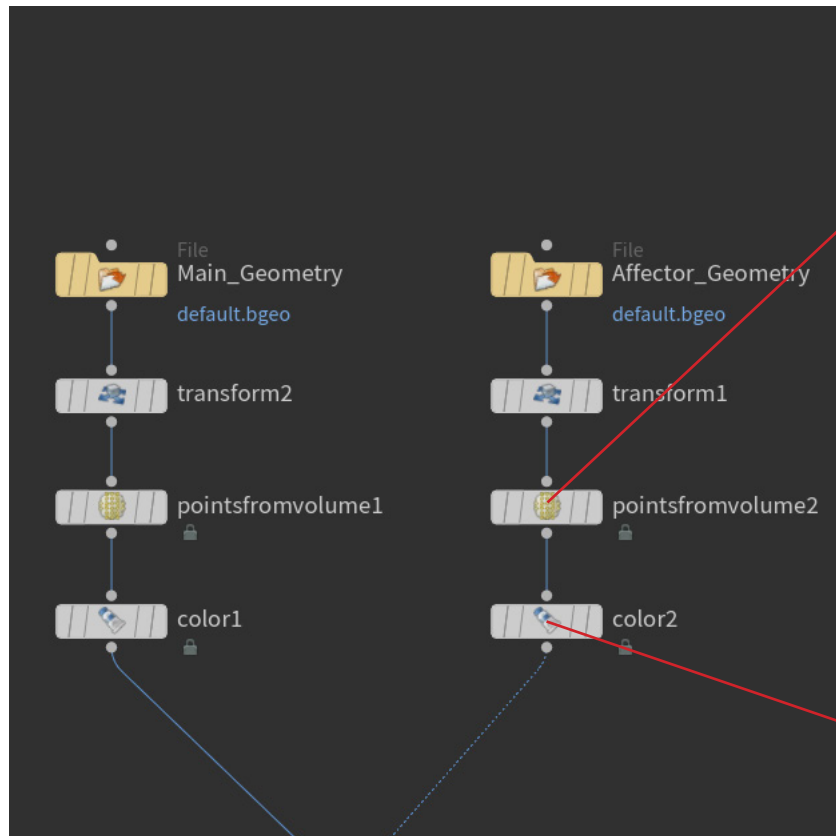


Figure 139a. Geometry inputs.

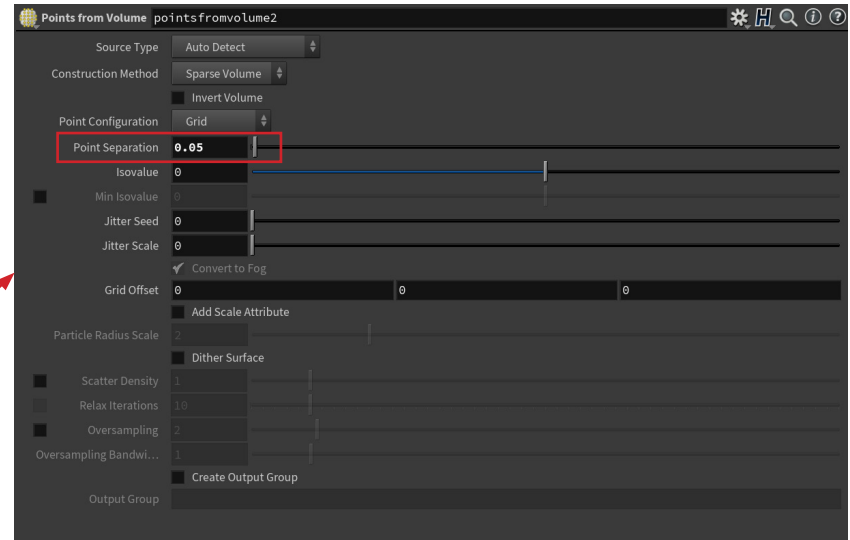


Figure 139b. Points from volume used to transform geometry into point clouds.

The points from volume tool takes the input geometries and transforms them into volumetric point clouds. The only setting to worry about here is the point separation, whatever value is used here must be kept consistent with the particle separation in the pyro source and the voxel size in the volume rasterize attributes. It is suggested to keep set this to something between 0.2 - 0.5 while working on your volume blends, but lowering this to 0.1 for your final volume outputs.

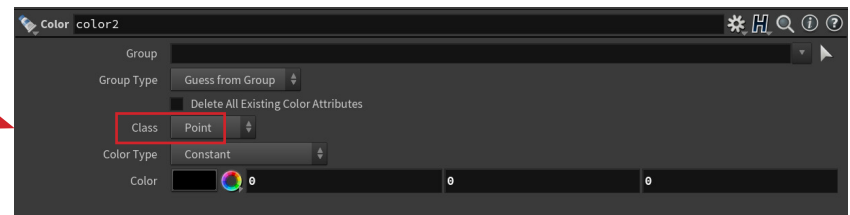


Figure 139c. Colour applied to point clouds.

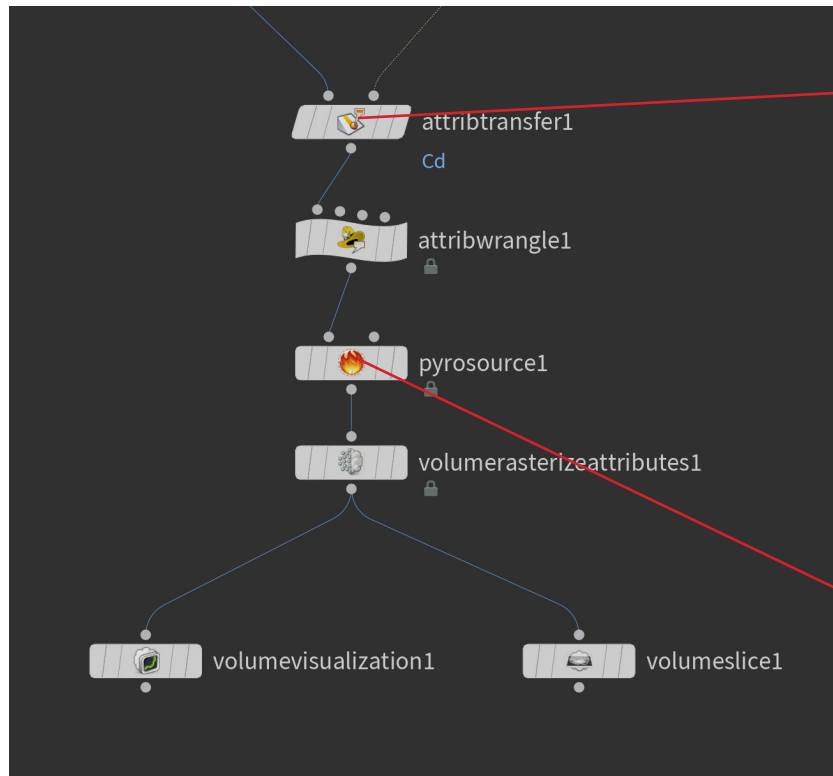


Figure 140a. Blending point clouds and producing a volume.

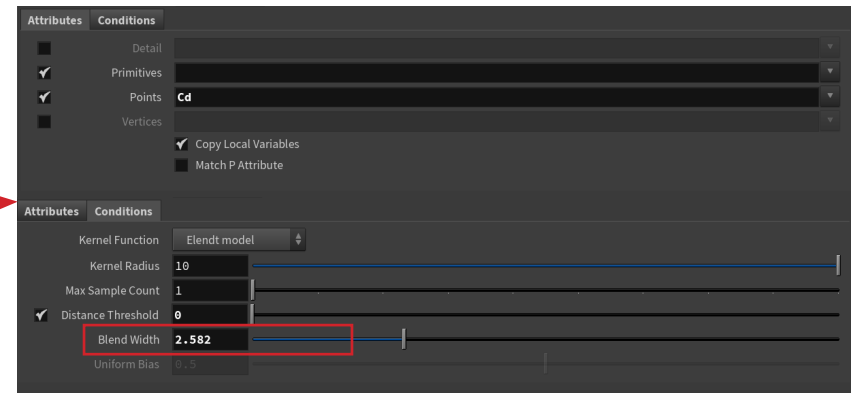


Figure 140b. Using blend width to create gradient falloff between two input point clouds.

Attribute transfer is used to transfer colour data from affector to main point cloud, The blend width controls the size of the gradient falloff.

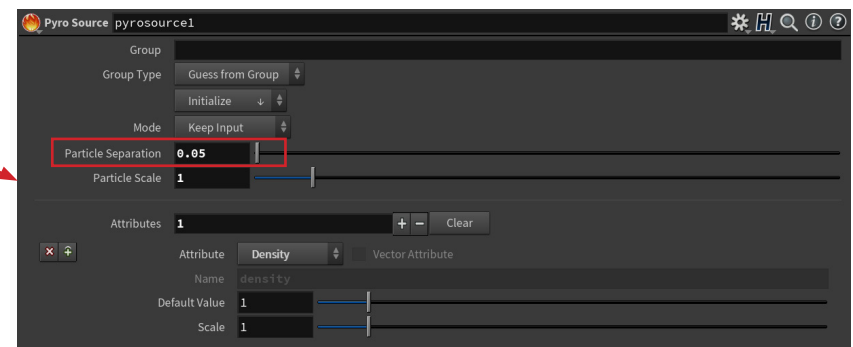


Figure 140c. Pyro source.

Pyro source prepares your resulting point cloud for transformation into a volume adding the density attribute. Key here is particle separation matches point separation in points from volume.

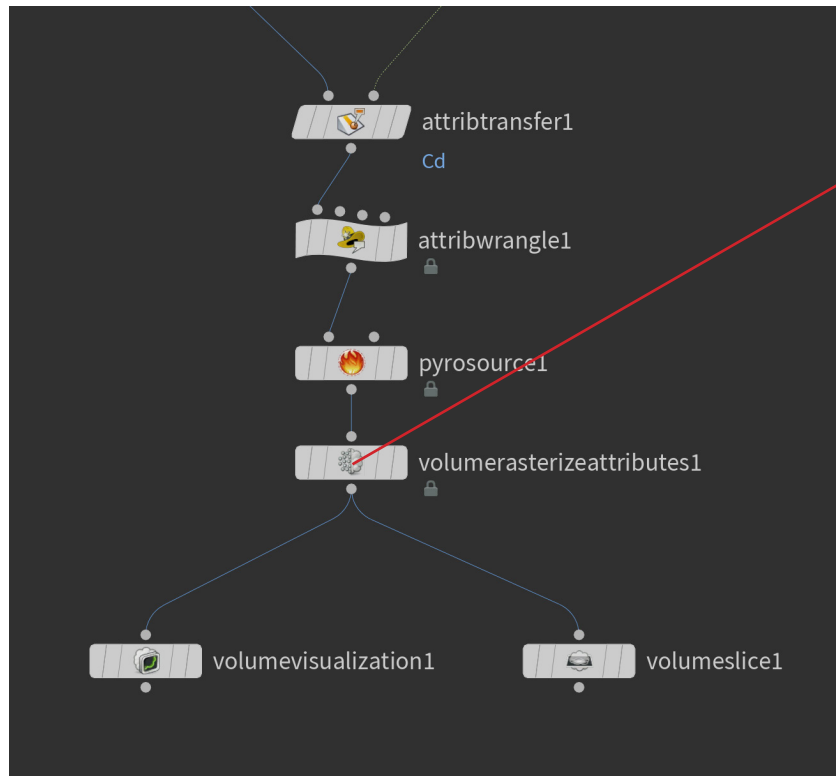


Figure 141a. Creating volume from point cloud.

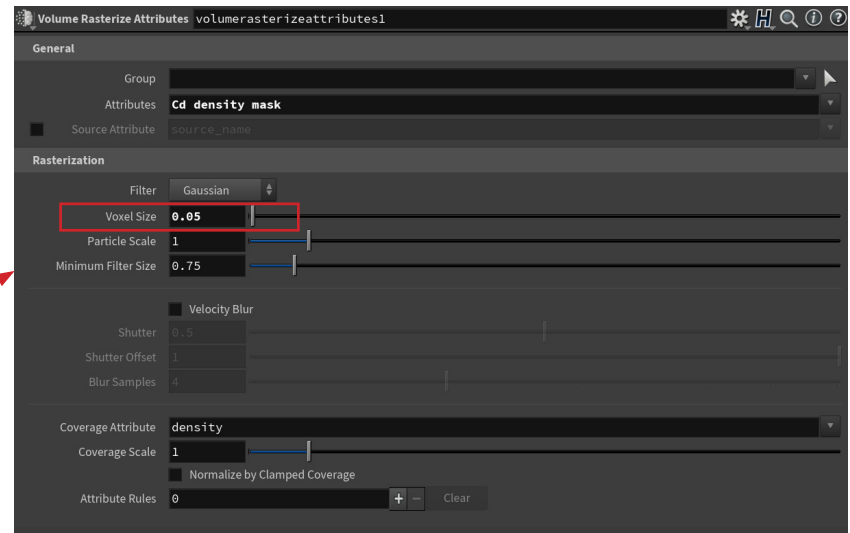


Figure 141b. Volume rasterize attributes used to form our volume for voxel printing.

Volume rasterize attributes takes the point clouds and a given set of point attributes and translates that into a volume. Voxel size should match particle separation from pyro source.

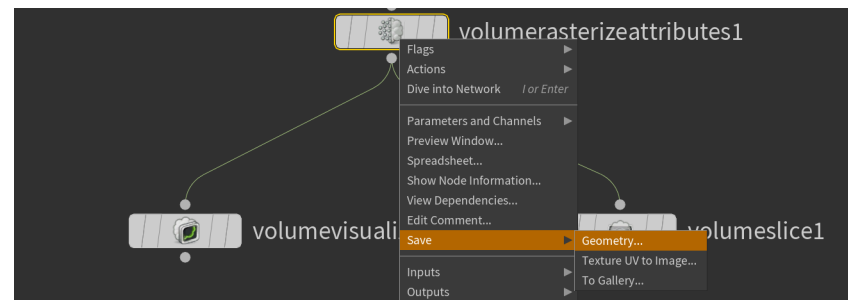


Figure 141c. Volume saved to be put in Voxel Slicer.

Once the volume is formed, right click on volume rasterize attributes and save geometry, this should be saved as a .bgeo file.

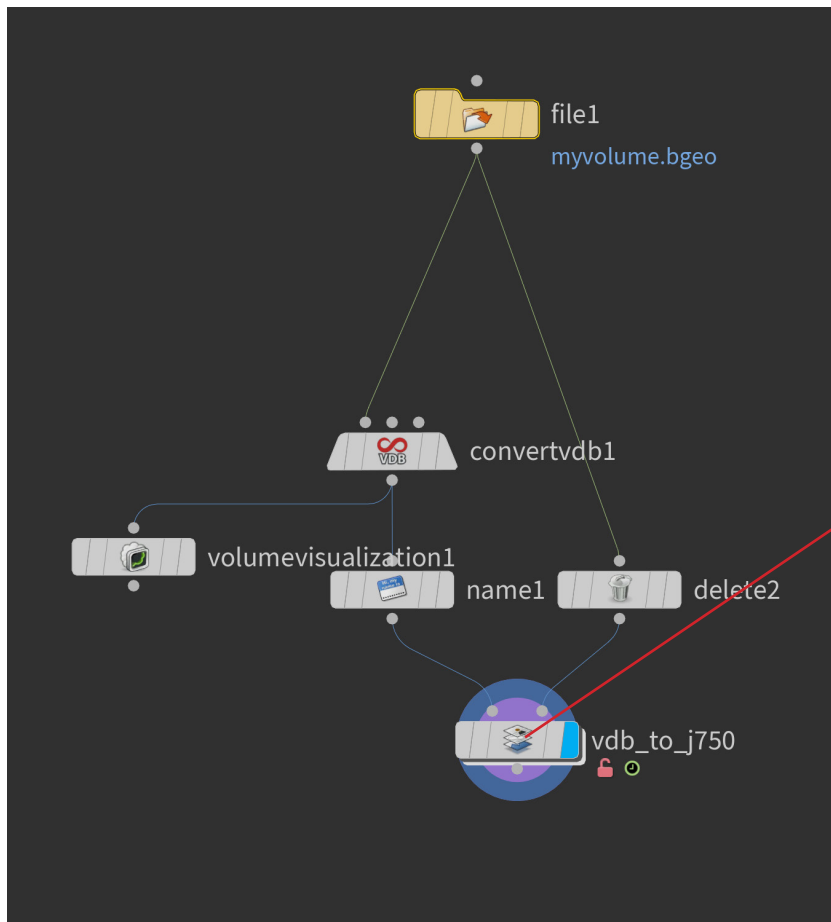


Figure 142a. Voxel Slicer.

The .bgeo file of the volume saved in figure 141c is imported into the Voxel Slicer file using the file tool.

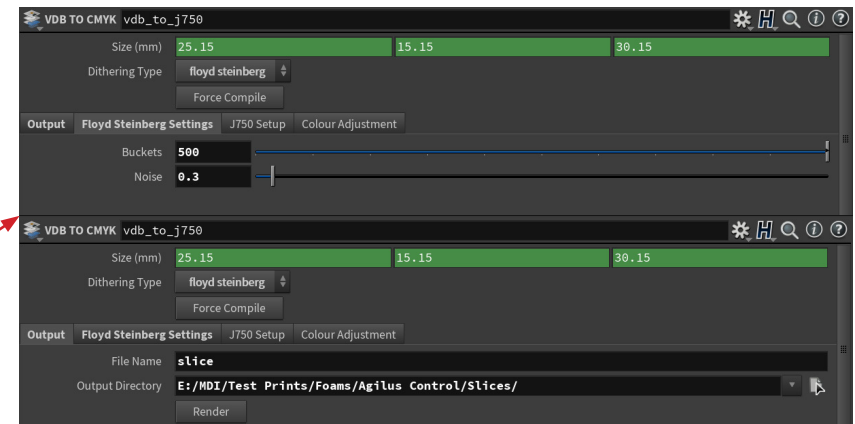


Figure 142b. Voxel Slicer settings and output controls.

Recommended settings for Voxel Slicer. To output your PNG stack in the output tab give a file name and an output directory, then hit render.



Figure 143. Render of shoe with material gradients. Geometry from: Neill, S. (2022). Parametric high heel design [3D Geometry] Work for MDI thesis: *The Iced Slipper* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

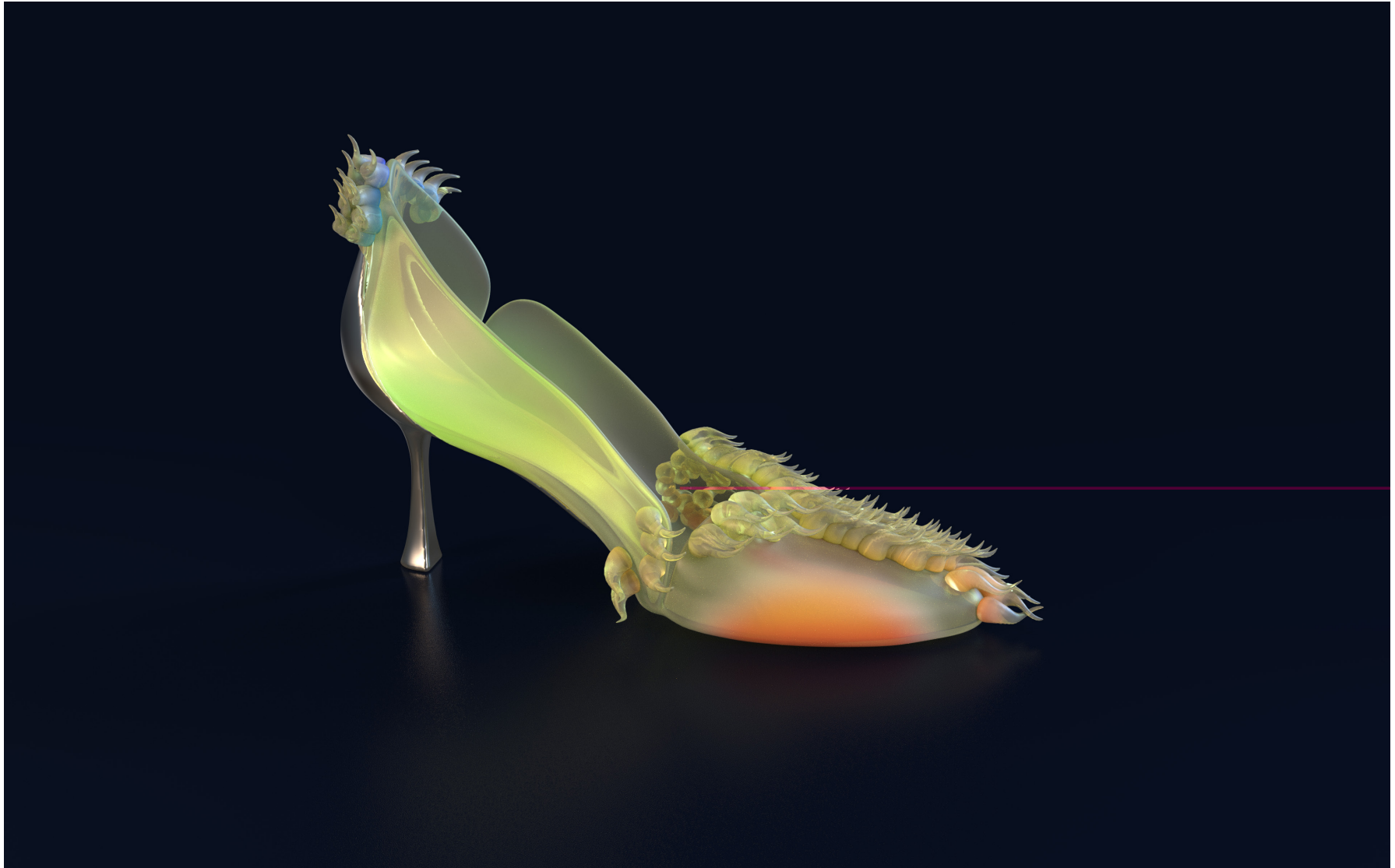


Figure 144. Render of shoe with material gradients. Geometry from: Neill, S. (2022). Parametric high heel design [3D Geometry] Work for MDI thesis: *The Iced Slipper* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

MRI MANIPULATION TOOL

The final outcome of the MRI Manipulation Tool allows for any image stack-based medical dataset to be sampled and converted into a volumetric point cloud for cutting with 3D geometry. This utilises and enhances current medical data voxel printing workflows, which use image stacks from volumetric medical datasets as voxel print slices. Once sampled, the resulting dataset point cloud can be cut with any 3D geometry, produced in any 3D software. The resulting cut medical dataset and input cutting geometry are then each converted into a separate volume, and both are used for voxel printing. This process allows for the creation of functional products containing medical data.

One of the core criteria of the creation of this process is that it is as easy as possible to use while still producing the desired results. This system uses only five nodes that require user inputs (sample grid, slice colour, slice alpha, cutting geometry file and point alpha adjust) and two basic transforms to scale and align the dataset and cutting geometry. The rest of the system is procedurally automated to produce volumes for voxel printing. This means that users with little to no Houdini or 3D volume modelling experience can very quickly learn how to use this system to produce 3D objects containing medical datasets.

Izzy Robb with no prior Houdini experience has utilised this tool in her MDI thesis to create a series of products that contain medical datasets, in doing so exploring how to add value to products by infusing them with personal medical data. This work really demonstrates the efficacy of this tool.

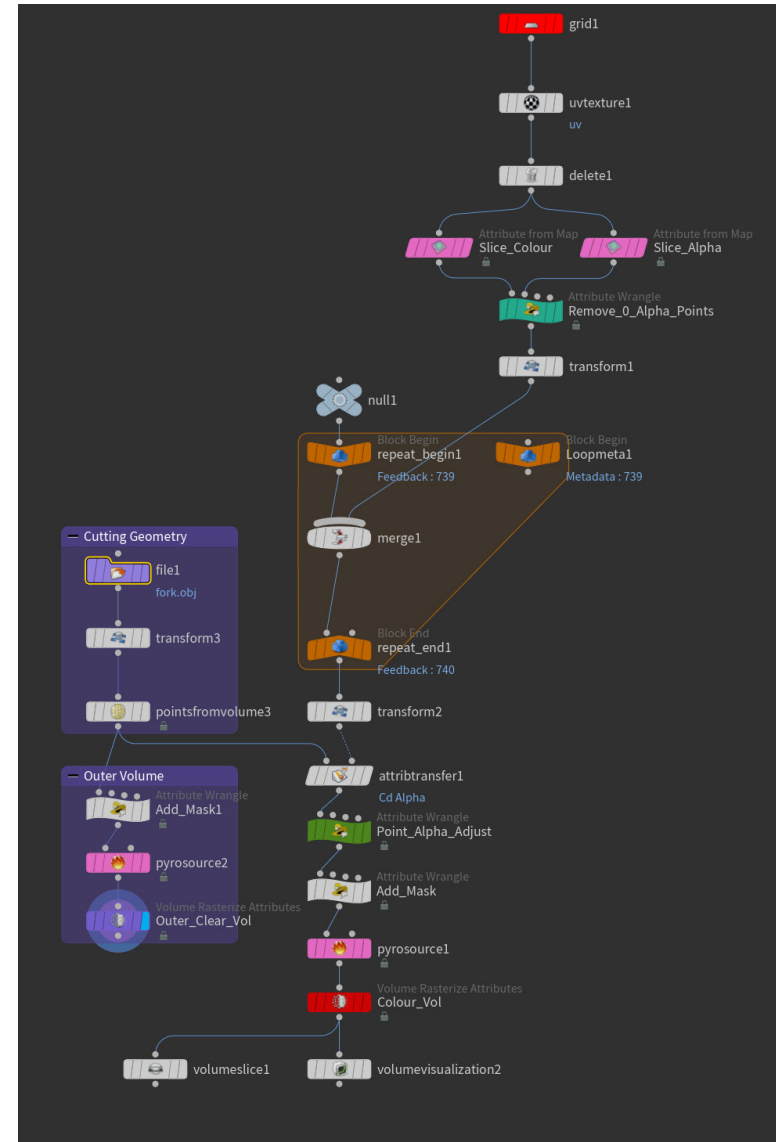


Figure 145. Full MRI manipulator tool.

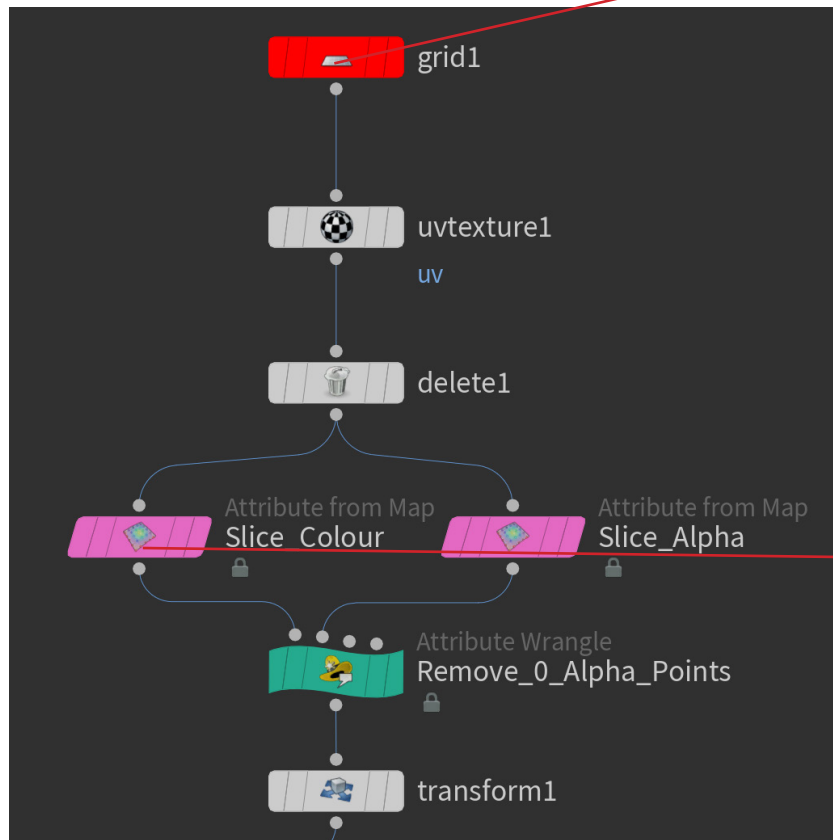


Figure 146a. Dataset input.

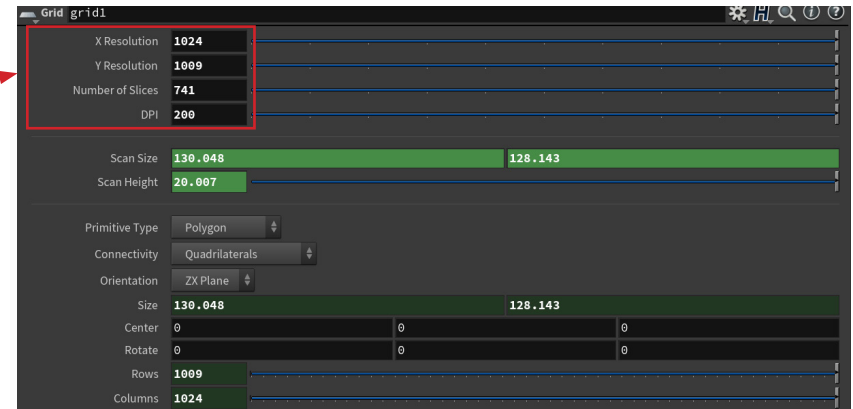


Figure 146b. Sampler grid controls.

The user inputs the sampler grid settings based on the images in their dataset stack. From this the sampler grid is generated to be the right size and resolution.

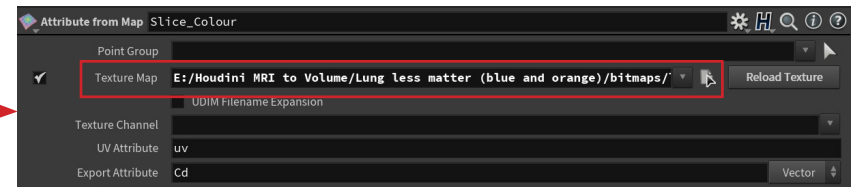


Figure 146c. Image input for medical dataset.

The dataset is input on the slice colour and slice alpha tools, for both use the file directory to find the first image and replace its stack number with:

```
`detail("../Loopmeta1/", "ivalue", 0)`
```

This is a detail function that tells the loop to change the image sampled for each repeated layer.

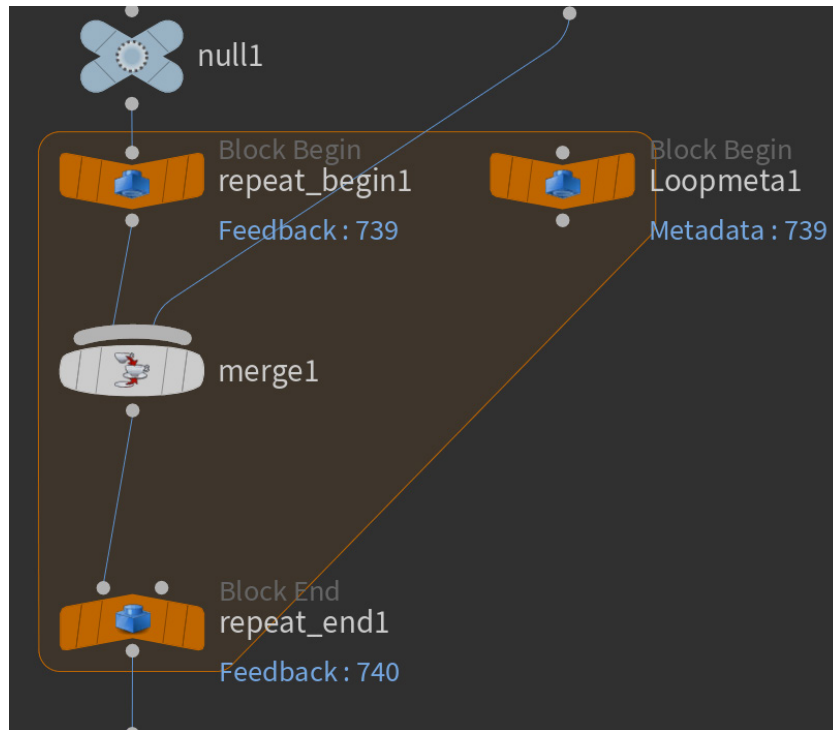


Figure 147a. Loop to sample full image stack in dataset.

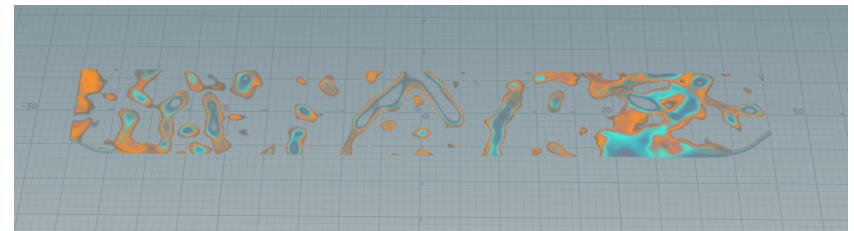


Figure 147b. Single input dataset image.

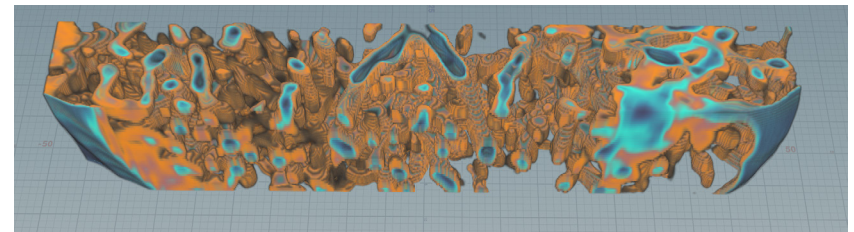


Figure 147a. Full dataset as volumetric point cloud after loop has run.

The loop repeats the input for every image in the dataset, so transforms the output from a single image to a volumetric point cloud made up of the entire image stack.

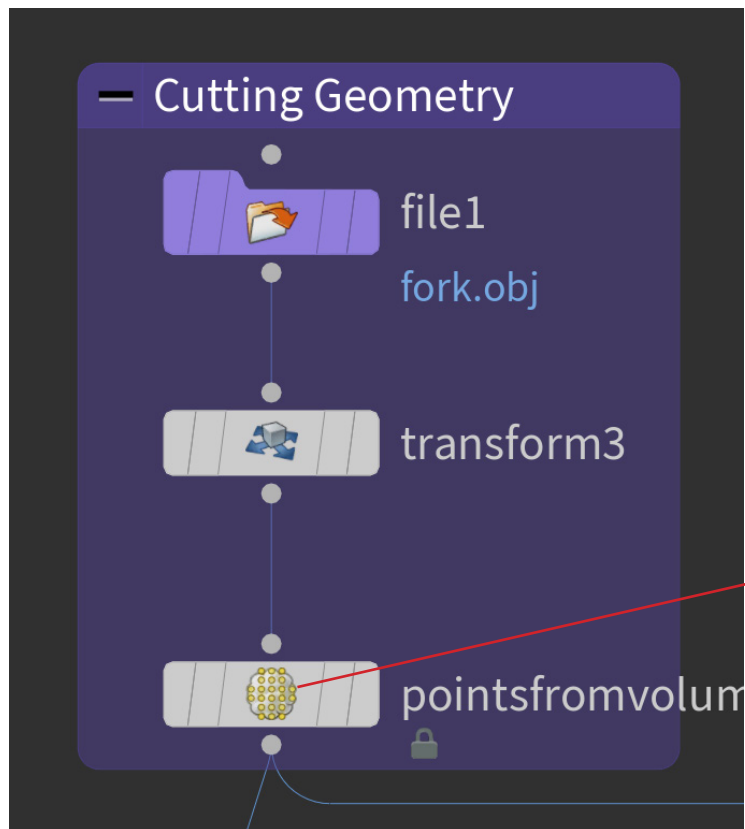


Figure 148a. Inputs for cutting geometry.

The geometry for cutting the dataset is input using the file tool, transform used to ensure it is the correct scale and in the right place.

The points from volume then translates this geometry into a point cloud that can sample the colour from the dataset point cloud, point separation is set and this needs to be the same as the voxel size of your final output volume.

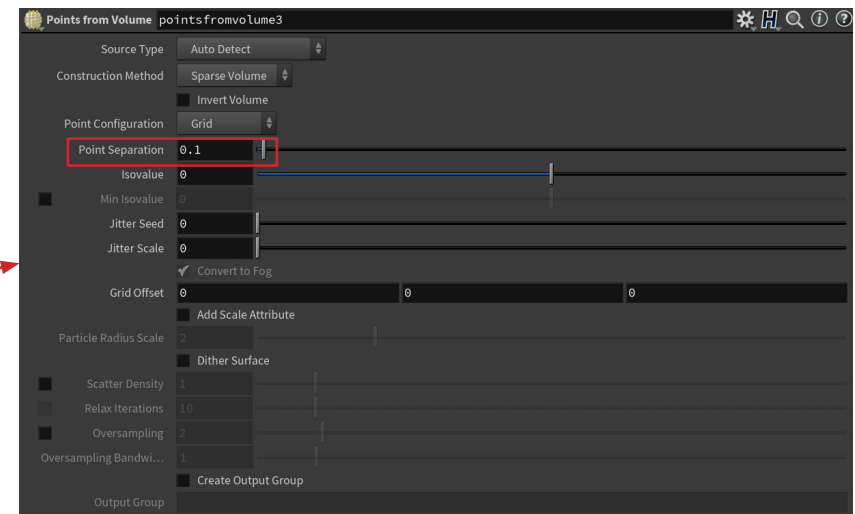


Figure 148b. Points from volume transforms cutting geometry into point cloud.

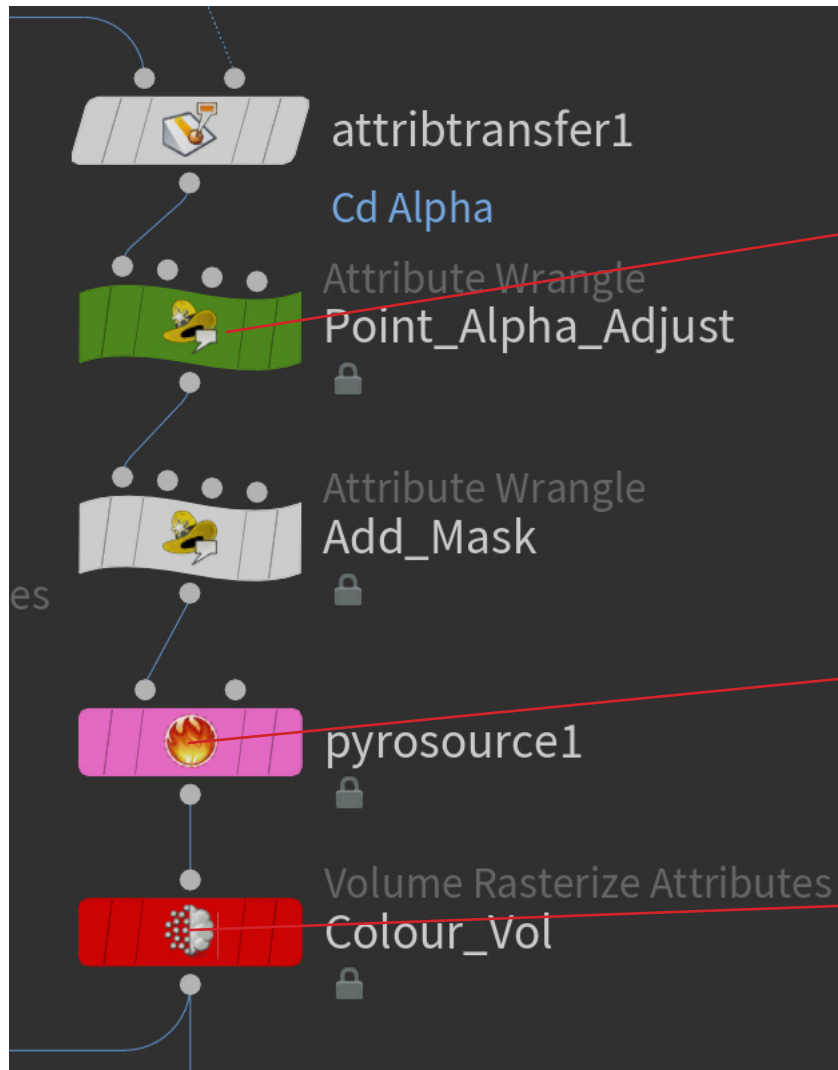


Figure 149a. Points from volume transforms cutting geometry into point cloud.

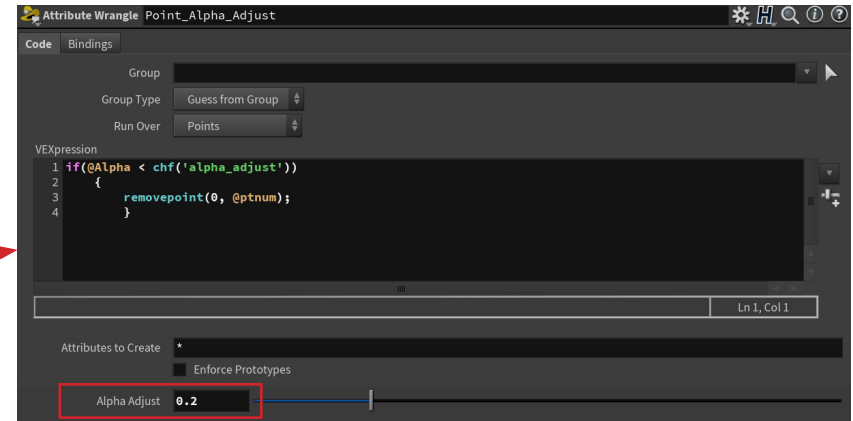


Figure 149b. Alpha adjust tool used to fix dataset point cloud.

The alpha adjust is applied to remove low alpha points from the resulting point cloud to make the volume more accurate to the original dataset. This value is user controlled and left up to their discretion.

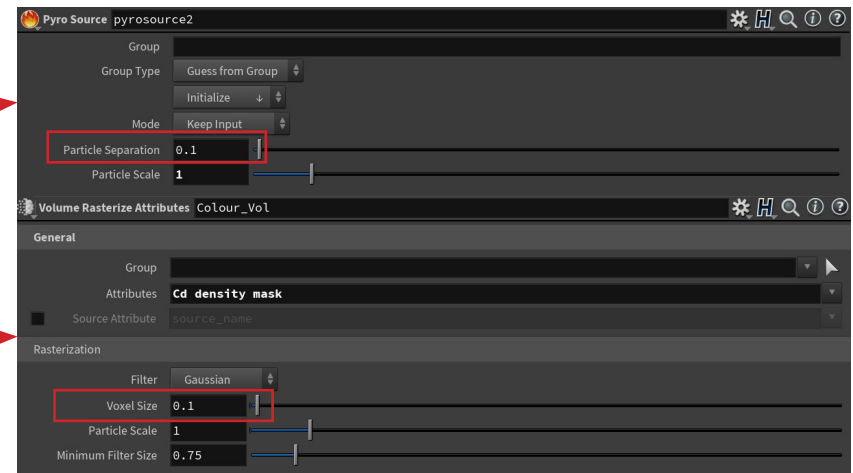


Figure 149c. Creating a the colour volume from cut dataset.

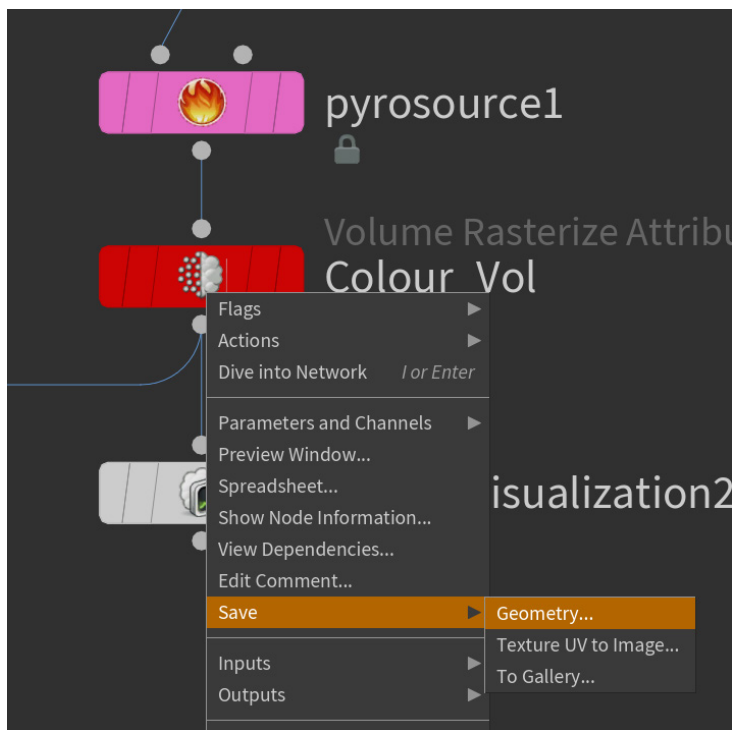


Figure 150. Saving colour volume to use in Voxel Slicer.

The colour volume is formed and saved as a .bgeo file to be input into the Voxel Slicer.

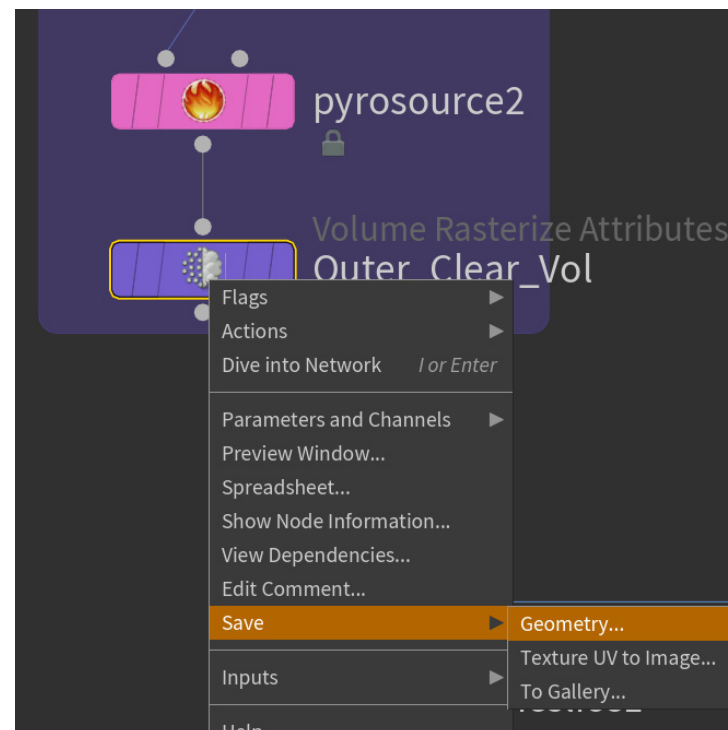


Figure 151. Saving clear background volume to use in Voxel Slicer.

A colourless volume is produced from the cutting geometry, this is also saved to be input into voxel slicer. This will be used to tell the printer to print the background from clear material.

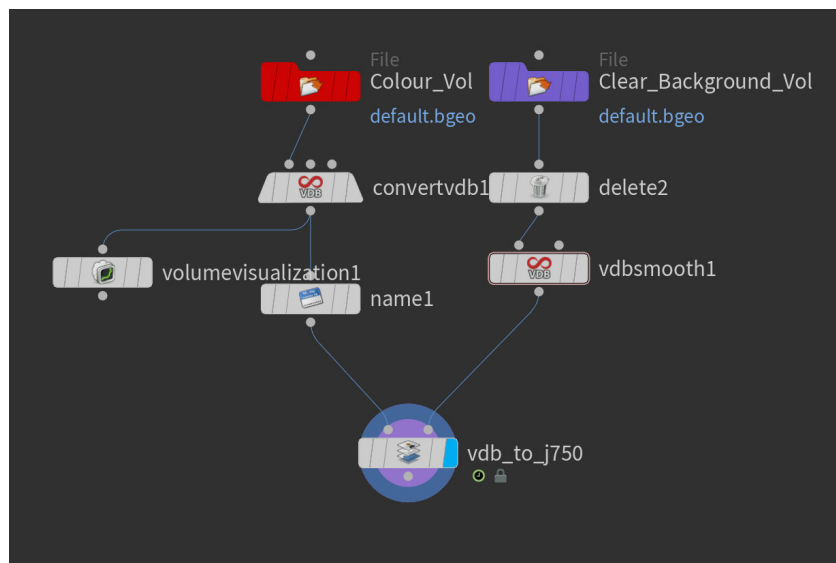


Figure 152. Voxel Slicer setup for medical datasets.

Both volumes are imported into the Voxel Slicer file, the colour goes in the left side and the clear background volume goes into the right.



Figure 153a. Robb, I. (2022). Voxel printed medical dataset forks. [Multi-material 3D print]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

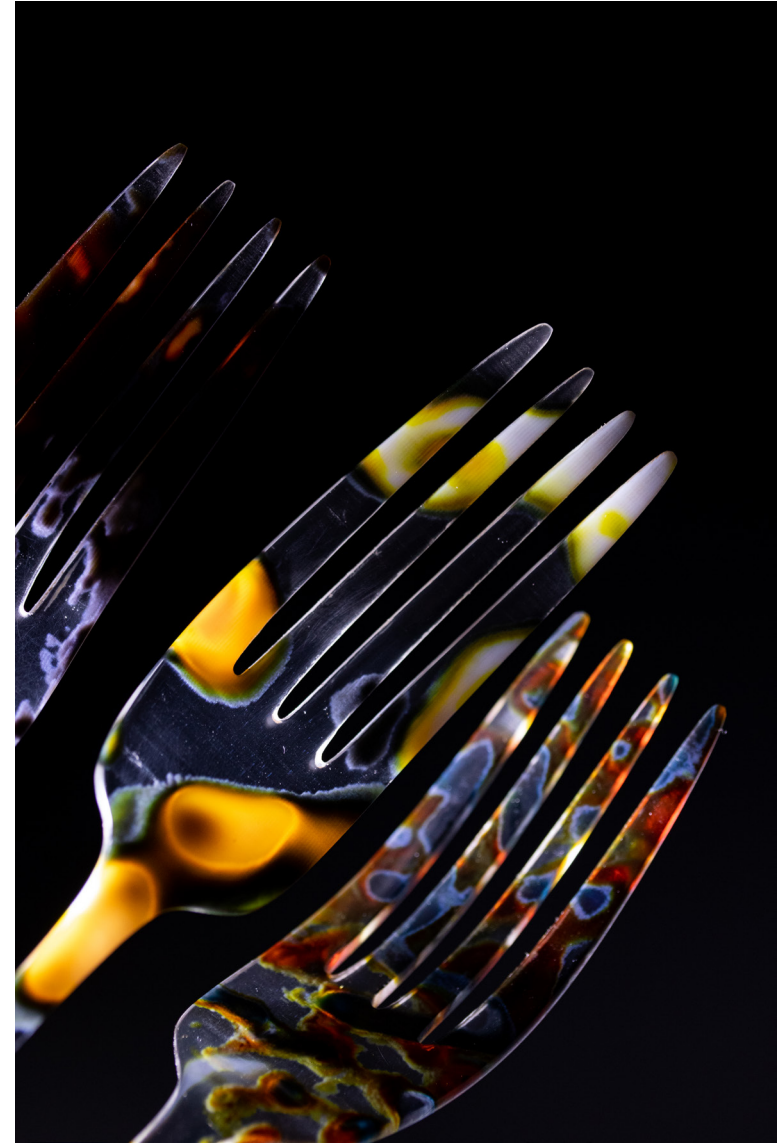


Figure 153b. Robb, I. (2022). Voxel printed medical dataset forks. [Multi-material 3D print]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

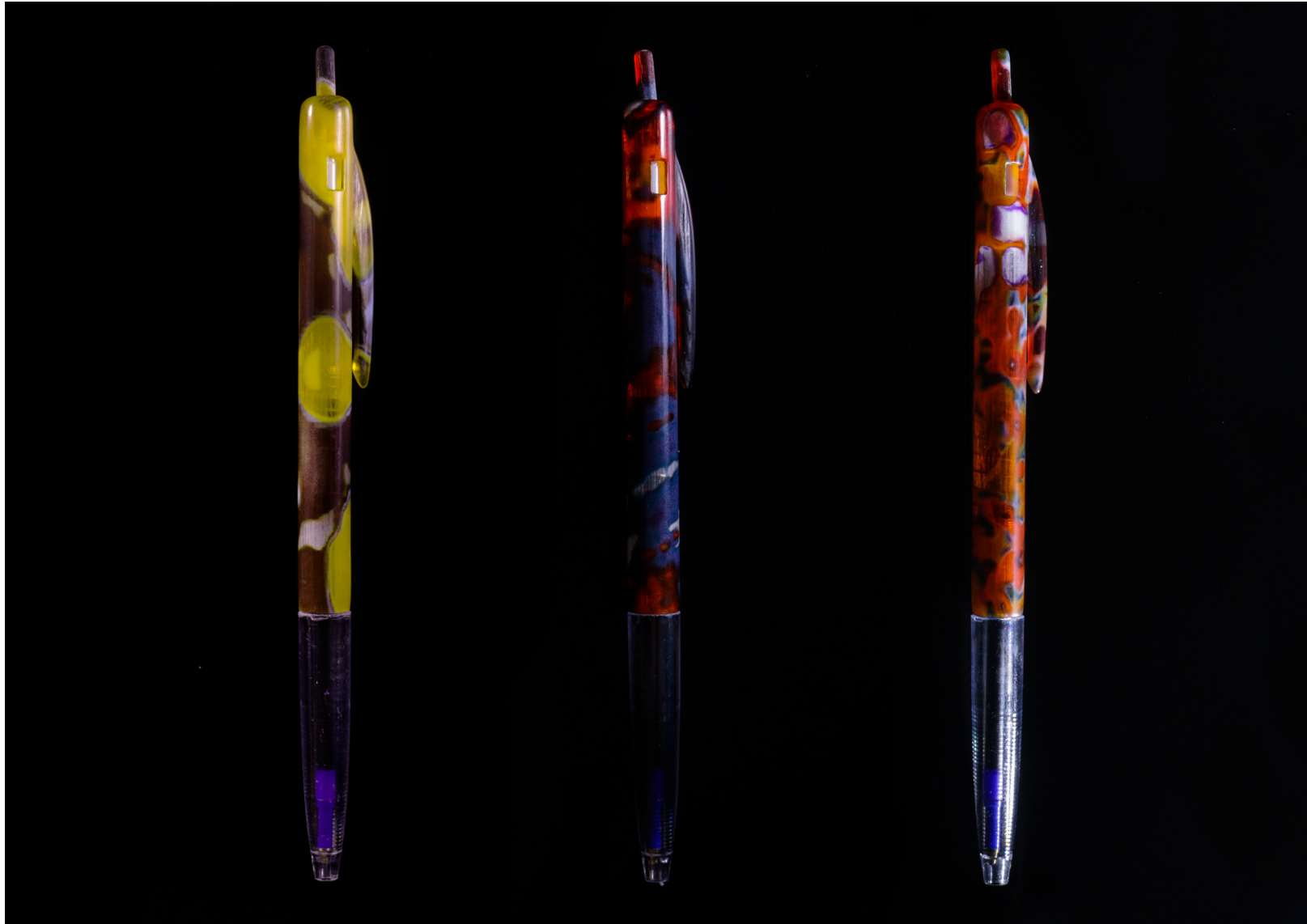


Figure 154. Robb, I. (2022). Voxel printed medical dataset pens. [Multi-material 3D print]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].



Figure 154. Robb, I. (2022). Voxel printed medical dataset glasses. [Multi-material 3D print]. Work created for MDI Thesis: *Body of Matter* [Unpublished manuscript, Open Access Te Herenga Waka-Victoria University of Wellington].

PROCEDURAL SOFT ROBOTS

This system demonstrates how the presented material gradient workflow can be incorporated into a procedural model to produce a dynamic 4D print, which utilises volumetric gradients of material made available through voxel printing.

The design specifications for the output soft robotic grippers are entirely controlled by a set of input parameters. These parameters are endlessly adjustable, so each one can be changed at any time to produce a different gripper result. This allows users to tailor the gripper to meet the specific needs of their fruit crops, so the system is capable of producing a wide array of different grippers. This system streamlines the workflow, removing the time and expertise needed to produce complex 3D models and volumes to voxel print functional 4D objects. So the system provides an accessible way to quickly tailor soft robotic grippers for a variety of fruits, automatically outputting a 3D volume for voxel printing.

As earlier stated, this system utilises volumetric gradients of material. These functionally graded materials allow for the use of the functional properties of both base materials (ie rigidity of Vero and flexibility of Agilus) without introducing points of weakness at the intersection of different materials. Resulting grippers for apples, kiwifruit and strawberries made with this system are demonstrated by the following renders.



Figure 155. Render of soft robotic fruit gripper.



Figure 156. Render of soft robotic fruit gripper.

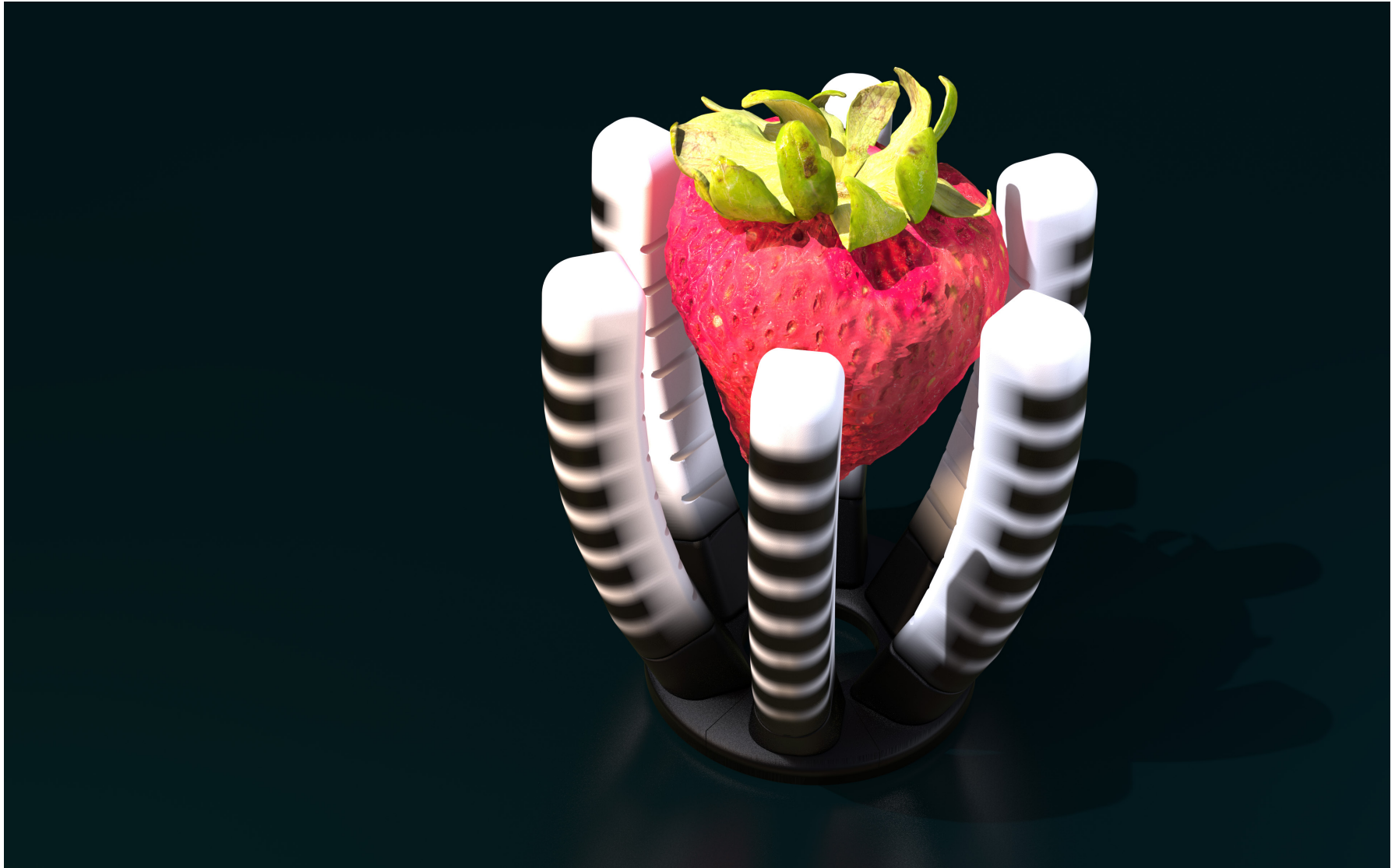


Figure 157. Render of soft robotic fruit gripper.

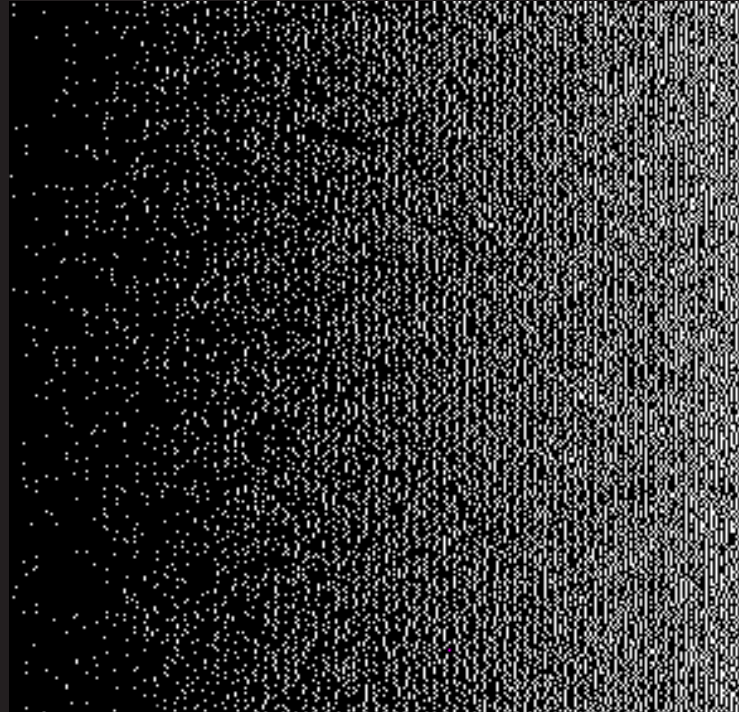


Figure 158. Section of a voxel print slice.

CHAPTER 5

DISCUSSION & CONCLUSION

OVERVIEW

This research sought to answer the question: how might we leverage procedural tools and workflows in order to make harnessing the capabilities of voxel printing more accessible?

This became the goal of the research as it became apparent through teaching and collaboration that there is real value in finding ways to make accessing the capabilities of voxel printing as easy and intuitive as possible. Since voxel level control is still in its infancy, with no real officially established tools, the workflows we have as a research group are still fairly limited. Exploring how to establish workflows to be more accessible not only expands the workflows themselves, but also expands the number of people finding and solving problems. This in turn expands the diversity of ideas and innovations.

The outcome of this research is three procedural tools for use in voxel printing, the output of which would be impossible to produce using any other fabrication method. Each one will be discussed in turn below.

Material Gradient Workflow

Prior to this research, our voxel printing workflow full control of volumetric gradients of material, this output provides a solution to this problem. The focus was to find a workflow that made designing with functionally graded voxel prints as accessible as possible, this settled-upon point cloud based workflow can use geometries produced in any 3D software and the process of using it to control material gradients is incredibly easy to use for anyone with any 3D modelling experience. The hope is that this will now enable many more researchers and designers to explore voxel printing with functionally graded materials.

MRI Manipulator Tool

Exploring our existing workflow for voxel printing using medical datasets, this tool expanded the capabilities of that process by sampling the datasets as a volumetric point cloud that can be manipulated and cut into 3D forms. Again the key consideration of this tool was to unlock new levels of control while keeping the process simple, requiring only a few user inputs and controls. While this was set-up with medical datasets in mind, this tool can be used to sample any image-based dataset, so could be used for a variety of different design explorations.

Soft Robotic Procedural System

This tool gives a contextual example as to how material gradients can be used for 4D prints. Entirely controlled by a set of user input parameters, it is capable of producing a wide array of soft robotic grippers for different fruit. Only requiring user input parameters and outputting a voxel print file for a functional soft robot, this system shows how procedural systems can be leveraged to produce complex outcomes while simplifying the design process.

As it sits currently, this system is set up more for development and testing. Having over 40 inputs to control the majority of the parameters manually, it is still rather elaborate to use. Ideally, for end users, the required parameters would be reduced to simplify the process, and more elements of the design would be automatically generated from these fewer inputs. An example of this would be the actuators being completely determined by the size of the fingers. However, to reach this point would require a substantial amount of material testing outside of the scope of this study.

LIMITATIONS

Covid-19

While the timings of this research mostly missed the major lockdowns, Covid-19 was in the background the entire time this research was conducted.

Adoption of New Software

At the beginning of this research my experience using Houdini was incredibly limited, this meant a substantial amount of learning was needed. In using the software for voxel printing and not VFX as it is intended means that this research uses Houdini in some fairly non-standard ways, so it is very difficult to find solutions to the specific voxel printing problems online. This meant that a significant amount of time during this research was spent experimenting with different workflows and failing, in order to find ways to achieve desired results.

Voxel Slicer software

Currently there is no official Voxel Slicer software so we have to use the Voxel Slicer developed by our research group. This software is currently set up for use with the J750, previous model of the printer, so we currently cannot utilise all eight material channels. The slicer still being in its infancy is prone to bugs, frequently crashing due to caching issues on the VRAM of the graphics card. Often there is a lot of unwanted noise on the output voxel PNG slices, so material would be placed where it isn't desired. This requires many workarounds that need to be found in the process of slicing voxel print files. However an updated version is on the way that will allow for more channels to be assigned, and allowing more freedom with their assignment.

Current Printer Materials

Although this study focussed on the software side of the printing process, 3D printer material limitations still affects design considerations at every stage of the process. One important aspect to consider is the ecological impact of extensive use of the materials. The thermoset nature of these materials means that once they are cured it's incredibly difficult, if not impossible to reuse and recycle printed material. Further, the cured resin is incredibly resistant to biodegradation. Excessive use of these materials would not be ecologically responsible, so it is important to consider what and why you are printing. The flexible material Agilus when compared to commonly used elastomers has fairly limited elastomeric properties especially for extension and recovery. Agilus has been shown to be prone to tearing and when printed in thicker bodies becomes very firm very fast. The limited elastomeric properties put limitations on dynamic functions of 4D prints.

Six Month Suspension

This research was suspended for 6 months between mid-March and mid-September 2021 in order to wait for J750-J850 upgrades and the release of the research package functionality. In that time no research work for the MDI was allowed to be conducted.

Research Package Functionality

Some functionality that is supposed to be included in the research package still isn't working and we have yet to find solutions to fix this. Of note air void printing is supposed to be possible using the voxel printing method, but it currently results in an error when the files are sent to the J850 printer. So it is currently not possible to print an object with both air voids and material gradients.

GrabCad Print

This software is used to prepare .gcvf files for voxel printing and sending them to the printer. Currently the previews for voxel prints within GrabCad print are low-resolution grey forms of the outside shape of the voxel print, so don't give any indication what the final print will look like. We have also discovered lots of issues around air printing, giving errors without any context. So functionality that should be available isn't.

OPPORTUNITIES

Materials

Stratasys have recently released their first ever sustainability report in which they express a commitment to mindful manufacturing and exploring more ecologically responsible practices (Stratasys, 2022). It would be great to see more ecologically responsible and bio-based printing materials become available as a part of this new commitment.

A new material with improved elastomeric properties than Agilus would greatly expand 4D printing capabilities and make voxel control of material architectures more effective for achieving dynamic functions.

Voxel Printing Tools and Workflows

The outcomes of this research provide accessible ways to utilise voxel printing functionality. The tools and workflows here can be utilised as a springboard for future researchers to build tools of their own to expand voxel printing capabilities.

End User Access

The procedural workflows explored here show how input parameters can be used to simplify and streamline the workflows to produce complex 4D prints. Focussing on making these procedural tools as streamlined and easy to use as possible can allow for end users to tailor custom 4D printed robotics without any expertise in 3D modelling or printing.

Control of Material Architectures

This research represents just the first steps in exploring how control of material architectures, unlocked through voxel printing, can allow for functionally graded materials. There is massive scope for exploration into how this level of control over material architectures can be leveraged to produce much more sophisticated and highly functional 4D prints.

Data-driven Material Control

Control over material architectures allows for material placement to be optimised to achieve sophisticated dynamic function. There is massive scope to explore how AI driven optimisation tools trained on real world data can be used to control material architectures for better performing dynamic 4D prints.

FUTURE RESEARCH

This research explored the first steps of producing volumetric gradients of material for functionally graded voxel printing. In the next steps research should explore how to utilise these ideas with data driven material modelling, exploring how real world data and AI driven optimisation of material architectures can be utilised to create voxel print files with optimised material distributions for dynamic functions. Doing this would start to really take advantage of the potential of voxel printing's microstructure control.

The ability to produce data rich material architectures give voxel printing potential as a key pillar in a synthetic evolution in the design of soft robotics structures. These four key pillars embedded intelligence, computer vision, AI optimisation and voxel printing.

Embedded intelligence refers to a soft robots ability to collect data and reflect on its environmental interactions and operational performance (Ang et al., 2022). The ability to embed flexible microprocessors (Biggs et al., 2021) and create soft sensors capable of simultaneous haptic and proprioceptive sensing (R. Truby et al., 2020; R. L. Truby et al., 2018) is going to allow soft robots to collect incredibly rich datasets on their performance. Computer vision here acts as an external observer also collecting data on the soft robots performance. The collective dataset could then be given to AI driven optimisation software to find form and material structures that enhance performance. Voxel printing with its microstructure material control is then used to produce a soft robot with a data rich material architecture based on this optimisation process. This process can be repeated, making it a form of synthetic evolution, allowing designer and computer to work in tandem to iteratively optimise soft robots. So future research should explore such approaches to optimisation.

FINAL EVALUATION

The resulting tools and workflows from this research demonstrate how procedural modelling can be utilised to make the complex processes for voxel printing more accessible. All of these workflows build upon the Voxel Slicer developed by Ben Jack, Dan Scudder and Zach Challies, exploring how to lower the barrier to entry to create 3D volumetric files for it to translate into PNG image slices. Voxel printing unlocks new levels of control over material distribution allowing for microstructural control over material property arrangement and significant amounts of data to be embedded into printed objects. Through the Material Gradient Workflow and MRI Manipulator Tool this research has explored and demonstrated user friendly ways to achieve both. The Soft Robotic Procedural System gives a contextual example illustrating how these workflows might be used for real world 4D printing. Utilising user input parameters has massive potential to allow end users without any design or 3D modelling experience to tailor objects to suit their needs, enabling them to utilise complex manufacturing processes while keeping the process of doing so easy to use.

This research posits that while exploration of the physical capabilities of voxel printing is important, enabling more designers to explore is equally as important. The presented tools tap into and enhance current design workflows, giving designers access to voxel printing capabilities in a way that is intuitive and easy to understand. In doing this, we can expand the community of designers and researchers exploring what voxel printing's unprecedented levels of material control will allow us to achieve.



CONCLUSION

This research sought to answer the question: how might we leverage procedural tools and workflows in order to make harnessing the capabilities of voxel printing more accessible? Voxel printing allows for unprecedented control of material distribution in 3D printed objects, but with this greater control comes significantly more complexity in the 3D print files, requiring every voxel of material to be defined. In exploring how to make the design of these voxel files more accessible, this research presents three different workflows. First, a Material Gradient Workflow for controlling volumetric gradient blends of materials. Second, an MRI Manipulator Tool, that allows medical datasets to be sampled and cut into 3D forms. Finally, a Soft Robotic Procedural System that allows for the customisation of soft robotic fruit pickers through input parameters. All of these workflows demonstrate how procedural workflows can utilise existing workflows and be controlled entirely by a small number of input parameters, allowing for the production of complex voxel files using an intuitive and easy to use workflow. The resulting tools lower the barrier to entry for voxel printing exploration and will allow a greater community of designers to explore and take advantage of these new capabilities. Just as the moving assembly line brought forward a new industrial age of high volume production, the microstructure control of voxel printing has the potential to herald a new revolution of making, as it allows us to move significantly beyond the limitations of human assembly.

LIST OF FIGURES

All figures not cited here are by the author.

Figure 9a. Frogley, C. (2021). *Cassette Necklace - close-up shot* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 9b. Frogley, C. (2021). *Cassette Necklace - in context shot* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 10a. Michelson, M. (2021). *Data of the Future - AI generated DNA images* [AI generated digital images]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 10a. Michelson, M. (2021). *Data of the Future - 3D printed DNA data storage* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 11a. Landon Moore, E. (2021). *Woofers - exploded render* [3D render]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 11b. Landon Moore, E. (2021). *Woofers - cross section* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. (Bottom) *Figure 11c.* Landon Moore, E. (2021). *Woofers* [Multi-material 3D print]. Work created for Industrial Design course INDN 332 at Victoria University of Wellington. Reprinted with permission.

Figure 12a. Roberts, A. (2022). *Creature made with 3MF colour 3D printing* [Multi-material 3D print]. In *Uncanny Bastards - Provoking the Film Industry*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21391242> Reprinted with permission.

Figure 12b. Roberts, A. (2022). *Creature made with 3MF colour 3D printing* [Multi-material 3D print]. In *Uncanny Bastards - Provoking the Film Industry*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21391242> Reprinted with permission.

Figure 13a. Robb, I. (2022). *Process cutting fork from medical data volume* [Screenshot]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

Figure 13b. Robb, I. (2022). *3D printed forks cut from medical datasets* [Multi-material 3D print]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

Figure 16. Hone, N. (2018). *Feather nurse - a pneumatically activated 4D print* [Multi-material 3D print]. In *Tangible Animation—Designing Organic Performance with Multi-Material 3D/4D Printing* [Victorial University of Wellington]. <http://researcharchive.vuw.ac.nz/handle/10063/8063>. Copyright 2022 Nicole Hone

Figure 17. Robinson, T. & Furneaux, W. (2019). *A series of 3D printed prosthetic eyes at varying scales and colours* [Multi-material 3D print]. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2022 Weta Workshop.

Figure 18. Jack, B. D. & Guy, B. (2017). *The style machine software interface* [Screenshot]. In *The Style Machine: Digital Tactility Through Generative Collaboration. 20th Generative Art Conference GA2017*, 12. Copyright 2022 Bernard Guy.

Figure 19. Robinson, T. & Furneaux, W. (2019). *a) The digital model is sampled by a slicing grid. b) Slice 650 of 992 images generated for a 2:1 eyeball. c) Visualisation of the voxels in a small section of the iris.* [Multi-material 3D print]. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2022 Weta Workshop.

Figure 20. Coulson, P. (2020). *Soft robotic pneumatic finger capable of three-dimensional motion* [Multi-material 3D print]. Well, Actuate(ly)...: Parametric Multi-Material 3D Printed Soft Robotics [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14072330.v1>. Copyright 2022 Patrick Coulson.

Figure 22. Hone, N. (2018). *Haven flower -a pneumatically activated 4D print* [Multi-material 3D print] In *Tangible Animation—Designing Organic Performance with Multi-Material 3D/4D Printing* [Victorial University of Wellington]. <http://researcharchive.vuw.ac.nz/handle/10063/8063>. Copyright 2022 Nicole Hone.

Figure 23. Coulson, P. (2020). *Soft robotic gripper* [Multi-material 3D print] Well, Actuate(ly)...: Parametric Multi-Material 3D Printed Soft Robotics [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14072330.v1>. Copyright 2022 Patrick Coulson.

Figure 24. Morris, A. (2020). *Voxel woman* [Multi-material 3D print] In *Beneath the Skin: Emulating human physiology using a novel bitmap-based “voxel” 3D-printing workflow*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.17151335.v1>. Copyright 2022 Ana Morris.

Figure 25. Salter, J. (2020). *3D printed future fossil* [Multi-material 3D print] In *Fossils from the Future* [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14060531.v1>. Copyright 2022 Jessica Salter.

Figure 27. Morris, A., Robb, I., Guy, B. (2021). *J850 diagram* [Digital diagram] In *The Voxel Workflow*. Retrieved from <https://made.ac.nz/wp-content/uploads/2021/11/The-Voxel-Workflow.pdf>.

Figure 143. Render of shoe with material gradients. Geometry from: Neill, S. (2022). *Parametric high heel design* [3D Geometry] In *The Iced Slipper*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21200590> Used with permission.

Figure 144. Render of shoe with material gradients. Geometry from: Neill, S. (2022). *Parametric high heel design* [3D Geometry] In *The Iced Slipper*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21200590> Used with permission.

Figure 153a. Robb, I. (2022). *Voxel printed medical dataset forks*. [Multi-material 3D print]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

Figure 153b. Robb, I. (2022). *Voxel printed medical dataset forks*. [Multi-material 3D print]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

Figure 154. Robb, I. (2022). *Voxel printed medical dataset pens*. [Multi-material 3D print]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

Figure 154. Robb, I. (2022). *Voxel printed medical dataset glasses*. [Multi-material 3D print]. In *Body of Matter - Physical Representations of Anatomical Data*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.21285033>. Reprinted with permission.

REFERENCES

- Adidas. (2022). *Adidas 4D Running Shoes* | adidas New Zealand. Adidas NZ. <https://www.adidas.co.nz/4d-shoes>
- Agritech New Zealand. (2021). About us. *AgriTech New Zealand*. <https://agritechnz.org.nz/about/>
- Altenhofen, C., Luu, T. H., Grasser, T., Dennstädt, M., Mueller-Roemer, J. S., Weber, D., & Stork, A. (2018). Continuous Property Gradation for Multi-Material 3D-Printed Objects. *Proceeding of the 29th Annual International Solid Freeform Fabrication Symposium*, 11.
- Ang, L.-M., Seng, K. P., & Wachowicz, M. (2022). Embedded intelligence and the data-driven future of application-specific Internet of Things for smart environments. *International Journal of Distributed Sensor Networks*, 18(6), 15501329221102372. <https://doi.org/10.1177/15501329221102371>
- Anthony, J. (2021, September 30). *Covid-19 one of many challenges, business leaders say*. Stuff. <https://www.stuff.co.nz/business/farming/agribusiness/126361462/covid19-one-of-many-challenges-business-leaders-say>
- Bader, C., Kolb, D., Weaver, J. C., & Oxman, N. (2016). Data-Driven Material Modeling with Functional Advection for 3D Printing of Materially Heterogeneous Objects. *3D Printing and Additive Manufacturing*, 3(2), 71–79. <https://doi.org/10.1089/3dp.2016.0026>
- Bader, C., Kolb, D., Weaver, J. C., Sharma, S., Hosny, A., Costa, J., & Oxman, N. (2018). Making data matter: Voxel printing for the digital fabrication of data across scales and domains. *Science Advances*, 4(5), eaas8652. <https://doi.org/10.1126/sciadv.aas8652>
- Bartlett, N. W., Tolley, M. T., Overvelde, J. T. B., Weaver, J. C., Mosadegh, B., Bertoldi, K., Whitesides, G. M., & Wood, R. J. (2015). A 3D-printed, functionally graded soft robot powered by combustion. *Science*, 349(6244), 161–165. <https://doi.org/10.1126/science.aab0129>
- Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy*, 13(1), 13–26. <https://doi.org/10.1080/15487733.2017.1394054>
- Biggs, J., Myers, J., Kufel, J., Ozer, E., Craske, S., Sou, A., Ramsdale, C., Williamson, K., Price, R., & White, S. (2021). A natively flexible 32-bit Arm microprocessor. *Nature*, 595(7868), 532–536. <https://doi.org/10.1038/s41586-021-03625-w>
- Boissonneault, T. (2019, October 7). Stratasys launches J750 Digital Anatomy 3D printer for ultra-realistic medical models. *3D Printing Media Network*. <https://www.3dprintingmedia.network/stratasys-j750-digital-anatomy-3d-printer/>
- Brunton, A., Arian, C. A., Tanksale, T. M., & Urban, P. (2018). 3D printing spatially varying color and translucency. *ACM Transactions on Graphics*, 37(4), 1–13. <https://doi.org/10.1145/3197517.3201349>
- Carrier, E. (2018, June 19). *Procedural World Generation of Ubisoft's Far Cry 5* | Etienne Carrier | Houdini HIVE Utrecht. <https://www.youtube.com/watch?v=NfizT369g60>
- Coulson, P. (2021). *Well, Actuate(ly)...: Parametric Multi-Material 3D Printed Soft Robotics* [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14072330.v1>
- Diemar, E.-L. (2021, May 19). *Could this apple picking robot provide a solution to Australia's labour shortage?* Create. <https://createdigital.org.au/this-apple-picking-robot-could-help-solve-australias-labour-shortage/>
- Dobrovski, E. L., Tsai, E. Y., Dikovskiy, D., Geraedts, J. M. P., Herr, H., & Oxman, N. (2015). Voxel-based fabrication through material property mapping: A design method for bitmap printing. *Computer-Aided Design*, 60, 3–13. <https://doi.org/10.1016/j.cad.2014.05.010>
- Eastwood, C. (2019). On-farm technology: Rural professionals vital to agritech future. *The Journal: Official Publication of the New Zealand Institute of Primary Industry Management Incorporated*, 23(4), 18–23.
- Fedrov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J.-C., Pujol, S., Bauer, C., Jennings, D., Fennessy, F. M., Sonka, M., Buatti, J., Aylward, S. R., Miller, J. V., Pieper, S., & Kikinis, R. (2022). *3D Slicer image computing platform*. 3D Slicer. <https://slicer.org/>
- Frankel, L., & Racine, M. (2010). *The Complex Field of Research: For Design, through Design, and about Design*. 12.
- Frayling, C. (1993). Research in art and design. *Royal College of Art Research Papers*, 1(1), 1–5.
- Ge, Q., Sakhaei, A. H., Lee, H., Dunn, C. K., Fang, N. X., & Dunn, M. L. (2016). Multimaterial 4D Printing with Tailorable Shape Memory Polymers. *Scientific Reports*, 6(1), 31110. <https://doi.org/10.1038/srep31110>
- Gerboni, G. (2018). *The incredible potential of flexible, soft robots*. https://www.ted.com/talks/giada_gerboni_the_incredible_potential_of_flexible_soft_robots
- Giaccardi, E., & Stappers, P. (2017). Research through Design. In *The encyclopedia of human-computer interaction* (2nd ed.). <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design>
- Grabcad. (2020a). *Best Practices for Working in KeyShot & GrabCAD Print* | GrabCAD Tutorials. <https://grabcad.com/tutorials/best-practices-for-working-in-keyshot-grabcad-print>
- Grabcad. (2020b). *Guide to Voxel Printing—GrabCAD Help Center*. <https://help.grabcad.com/article/230-guide-to-voxel-printing?locale=en>

- Gul, J. Z., Sajid, M., Rehman, M. M., Siddiqui, G. U., Shah, I., Kim, K.-H., Lee, J.-W., & Choi, K. H. (2018). 3D printing for soft robotics – a review. *Science and Technology of Advanced Materials*, 19(1), 243–262. <https://doi.org/10.1080/14686996.2018.1431862>
- Hanington, B., & Martin, B. (2012). *Universal Methods of Design: 100 Ways to Explore Complex Problems, Develop Innovative Strategies, and Deliver Effective Design*. So. Quarto Publishing Group USA. <http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=3399583>
- Hone, N. (2018). *Tangible Animation—Designing Organic Performance with Multi-Material 3D/4D Printing* [Victoria University of Wellington]. <http://researcharchive.vuw.ac.nz/handle/10063/8063>
- Hosny, A., Keating, S. J., Dilley, J. D., Ripley, B., Kelil, T., Pieper, S., Kolb, D., Bader, C., Poblath, A.-M., Griffin, M., Nezafat, R., Duda, G., Chiocca, E. A., Stone, J. R., Michaelson, J. S., Dean, M. N., Oxman, N., & Weaver, J. C. (2018). From Improved Diagnostics to Presurgical Planning: High-Resolution Functionally Graded Multimaterial 3D Printing of Biomedical Tomographic Data Sets. *3D Printing and Additive Manufacturing*, 5(2), 103–113. <https://doi.org/10.1089/3dp.2017.0140>
- Hubbard, J. D., Acevedo, R., Edwards, K. M., Alsharhan, A. T., Wen, Z., Landry, J., Wang, K., Schaffer, S., & Sochol, R. D. (2021). Fully 3D-printed soft robots with integrated fluidic circuitry. *Science Advances*, 7(29), eabe5257. <https://doi.org/10.1126/sciadv.abe5257>
- Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X., & Whitesides, G. M. (2011). Soft Robotics for Chemists. *Angewandte Chemie*, 123(8), 1930–1935. <https://doi.org/10.1002/ange.201006464>
- Iuarte, I. F., Boddeti, N., Hassani, V., Dunn, M. L., & Rosen, D. W. (2019). Design and additive manufacture of functionally graded structures based on digital materials. *Additive Manufacturing*, 30, 100839. <https://doi.org/10.1016/j.addma.2019.100839>
- Jack, B. D., & Guy, B. (2017). *The style machine: Digital tactility through generative collaboration*. 12.
- Jha, K., Doshi, A., Patel, P., & Shah, M. (2019). A comprehensive review on automation in agriculture using artificial intelligence. *Artificial Intelligence in Agriculture*, 2, 1–12. <https://doi.org/10.1016/j.aiia.2019.05.004>
- Johnson, N. (2021, March 15). *FW Article: Automation a mixed blessing for fruit sector*. <https://farmersweekly.co.nz/s/fw-article/automation-a-mixed-blessing-for-fruit-sector-MCX-SGU4NVAV5GGTHAC5BGEJ3F24I>
- Kang, H., Zhou, H., & Chen, C. (2020). Visual Perception and Modeling for Autonomous Apple Harvesting. *IEEE Access*, 8, 62151–62163. <https://doi.org/10.1109/ACCESS.2020.2984556>
- Kelly, R. (2021, May 21). *Shortage of workers causing stress for farmers*. Stuff. <https://www.stuff.co.nz/business/farming/125190004/shortage-of-workers-causing-stress-for-farmers>
- Kolb, D. (2017). *Printing the invisible: Bridging the gap between data and matter through voxel-based 3D printing* [Thesis, Massachusetts Institute of Technology]. <https://dspace.mit.edu/handle/1721.1/112911>
- Kolodny, L., & Black, E. (2019, May 11). *This robot can pick tomatoes without bruising them and detect ripeness better than humans*. CNBC. <https://www.cnbc.com/2019/05/11/root-ai-unveils-its-tomato-picking-robot-virgo.html>
- Kootstra, G., Wang, X., Blok, P. M., Hemming, J., & van Henten, E. (2021). Selective Harvesting Robotics: Current Research, Trends, and Future Directions. *Current Robotics Reports*, 2(1), 95–104. <https://doi.org/10.1007/s43154-020-00034-1>
- Koslow, T. (2019, April 11). How LAIKA used 3D printing and Cuttlefish software to bring 'Missing Link' to life. *3D Printing Media Network*. <https://www.3dprintingmedia.network/laika-3d-printing-cuttlefish-missing-link/>
- Kumar, K., Liu, J., Christianson, C., Ali, M., Tolley, M. T., Aizenberg, J., Ingber, D. E., Weaver, J. C., & Bertoldi, K. (2017). A Biologically Inspired, Functionally Graded End Effector for Soft Robotics Applications. *Soft Robotics*, 4(4), 317–323. <https://doi.org/10.1089/soro.2017.0002>
- Li, Y., Feng, Z., Hao, L., Huang, L., Xin, C., Wang, Y., Bilotti, E., Essa, K., Zhang, H., Li, Z., Yan, F., & Peijs, T. (2020). A Review on Functionally Graded Materials and Structures via Additive Manufacturing: From Multi-Scale Design to Versatile Functional Properties. *Advanced Materials Technologies*, 5(6), 1900981. <https://doi.org/10.1002/admt.201900981>
- Liu, Z., Meyers, M. A., Zhang, Z., & Ritchie, R. O. (2017). Functional gradients and heterogeneities in biological materials: Design principles, functions, and bioinspired applications. *Progress in Materials Science*, 88, 467–498. <https://doi.org/10.1016/j.pmatsci.2017.04.013>
- Lo, C. (2019, January 23). *3D-printed anatomical models: The next generation of surgical guides*. Verdict Medical Devices. https://medical-technology.nridigital.com/medical_technology_jan19/form_and_function_a_revolution_in_3d-printed_anatomical_models
- Loh, G. H., Pei, E., Harrison, D., & Monzón, M. D. (2018). An overview of functionally graded additive manufacturing. *Additive Manufacturing*, 23, 34–44. <https://doi.org/10.1016/j.addma.2018.06.023>
- Mahmud, M. S. A., Abidin, M. S. Z., Emmanuel, A. A., & Hasan, H. S. (2020). Robotics and Automation in Agriculture: Present and Future Applications. *Applications of Modelling and Simulation*, 4(0), 130–140.

Milton, A., & Rodgers, P. (2013). *Research Methods for Product Design*. Laurence King Publishing. <http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=5741494>

Ministry for Primary Industries. (2020a). *Fit for a better world: Accelerating our economic potential*. <https://www.mpi.govt.nz/dmsdocument/41031-fit-for-a-better-world-accelerating-our-economic-potential>

Ministry for Primary Industries. (2020b). *Situation and outlook for primary industries: December 2020*. https://www.beehive.govt.nz/sites/default/files/2020-12/SOPI%20December%202020_0.pdf

Ministry for Primary Industries. (2021a). *Situation and outlook for primary industries: June 2021*. <https://www.mpi.govt.nz/dmsdocument/45451-Situation-and-Outlook-for-Primary-Industries-SOPI-June-2021>

Ministry for Primary Industries. (2021b). *Situation and outlook for primary industries: December 2021*. <https://www.mpi.govt.nz/dmsdocument/49066-Situation-and-Outlook-for-Primary-Industries-SOPI-December-2021>

Ministry for Primary Industries. (2022). *Sustainable Food and Fibre Futures | MPI - Ministry for Primary Industries. A New Zealand Government Department*. Ministry for Primary Industries. <https://www.mpi.govt.nz/funding-rural-support/sustainable-food-fibre-futures/>

Ministry of Business Innovation & Employment. (2020). *Growing innovative industries in New Zealand: Agritech industry transformation plan—July 2020* (p. 54).

Momeni, F., M.Mehdi Hassani.N, S., Liu, X., & Ni, J. (2017). A review of 4D printing. *Materials & Design*, 122, 42–79. <https://doi.org/10.1016/j.matdes.2017.02.068>

Morris, A. (2020). *Beneath the Skin: Emulating human physiology using a novel bit-map-based “voxel” 3D-printing workflow*. [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.17151335.v1>

Nervous System. (2015). *Data-driven midsoles with New Balance*. Projects by Nervous System. <http://n-e-r-v-o-u-s.com/projects/index.php?albums/new-balance-midsoles/>

Nike. (2018). *Nike Flyprint is the First Performance 3D Printed Textile Upper*. Nike News. <https://news.nike.com/news/nike-flyprint-3d-printed-textile>

Oliveira, L. F. P., Moreira, A. P., & Silva, M. F. (2021). Advances in Agriculture Robotics: A State-of-the-Art Review and Challenges Ahead. *Robotics*, 10(2), 52. <https://doi.org/10.3390/robotics10020052>

Ou, J., Dublon, G., Cheng, C.-Y., Heibeck, F., Willis, K., & Ishii, H. (2016). Cilllia: 3D Printed Micro-Pillar Structures for Surface Texture, Actuation and Sensing. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 5753–5764. <https://doi.org/10.1145/2858036.2858257>

Oxman, N. (2011). Variable property rapid prototyping: Inspired by nature, where form is characterized by heterogeneous compositions, the paper presents a novel approach to layered manufacturing entitled variable property rapid prototyping. *Virtual and Physical Prototyping*, 6(1), 3–31. <https://doi.org/10.1080/17452759.2011.558588>

Oxman, N. (2015). *Design at the intersection of technology and biology*. https://www.ted.com/talks/neri_oxman_design_at_the_intersection_of_technology_and_biology

Patel, S. V., & Kiatkulpiboone, N. (2020). Voxel Harvest: Multi-sensory Design of a Biomedical Device from Image-Based Inputs. In C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, & S. Weinzierl (Eds.), *Impact: Design With All Senses* (pp. 173–188). Springer International Publishing. https://doi.org/10.1007/978-3-030-29829-6_14

Pei, E. (2014). 4D printing—Revolution or fad? *Assembly Automation*, 34(2), 123–127. <https://doi.org/DOI:10.1108/AA-02-2014-014>

Pei, E., Loh, G. H., Harrison, D., Almeida, H. de A., Monzón Verona, M. D., & Paz, R. (2017). A study of 4D printing and functionally graded additive manufacturing. *Assembly Automation*, 37(2), 147–153. <https://doi.org/10.1108/AA-01-2017-012>

Prince, J. D. (2014). 3D Printing: An Industrial Revolution. *Journal of Electronic Resources in Medical Libraries*, 11(1), 39–45. <https://doi.org/10.1080/15424065.2014.877247>

Rad, C.-R., Hancu, O. H., & Lapusan, C. (2020). Aspects regarding “soft” grasping in smart agricultural harvesting tasks. *Acta Technica Napocensis - Series: Applied Mathematics, Mechanics, and Engineering*, 63(4). <https://atna-mam.utcluj.ro/index.php/Acta/article/view/1420>

Radford, A., Kim, J. W., Hallacy, C., Ramesh, A., Goh, G., Agarwal, S., Sastry, G., Askill, A., Mishkin, P., Clark, J., Krueger, G., & Sutskever, I. (2021). *Learning Transferable Visual Models From Natural Language Supervision* (arXiv:2103.00020). arXiv. <http://arxiv.org/abs/2103.00020>

Rafiee, M., Farahani, R. D., & Therriault, D. (2020). Multi-Material 3D and 4D Printing: A Survey. *Advanced Science*, 7(12), 1902307. <https://doi.org/10.1002/adv.201902307>

Ranzani, T., Gerboni, G., Cianchetti, M., & Menciassi, A. (2015). A bioinspired soft manipulator for minimally invasive surgery. *Bioinspiration & Biomimetics*, 10(3), 035008. <https://doi.org/10.1088/1748-3190/10/3/035008>

Rialti, R., Marrucci, A., Zollo, L., & Ciappei, C. (2022). Digital technologies, sustainable open innovation and shared value creation: Evidence from an Italian agritech business. *British Food Journal, ahead-of-print(ahead-of-print)*. <https://doi.org/10.1108/BFJ-03-2021-0327>

- Richards, D., Abram, T., & Rennie, A. (2017). Designing Digital Materials with Volumetric Gradients. *Undefined*. <https://www.semanticscholar.org/paper/Designing-Digital-Materials-with-Volumetric-Richards-Abram/d7b3369bf9a77ebacd0cecf1a87ea4acfa73fca>
- Robinson, T., & Furneaux, W. (2019). Voxel printing using procedural art-directable technologies. *ACM SIGGRAPH 2019 Posters*, 1–2. <https://doi.org/10.1145/3306214.3338555>
- Rodriguez Ramirez, E. (2017). A Postgraduate Thesis Model for Research through Design Based on Design Criteria. *The International Journal of Designed Objects*, 11, 11–27. <https://doi.org/10.18848/2325-1379/CGP/v11i04/11-27>
- Rogers, A. (2017). Prototyping with polyjet 3d printing. *Appliance Design*, 65(7), 25–26.
- Root AI. (n.d.). *Root AI - Join the future of farming*. Retrieved March 3, 2022, from <https://root-ai.com/>
- Rus, D., & Tolley, M. (2015). Design, fabrication and control of soft robots. *Nature*, 521, 467–475. <https://doi.org/10.1038/nature14543>
- Sachyani Keneth, E., Kamyshny, A., Totaro, M., Beccai, L., & Magdassi, S. (2021). 3D Printing Materials for Soft Robotics. *Advanced Materials*, 33(19), 2003387. <https://doi.org/10.1002/adma.202003387>
- Salter, J. (2021). *Fossils from the Future* [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. <https://doi.org/10.26686/wgtn.14060531.v1>
- Schaffner, M., Faber, J. A., Pianegonda, L., Rühls, P. A., Coulter, F., & Studart, A. R. (2018). 3D printing of robotic soft actuators with programmable bioinspired architectures. *Nature Communications*, 9(1), 878. <https://doi.org/10.1038/s41467-018-03216-w>
- Schneider, B. (2007). Design as Practice, Science and Research. In R. Michel (Ed.), *Design Research Now* (pp. 207–218). DE GRUYTER. https://doi.org/10.1007/978-3-7643-8472-2_12
- Self-Assembly Lab. (2018). *Liquid printed pneumatics*. Self-Assembly Lab. <https://selfassemblylab.mit.edu/liquid-printed-pneumatics>
- Shepherd, R. F., Ilievski, F., Choi, W., Morin, S. A., Stokes, A. A., Mazzeo, A. D., Chen, X., Wang, M., & Whitesides, G. M. (2011). Multigait soft robot. *Proceedings of the National Academy of Sciences*, 108(51), 20400–20403. <https://doi.org/10.1073/pnas.1116564108>
- Shintake, J., Caccuciolo, V., Floreano, D., & Shea, H. (2018). Soft Robotic Grippers. *Advanced Materials*, 30(29), 1707035. <https://doi.org/10.1002/adma.201707035>
- SideFX. (2022). *Houdini—3D modeling, animation, VFX, look development, lighting and rendering* | SideFX. <https://www.sidefx.com/>
- Skylar-Scott, M. A., Mueller, J., Visser, C. W., & Lewis, J. A. (2019). Voxelated soft matter via multimaterial multinozzle 3D printing. *Nature*, 575(7782), 330–335. <https://doi.org/10.1038/s41586-019-1736-8>
- Smelik, R. M., Tutenel, T., Bidarra, R., & Benes, B. (2014). A Survey on Procedural Modelling for Virtual Worlds. *Computer Graphics Forum*, 33(6), 31–50. <https://doi.org/10.1111/cgf.12276>
- Snow, V., Rodriguez, D., Dynes, R., Kaye-Blake, W., Mallawaarachchi, T., Zydenbos, S., Cong, L., Obadovic, I., Agnew, R., Amery, N., Bell, L., Benson, C., Clinton, P., Dreccer, M. F., Dunningham, A., Gleeson, M., Harrison, M., Hayward, A., Holzworth, D., ... Stevens, D. (2021). Resilience achieved via multiple compensating subsystems: The immediate impacts of COVID-19 control measures on the agri-food systems of Australia and New Zealand. *Agricultural Systems*, 187, 103025. <https://doi.org/10.1016/j.agsy.2020.103025>
- Spanaki, K., Sivarajah, U., Fakhimi, M., Despoudi, S., & Irani, Z. (2022). Disruptive technologies in agricultural operations: A systematic review of AI-driven AgriTech research. *Annals of Operations Research*, 308(1), 491–524. <https://doi.org/10.1007/s10479-020-03922-z>
- Sparrman, B., du Pasquier, C., Thomsen, C., Darbari, S., Rustom, R., Laucks, J., Shea, K., & Tibbits, S. (2021). Printed silicone pneumatic actuators for soft robotics. *Additive Manufacturing*, 40, 101860. <https://doi.org/10.1016/j.addma.2021.101860>
- Stratasys. (2022). *J8 Series 3D Printers Designed for Designers: J850, J835, & J826* | Stratasys. <https://www.stratasys.com/mx/3d-printers/j8-series>
- Stevens, R. (2015). *Computers as Co-authors (2015)* | MADE. <https://made.ac.nz/project/computers-as-co-authors/>
- Stevenson, K. (2018, January 17). *3D Design Futures: An Interview with Dr. Daniel Richards, Part 2 « Fabbaloo*. Fabbaloo. <https://www.fabbaloo.com/blog/2018/1/17/3d-design-futures-an-interview-with-dr-daniel-richards-part-2>
- Stratasys. (2020). *What is PolyJet Technology for 3D Printing?* Stratasys. <https://www.stratasys.com/polyjet-technology>
- Stratasys. (2022). *Stratasys esg and sustainability report* (No. 1; p. 94). <https://www.stratasys.com/siteassets/about-us/sustainability/stratasys-esg-and-sustainability-report.pdf?v=498fbf>
- Stute, F., Mici, J., Chamberlain, L., & Lipson, H. (2018). Digital Wood: 3D Internal Color Texture Mapping. *3D Printing and Additive Manufacturing*, 5(4), 285–291. <https://doi.org/10.1089/3dp.2018.0078>

Sydney Gladman, A., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., & Lewis, J. A. (2016). Biomimetic 4D printing. *Nature Materials*, 15(4), 413–418. <https://doi.org/10.1038/nmat4544>

Tangible Media Group. (2015, October). *BioLogic* [InteractiveResource]. <http://tangible.media.mit.edu/project/biologic>

Technology Investment Network. (2020). *New Zealand agritech insights report: 2020*. https://ndhadeliver.natlib.govt.nz/delivery/StreamGate?is_mobile=false&metadata=xsl&is_rtl=false&dps_dvs=1645491496903~325&dps_pid=FL55442774

Technology Investment Network. (2021). *New Zealand agritech insights report: 2021*. https://ndhadeliver.natlib.govt.nz/delivery/StreamGate?is_mobile=false&metadata=xsl&is_rtl=false&dps_dvs=1645491475610~119&dps_pid=FL70847205

Tibbits, S. (2014). 4D Printing: Multi-Material Shape Change. *Architectural Design*, 84(1), 116–121. <https://doi.org/10.1002/ad.1710>

Tibbits, S., McNelly, C., Olguin, C., Dikovsky, D., & Hirsch, S. (2014). 4D PRINTING AND UNIVERSAL TRANSFORMATION. *MATERIAL AGENCY*, 10.

Truby, R., Della Santina, C., & Rus, D. (2020). Distributed Proprioception of 3D Configuration in Soft, Sensorized Robots via Deep Learning. *IEEE Robotics and Automation Letters*, PP, 1–1. <https://doi.org/10.1109/LRA.2020.2976320>

Truby, R. L., Wehner, M., Grosskopf, A. K., Vogt, D. M., Uzel, S. G. M., Wood, R. J., & Lewis, J. A. (2018). Soft Somatosensitive Actuators via Embedded 3D Printing. *Advanced Materials*, 30(15), 1706383. <https://doi.org/10.1002/adma.201706383>

United Nations. (2017). *World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100*. United Nations; United Nations. <https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100>

Vegetable Growers News. (2021). *AppHarvest acquires Root A1 and its signature data-collecting robot, Virgo*. Vegetable Growers News. <https://vegetablegrowersnews.com/news/appharvest-acquires-root-a1-and-its-signature-data-collecting-robot-virgo/>

Williams, H. A. M., Jones, M. H., Nejati, M., Seabright, M. J., Bell, J., Penhall, N. D., Barnett, J. J., Duke, M. D., Scarfe, A. J., Ahn, H. S., Lim, J., & MacDonald, B. A. (2019). Robotic kiwifruit harvesting using machine vision, convolutional neural networks, and robotic arms. *Biosystems Engineering*, 181, 140–156. <https://doi.org/10.1016/j.biosystemseng.2019.03.007>

Yao, L., Ou, J., Wang, G., Cheng, C.-Y., Wang, W., Steiner, H., & Ishii, H. (2015). bioPrint: A Liquid Deposition Printing System for Natural Actuators. *3D Printing and Additive Manufacturing*, 2(4), 168–179. <https://doi.org/10.1089/3dp.2015.0033>

Yap, Y. L., Sing, S. L., & Yeong, W. Y. (2020). A review of 3D printing processes and materials for soft robotics. *Rapid Prototyping Journal*, 26(8), 1345–1361. <http://dx.doi.org/10.1108/RPJ-11-2019-0302>

Zhang, C., Chen, F., Huang, Z., Jia, M., Chen, G., Ye, Y., Lin, Y., Liu, W., Chen, B., Shen, Q., Zhang, L., & Lavernia, E. J. (2019). Additive manufacturing of functionally graded materials: A review. *Materials Science and Engineering: A*, 764, 138209. <https://doi.org/10.1016/j.msea.2019.138209>

Zhou, J., Chen, S., & Wang, Z. (2017). A Soft-Robotic Gripper With Enhanced Object Adaptation and Grasping Reliability. *IEEE Robotics and Automation Letters*, 2(4), 2287–2293. <https://doi.org/10.1109/LRA.2017.2716445>

Zimmerman, J., Stolterman, E., & Forlizzi, J. (2010). *An Analysis and Critique of Research through Design: Towards a formalization of a research approach*. 2010, 310–319. <https://doi.org/10.1145/1858171.1858228>

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