Expand Material Presence to Material Experience with Volumetric Thinking - Voxel Based Multi-Material Printing in Designing Objects

by
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Abstract

Material serves as the first touchpoint between an object and a person. In current product development, material together with color and finishing is regarded as a separate entity from the form and function design. Every material needs to be paired with a series of optimal manufacturing processes for the desired effect. In many cases, this is handled with material design specialists. People perceive a material primarily by its surface: chromatic, tactile, and decorative identity it displays or the temperature and hardness when touching it. Typically, this material surface can be viewed as a two-dimensional entity that reveals limited-expression and information to be delivered via human intervention.

In this thesis, we propose to get away from surface obsession in object and industrial design, by adding another dimension to the material interface. By embedding information into three-dimensional matter, we introduce volumetric material: a new material organization that responds directly to the user intervention or the environment. With multi-material 3D printing, we envision a future in product development where the design of surface detail, texture, reflexivity can finally be merged with the overall product composition from the beginning of the design process. With voxel printing capability, we designed and tested material interface with depth and explored volumetric behavior that is both visually and functionally meaningful to the user, and discussed the results.

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Contents

Chapter 1
Introduction

We envision a future where industrial and product designers can prototype any design without technical barriers like surface finishing, color and texture matching; where physical prototype can achieve any appearance and property designed in CAD software and visualization tools; where industrial designers can create materials that directly apply to the designed form without the assistance of a CMF (color, material, finishing) designer. With the rapid development of multi-material 3D printing, this future becomes a rational hypothesis – not only in designing and prototyping but also in mass production without manufacturing barriers.

The current process of material visualization in product design not only slows down the design process but also limits the imaginations of what material can be in terms of form, textiles, and even a dynamic property that changes over time or with user intervention, etc. In most cases, the material creation is separate from the object design. Many design agencies assemble an existing material collection instead of material creation due to limited manufacturability and lack of expertise. There is an emerging “material service” ran by CMF specialists that help connect designers and suppliers for brand and product innovation. For example, Chris Lefteri Design (2019) works closely with major companies and consumer brands like LG, Google, and Philips to deliver innovative material solutions. Their philosophy is that thinking about materials right from the beginning of a project is the key to the success of a product launch (Ibid). Even without the help of external material services, most product design agencies have CMF designers who actively collect material information and explore material trends from design weeks, exhibitions, or directly from suppliers.

We foresee the opportunity in material creation instead of material collection for product designers and agencies, using multi-material 3D printing. So that material creation does not separate from the object design, and the material itself does not has to be a single layer of a separate entity that only exists uniformly on a product surface. By assigning different material properties to each voxel in multi-

Figure 1-1 a footwear prototype with soft-lattice, printed by Stratasys J750

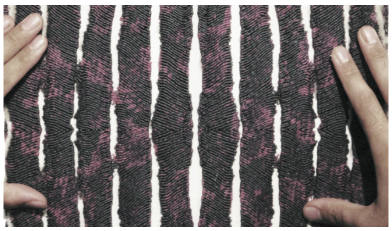


Figure 1-2 3D Sampling Textures printed by Straasys J750

Figure 1-3 3D-printed death masks by Mediated Matter Group (Bader et al., 2016)

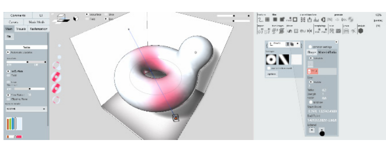


Figure 1-4 user interface of Monolith

material printing, designers can create object interfaces with various material distributions that can display unique material expressions.

Prior arts in creating 3D printed material with unique distributions are mainly around voxel printing. One common application is in experimenting with textile design. Digital Manufacturing and Design Center (DManD) at Singapore University of Technology and Design has developed a series of projects around 3D digital textiles. For example, Figure 1-1 shows a footwear prototype designed with soft lattice using a custom slicer to control stiffness and behavior of the material (citation); Figure 1-2 presents a textile surface synthesized from 3D scans of snake-skin and mushroom laminae and printed with Stratasys J750 (citation). MIT Media Lab's Mediated Matter Group has developed a data-driven material modeling (DdMM) process (Bader et al., 2016), which applies user-generated data sets to design and print models with volumetric information. This modeling application is used in arts and installations (Figure 1-3).

The current methods to collect and manipulate voxel information for 3D printing are mainly through 3D sampling using an external data set or user-generated data sets. Other than the data-driven methodology, Michalatos and Payne (2018) have developed Monolith: a voxel-based modeling engine for multi-material 3D Printing, which allows free creation in model geometry and visually manipulating the voxel channels (Figure 1-4).

By looking into the process of traditional material design and look beyond the material surface with multi-material 3D printing, I introduce the concept of volumetric material: a new material organization embedding information to the matters, which respond directly to the user intervention or the environment. On a product level, this new materialization could have either functional or expressive purposes, as shown in Figure 1-5.

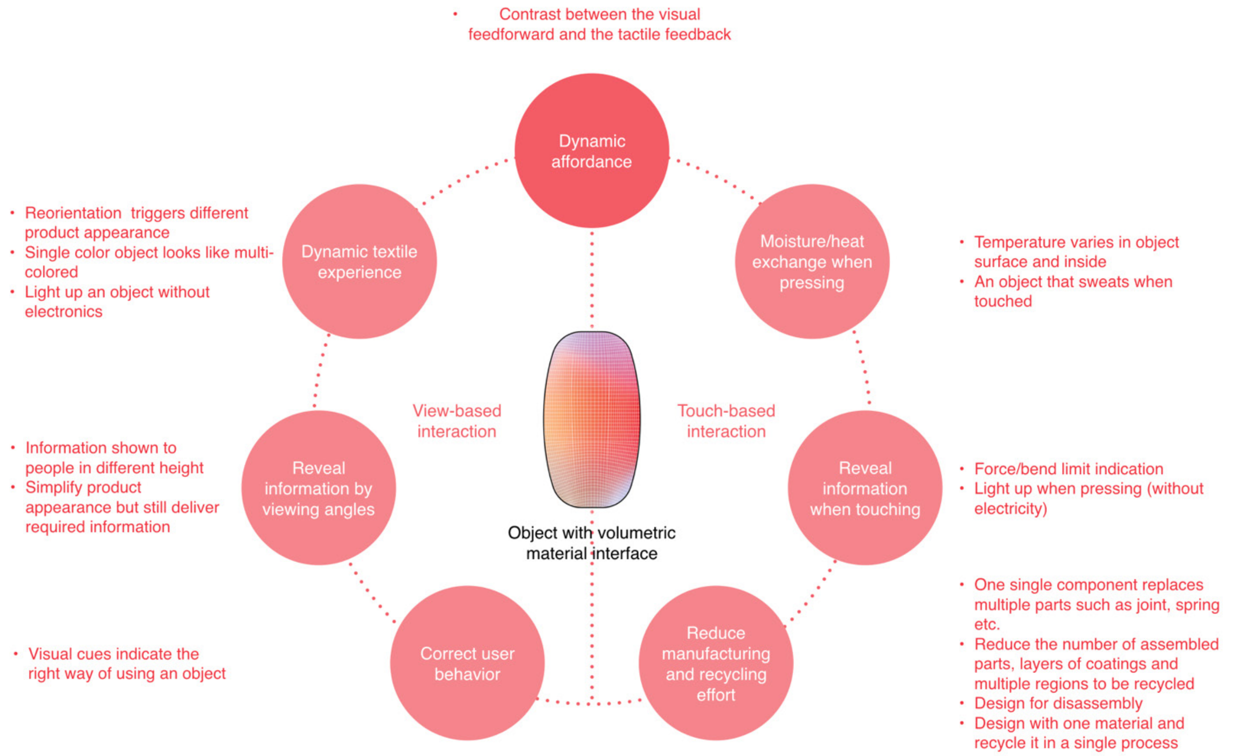


Figure 1-5 Possible applications of volumetric material in objects/products design

1.1 Method

Figure 1-6 previous exploration on optical effect with volumetric material

My thesis focused more on exploring view-based interaction and a bit with touch-sensitive interaction using volumetric material. I started by exploring different visual effects a volumetric material can create by designing and printing some optical test blocks with Stratasys J750 (Figure 1-6). We decided to go deeper with the lenticular effect as the printer gives massive freedom in manipulating both lens and content geometry simultaneously; also, the visual effect it gives is obvious and promising to prove our hypothesis. In order to validate the lenticular effect concerning the geometry design, we defined a workflow that can test out the result efficiently. First, we researched traditional lenticular sheet design and got an overall understanding of the relationship between the lenticule geometry and its optical effect. Derived from the previous calculations done by lenticular printing experts, we created a new method to determine the lenticule geometry, which can serve my purpose in getting the largest viewing angle. we printed out lenticular lenses with different geometry and tested the effect on patterns printed on paper.

Comparing the observation result with previous calculation, we got a general idea of the pros and cons of my design workflow. With the experience in 2D surface lenticular design, we applied lenticular design to three-dimensional objects with uniform section profiles and free form objects, respectively. Substantially, we created some objects with optical textiles that provide dynamic experience with user intervention.

Following this section, we will cover the following topics. In Chapter 2, we dig into the background of material design in product development and discuss the trends in designing sensory and interactive material with 3D printing.

In Chapter 3, we introduce the concept of volumetric materiality and its potential application in product/object design. We also present some relevant research projects around multi-material 3D printing that can support or inspire the design of volumetric materials.

In Chapter 4, we outline the approach to calculate, design and test lenticular effect with printed lenses and pattern contents. We tested both on two-dimensional surfaces and then on three-dimensional objects. Based on the key finding in the tests, we create some objects using optical textiles and prove the functionality of volumetric material.

In Chapter 5, we present the primary contributions of this research in both micro and marco level.

Chapter 2
Background

In this chapter, we first dive into the current role of material design in commercial product development and propose a workflow that integrates material with form and function design; secondly, we present relevant design attempts that relate material with sensations: by manipulating material interface, the object triggers different user experiences or emotional feedback; the third part of this chapter outlines research concerning with interactive material which provokes dynamic sensory perceptions. This chapter reveals the current trend of exploring new material as an essential stage of product innovation, also foresees the future of material design using 3D printing.

2.1 The Role of Material Design in Product Development

Figure 2-1 Seymourpowell material library

Figure 2-2 creating a material board for a client project

During my time at Seymourpowell[1], I got familiar with CMF design and its role in product development. Seymourpowell has collected a physical "material library" (Figure 2-1), where they store and categorize materials from different suppliers. They also conduct trend research on new materials and get new samples from suppliers from time to time. The invention of a physical library is due to the need to touch and see the material: getting a sense of it, other than merely looking at a picture or rendering. The role of a CMF designer is not only in maintaining this material library for future inspirations but also on proposing the right CMF/mood board for a product identity both in concept and prototyping phases (Figure 2-2). Although the tasks of a CMF design are relatively specific, it is mostly separated from form design, making the whole industrial design process fairly linear. The reasons behind are quite obvious: first, color, material, finishing is in the intersection of design, engineering, sales, purchasing and manufacturing, having the qualities and understanding in all segments requires years of professional practice and accumulated real-world experience; second, there's a unpeaceable gap between concept design and design for mass production, it's hard to get everything designed in CAD right to a

[1] Seymourpowell is a London based product and innovation design consultancy, where I worked as a graduate intern in summer 2019. I was doing design research and product design at foresight team and product team.

physical prototype, not even mention a final product. A CMF designer's "final touch" is essential for bringing a concept to reality, and for the success of a product launch.

Liliana Becerra sees CMF design as "the puzzle of elements" with multiple correct solutions based on individual design and target users (Becerra, 2016). For example, the color appears more muted and visually softer if the surface is processed with a soft-touch finish (Ibid). The color, material, finishing, and product form, brand identity are highly intertwined and cannot be considered separately in the design process. Usually, it requires a great number of experiments, trials, and errors to get the best final product.

After the talk with Caroline Jacob[2] and observation of her work, I started to wonder: what if a CMF designer can not only choose the material from existing manufacture but to create and test any material/texture that is truly designed for specific form/purpose; what if the physical and digital material library can be merged into one, anything designer creates in the software can be smoothly transit to the reality without complicated secondary process; what if any designer can be the CMF designer for their project, creating material and properties that don't exist before? It all becomes possible with multi-material 3D printing. Figure 2-4 below envisions a new industrial design workflow with the help of multi-material 3D printing.

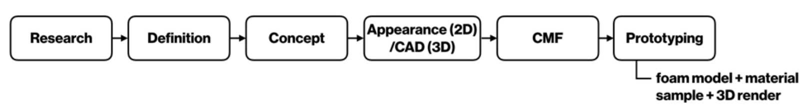


Figure 2-3 current design process for industrial design

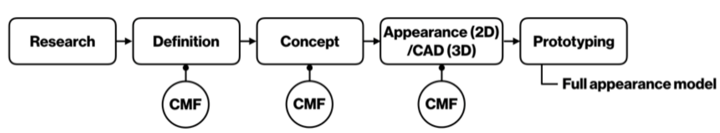


Figure 2-4 A proposed process where CMF design penetrates the whole design

[2] Caroline Jacob is the CMF designer at Seymourpowell who shared valuable insights about CMF design and sparks great inspiration of the future in CMF design with me.

2.2 Designing Material, Designing Senses

Bringing digital CMF to reality is not only a functional need for designers but also a new fashion in designing sensory responses toward an object/product. The material perception provokes direct feelings/understanding of the object itself. For example, people see polished stainless steel as premium or high-end; wood surface feels warmer than metal looked object even without touching it; matte silicone always indicates its purpose of protection as it is soft and flexible. Some designers and studios expand this material knowledge to sensory perceptions in real-world product design; some are trying to build a bridge between the digital and analog world of design.

Figure 2-5 Geta by Shuhei Hasado. Made with white ash by traditional wall plastering. Published in "Designing in Design" by Kenya Hara.

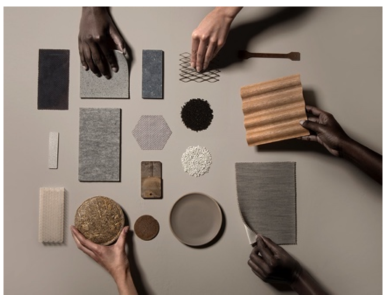


Figure 2-7 Experimenting different materials in product development, Layer Design

2.2.1 Sense-driven design in real-world applications

Japanese designer Kenya Hara believes the creation of a product is a process of designing senses: material, color, shape, and texture are the outside stimuli that awakens people's internally stored memories; these stimuli largely affect how people imagine the world and interpret objects. The design shows in Figure 2-5 gives an idea of how it would feel like to wear it without actually experiencing it (Hara, 2011). London design studio "Layer Design" follows a materials-driven design strategy in their process where they are constantly collecting information and technology around materials as a database of rational inspiration for future projects, as shown in Figure 2-7 (Hubert, 2019). Nendo Studio (2018) designs steel furniture to look like watercolor-painted paper (Figure 2-8). The surfaces are sanded repeatedly and finished with matte white paint so that the blue gradient marking looks soaked naturally into the furniture. With the same volume, this furniture feels much less weighted like a piece of paper. Orijeen Studio (2018) designed a cabinet with a lenticular surface that can change its color based on the viewer's position and movement (Figure 2-6). This visual change reminds people about the relationship between the object and the user.

Figure 2-6 Color flow designed by Orijeen, 2018

Figure 2-8 Steel furniture designed by Nendo Studio, 2018

2.2.2 Toeing the line between fantasy and reality

People are getting more used to virtual objects/space due to the emerging technology in AR/VR, 3D animation, and high-fidelity renderings. There is a new trend of building objects and spaces inspired by the virtual world, by mimicking the light, texture, color that only appears in a computer rendering. The upper image in Figure 2-9 shows a digital rendering that shares incredible similarities in atmosphere and lighting with the lower image, which is the physical set design. While a "dream-like" rendering is quite common in designers' eyes, being inside the physical "otherworldly landscape in dreamlike colors" is still an amazing experience that one can rarely taste in reality. The two projects (Figure 2-10) created by Wang & Söderström Studio (2019) is another example of bringing digital objects into reality by keeping both form and texture in 3D printing. The same philosophy was recently applied in product design, as shown in Figure 2-11, the finishing fakes the real nature of the object itself, created this fantasy that only exists in 3D illustration or graphic design.

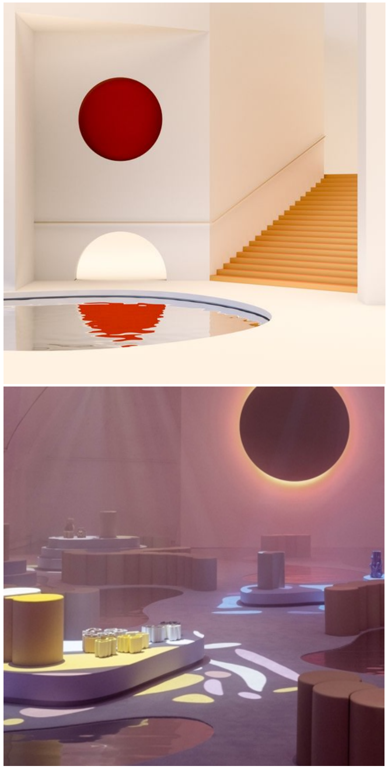


Figure 2-9 upper: architecture rendering by Alexis Christodoulou; lower: "Tides" exhibited in Milan Design Week 2019 by Wang & Söderström Studio.

Figure 2-10 upper: "Water matters" (2018), 3D art by Wang & Söderström; lower: "Common odd things" (2018) physical sculpture by Wang & Söderström.

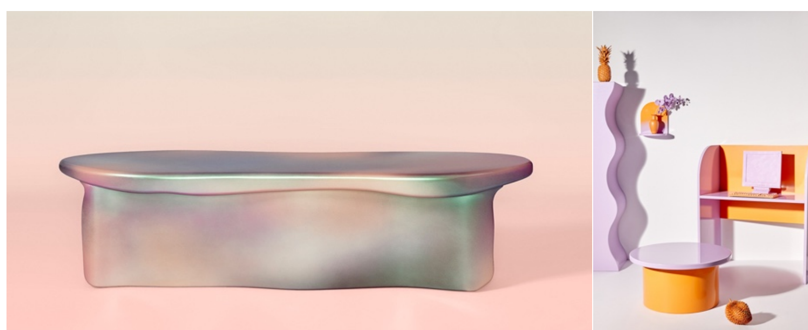


Figure 2-11 left: 'guise' collection by Odd matter (2019), a chair designed with 17th-century scagliola technique; right: furniture designed by Objects for Objects (2019)

2.3 Dynamic Functionality and Responsive Senses

In most cases mentioned above, the feelings evoked by specific material stays consistent overtime as most material surfaces are viewed as "static" - they do not display responsively or reveal additional information other than how people perceive them conventionally. There have been several experiments on creating interactive materials that can display dynamically or respond to users' intervention.

2.3.1 Material as interface:

User interface (UI) in the field of industrial design and HCI refers to the action between humans and machines, mostly digital. Joep Elderman from the Eindhoven University of Technology gives a unique perspective about user interface: he sees the handle of a hammer as the interface of the object, for both holding and controlling the device. It allows precise control and powerful blows by holding the hammer near the head and the back, respectively (Elderman et al., 2017). In his definition, the object surface or material surface becomes the interface for controlling and operating, with or without digital elements.

However, most of today's product interaction still relies on apps and digital screens. User experience is mostly evaluated by-products' digital performance and less in physical form/functions. There has been increasing debate around how tangible design could evolve to enrich interaction between humans and objects. There are two previous explorations to make the object surface more interactive. One is embedding digital elements (electronics) into materials. The other is redesigning materialization. The former direction has been explored extensively at research institutes such as MIT Media Lab and Self-Assembly Lab. Typical projects are like robotic textiles, smart fabric, shape-changing interfaces, and material touch screen. The latter one is relatively new in product/object design as the digital information embedded in the raw material is quite basic to be actuated by simple input. Some of the most related research topics are summarized below:

- Graphical user interface (GUI) – tangible user interface (TUI) - material user interface (MUI)
  Ishii (2012) defines TUI as a form of interaction that embodies digital information in physical space. Comparing to screen-based interaction, TUI enhances direct engagement with the digital world, thus expands the affordance of physical objects. He also visions the future of interface design (radical atoms) based on human-material interaction – a single material that integrates user input, input processing, and feedback - where all digital information has a physical manifestation to allow direct communications.

- Interactive materiality and dynamic affordance
  Elderman (2017) reads interactive materiality in a voxel-level: it is a composition of matters which can become dynamic and change by user or system intervention. These dynamic matters can be either quantifiable and objective (e.g., material density) or more subjective and qualitative (e.g., textural sensation). Objects made from interactive material reveal dynamic properties. He argues that products made from such materials have "dynamic affordance" (Gibson, 1979) – designers can change the harmony between visual feedforward and touch feedback by creating an unexpected tactile response.

- Digital material and programmable matter/materials
  Tibbits (2012) refers to "digital materials" with another definition - it has to carry digital information and able to translate that to the analog world regardless of whether it contains electronics or not – this concept indicates that digital data can be inherently built-in analog (raw) material. Programmable matter is a paradigm that matter responds to user input and autonomous sensing to change its physical properties. MIT's Self-Assembly Lab further defines programmable materials to be highly dynamic in form and function and able to reveal digital information. They've developed a series of new materials with the ability on programmable actuation, sensing, and self-transformation.

2.3.2 Interactive material based on means of interventions

We categorized the most related research based on different means of actuation (Figure 2-12). For me, "interactive material" is a physical material that contains additional information that can be translated into the analog world with user intervention. On a product level, this additional information can be either functional or expressive. Among the three categories of intervention, I see the latter two with great potential in product design, as the single material can display multiple properties and functions without a complex system.

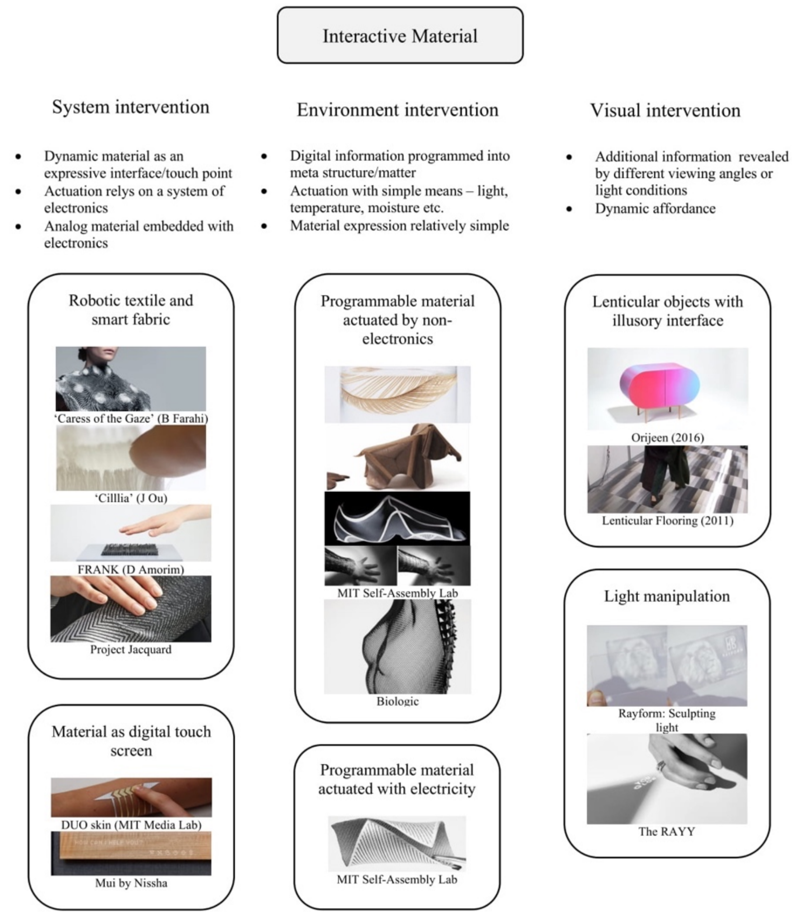


Figure 2-12 projects around "interactive material"

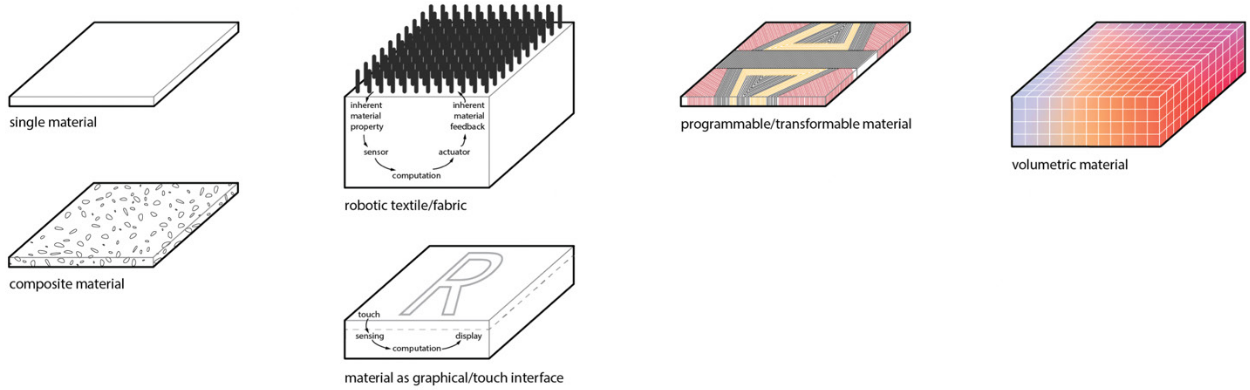
Chapter 3
Volumetric Material and Multi-material 3D Printing

This chapter introduces the concept of *volumetric material*: to get away from surface obsession in object/industrial design, adding another dimension to the material interface. With Stratasys J750: a multi-material printer with full-color capability, texture mapping, and color gradients, we want to design material interface with depth and explore volumetric behavior that is both visually and functionally meaningful to the user. We assume the resulting volumetric material would display a materialization of separate properties and identities with unique material expressions.

3.1 Revisit Material Interface with Volumetric Thinking

Previous examples like robotic textiles are designed under the assumption that material itself cannot display; it needs another medium, such as electronics, to reveal certain information. Although the material interface has the depth to display a dynamic motion or property, it requires all the individual material units to be actuated separately to achieve the designed result.

While self-assembled material has proven that material can display by itself through very simple actuation like light, temperature, moisture change, etc., the information it can display, or the dynamic outcome is highly limited. Usually, it is simple shape-changing on the material surface (Figure 3-1) and needs to be maintained in certain conditions.



- Static material properties
- Mass production

- Dynamic material display
- Actuation relys on electronics and computation power

- Dynamic material – form changing
- Single material can display dynamically
- Manipulating materials on surface level
- Limited actions

- Dynamic material display
- Manipulating materials on voxel level / volumetric pixel.

Figure 3-1 a comparison of common interactive material and volumetric material

By adding another dimension to material interface, we introduce Volumetric Material: a new material organization embedding information to the matters, which respond directly to the user intervention or the environment. It is assumed that the result volumetric material would display a materialization of separate properties/identities with unique functions and expressions such as:

- Distorting material can display dynamic properties like color or transparency changing or reveal visual information
- Light manipulation: manipulate light direction, reflection, and refraction
- One single material mimicking multi-material identities which reveal different properties like touch, acoustics, structural corrugation, or thermal properties (Stratasys, 2016).

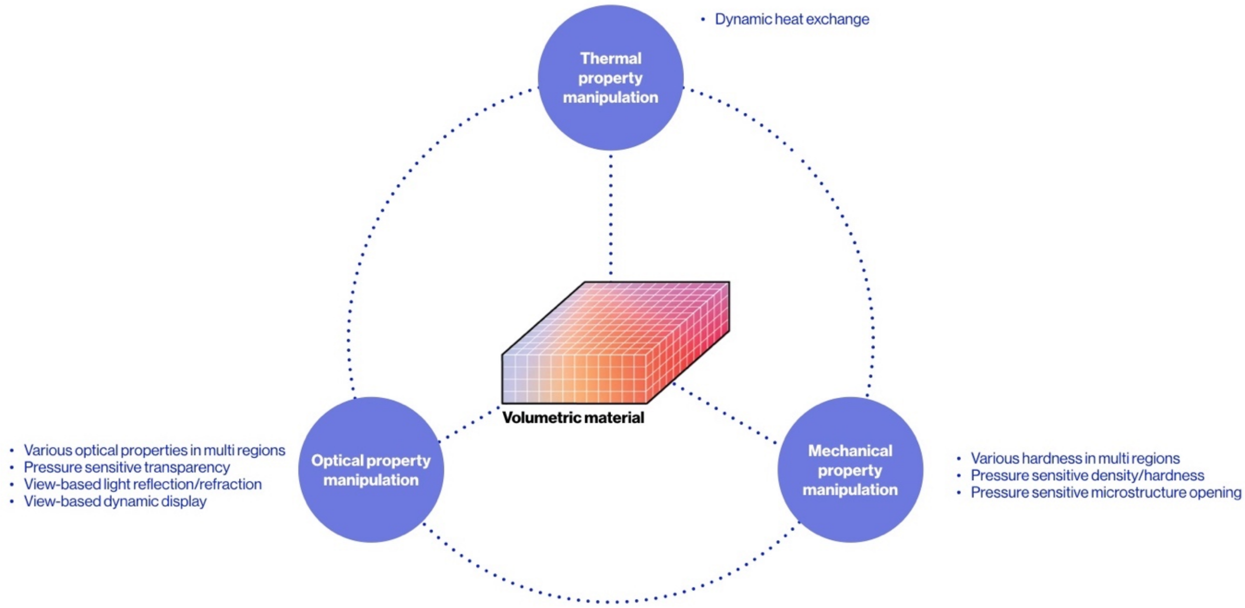


Figure 3-2: matter and property manipulation in volumetric material

On a product level, this new materialization could have either functional or expressive purpose, such as:

- Provide additional information such visual or textile cues to guide how to use the object, or correct user behavior
- create dynamic human product relationships
- play with user expectations by creating a contrast between the visual feedforward of looking at an object and the tactile feedback of touching it
- “one” material for all, all for “one” material – replacing the multi-component object with “one material” that mimics all components’ properties. Reducing material, manufacturing, and recycling costs and efforts.

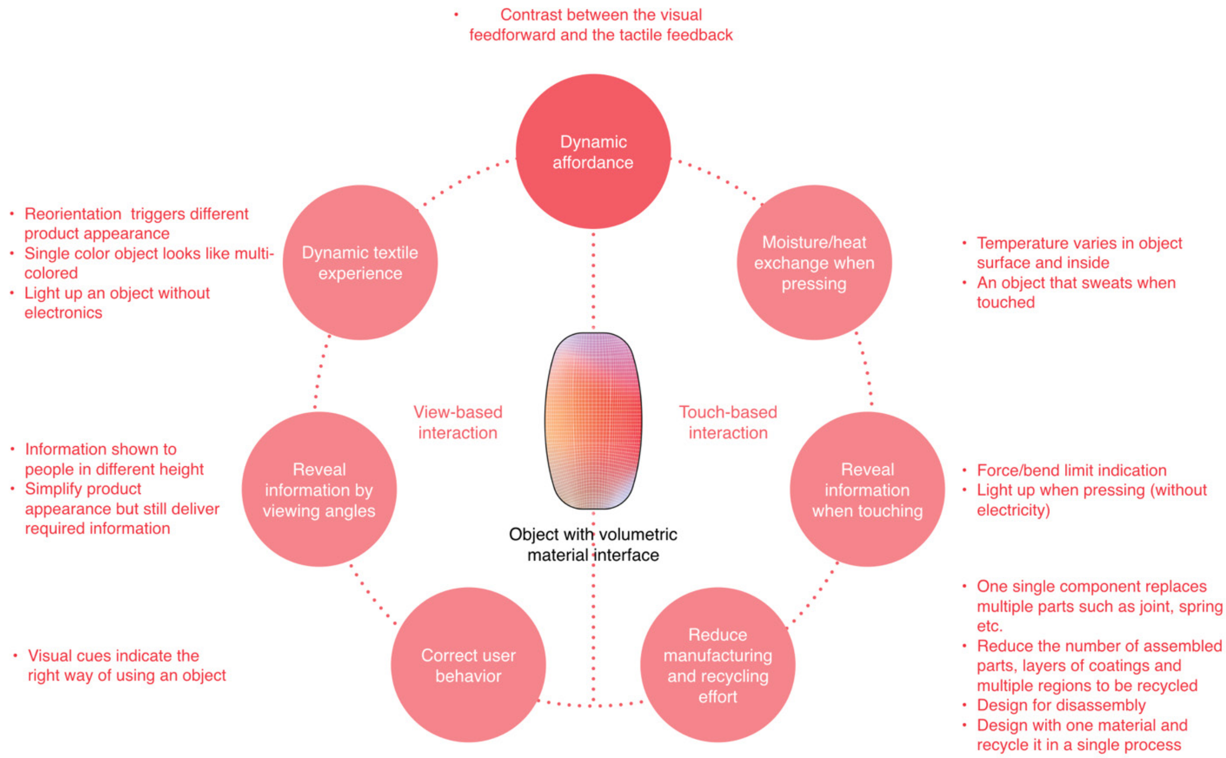


Figure 3-3: Possible applications of volumetric material in objects/products design

3.2 Multi-Material 3D Printing

Figure 3-4 a shoe protptype and a medical model printed by Statasys J750

Figure 3-5 products printed by Statasys J750

The easiest way to fabricate volumetric material is through multi-material 3D printing since the designer can customize the material property in each voxel. All the models in this thesis are printed by Stratasys J750 - with full-color capability, texture mapping, and color gradients.

The three main purposes of Stratasys J750 are prototyping, products, and material research. The most common application is prototyping, which includes functional prototyping - which contains both flexible and rigid material; and rapid prototyping with multicolor printing (Figure 3-4). There are not many examples of mass-produced products printed by Stratasys: most of the current applications are highly customizable products like earphones and glasses frame (Figure 3-5).

Most of the research topics with Stratasys J750 are around voxel printing, especially in textile (Figure 3-6) and metamaterial design (Figure 3-7).

Figure 3-6 left: functionally graded lattice structure with seamless blends of multi-materials (Stratasys, 2017); mid: 3D textile (ibid); right: Voxel Harvest: Metamaterial Programming (Stratasys, 2017)

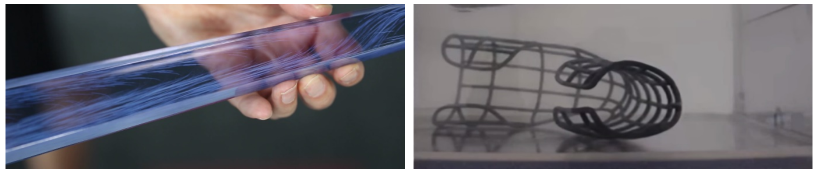


Figure 3-7 left: interlocking table by voxel printing (Stratasys, 2017); right: 4D printing (ibid)

3.2.1 The current process of voxel printing with Stratasys J750

Stratasys works with GrabCAD Print for model processing. To print a multi-material model, we have to separate the parts to be printed with different materials manually. The GrabCAD Voxel Print Utility allows users to set color and material for each point, which is also known as "voxel" –a three-dimensional version of the pixel. With the GrabCAD Voxel Print Utility, users can produce complex material distribution like a gradient or a sophisticated pattern (GrabCAD, 2019).

However, the Voxel Print Utility is almost the last step before printing. In order to prepare the 3D model ready to be processed in the software, we have to first slice the model and generate a set of BMP. or PNG. image files, which are normally done in Matlab. Based on these image files, the software can generate a GrabCAD Voxel File (*.GCVF) that is ready to be printed by the printer (Ibid).

We explored several research projects on how to generate 3D models that have voxel information or slice models that contains property information in each slice. Three main research projects will be introduced as follows:

1) Monolith (Michalatos and Payne, 2018)

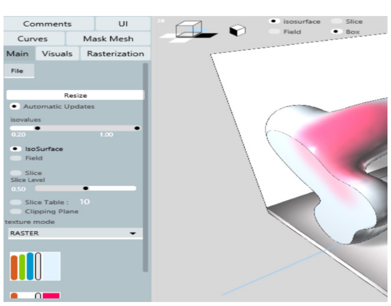


Figure 3-8 Monolith user interface

Monolith is a voxel-based modeling engine for multi-material 3D Printing. It is geometry-based and allows preview during the modeling process. Monolith can be used to generate a new geometry within the software or as a plug-in in grasshopper. However, it cannot work directly with an external 3D model, such as stl. files, and the modeling capability is quite limited

Figure 3-10 voxel model created by Monolith and printed by Stratasys J750

within the software. Users can export slices, meshes, or voxel files from Monolith.

Figure 3-10 shows a model we designed with Monolith and printed with Stratasys J750 in the phase of material exploration.

2) Scanning and printing with an external data set

   A scanned model contains volumetric information that can be processed in software like Houdini or Matlab to become a printable voxel model. The research shown in Figure 3-9 uses Houdini to sample data and convert RGB data to match the printer's available colors.

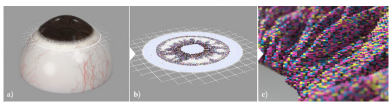


Figure 3-9 The workflow of processing a digital model from a scan model to voxel model (Robinson and Furneaux, 2019)

3) Printing with a user-generated data set

   MIT Media Lab's Mediated Matter Group has developed a data-driven material modeling (DdMM) process (Bader et al., 2016) which uses user-generated data sets to "grow" 3D models that contain volumetric information. The data sources manipulate material distribution, and a framework was designed to process the data into printable slices (Figure 3-11).

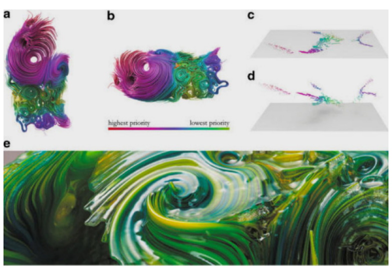


Figure 3-11 the workflow of a data-driven voxel modeling process (Bader et al., 2016)

All of the three methods mentioned above have different limitations. The geometry-based software Monolith only allows voxel manipulation on a certain form. While the scanning method requires a digital model with initial voxel information and traditional stl. files do not contain this kind of information. While DdMM does not give the creative control we need in product design. In section 4.1, we introduce a novel pipeline to work with voxel models that is familiar to designers' modeling workflow. For most digital modeling formats such as stl., we can generate volumetric information inside the model.

Chapter 4
Approach

Following the introduction of volumetric material and its potential properties/applications, this chapter describes the approach to validate my concept. Heavily based on trials and observation, we first test optical volumetric material on two-dimensional surfaces and then on three-dimensional objects. To begin with the material exploration, we present a novel voxel printing pipeline for designers. In order to validate the lenticular effect with respect to the geometry design, we then research traditional lenticular sheet design and invent a new calculation method to determine lens geometry that enables the maximum viewing angle. To validate our calculation and observe the lenticular effect, we tested lenticular lenses on ink printed pattern first and then on three-dimensional objects with pattern 3D printed pattern on the surface. We also test the lenticular effect on a surface made from flexible materials, so that the optical effect responds dynamically with user intervention. Finally, we create some objects using optical textiles and prove the functionality of volumetric material.

All the models in this section are printed by Stratasys J750. We used the "high mix" mode with the layer thickness of 0.027mm for a quicker testing result. All the lenticular lenses are printed with Polyjet material VeroClear; other printer materials we used in this thesis are Vero PureWhite, VeroBlackPlus, VeroCyanV, VeroMagentaV, VeroWhitePlus, VeroYellowV and Agilus30 Clear (flexible material). All the stl. files are processed and color assigned in GrabCAD Print software before sent to the printer.

4.1 A Novel Voxel Printing Pipeline for Designer

In the process of designing voxel printing objects with surface information, we designed a set of workflows for material exploration, which is derived from the traditional 3D modeling process of industrial design.

4.1.1 Volume rasterization

Traditional "polygon mesh" and "Non-Uniform Rational Basis Spline" (NURBS) only records information of the edge and surface of a shape, while voxel printing requires pixel information inside each slice. To generate these sections, we used a grasshopper script that can animate the cut surface of a closed object (Figure 4-1). It records the section of a closed volume from bottom to top, which matches the 3D printing sequence. The section and background color are assigned to red and green respectively, for post-processing.

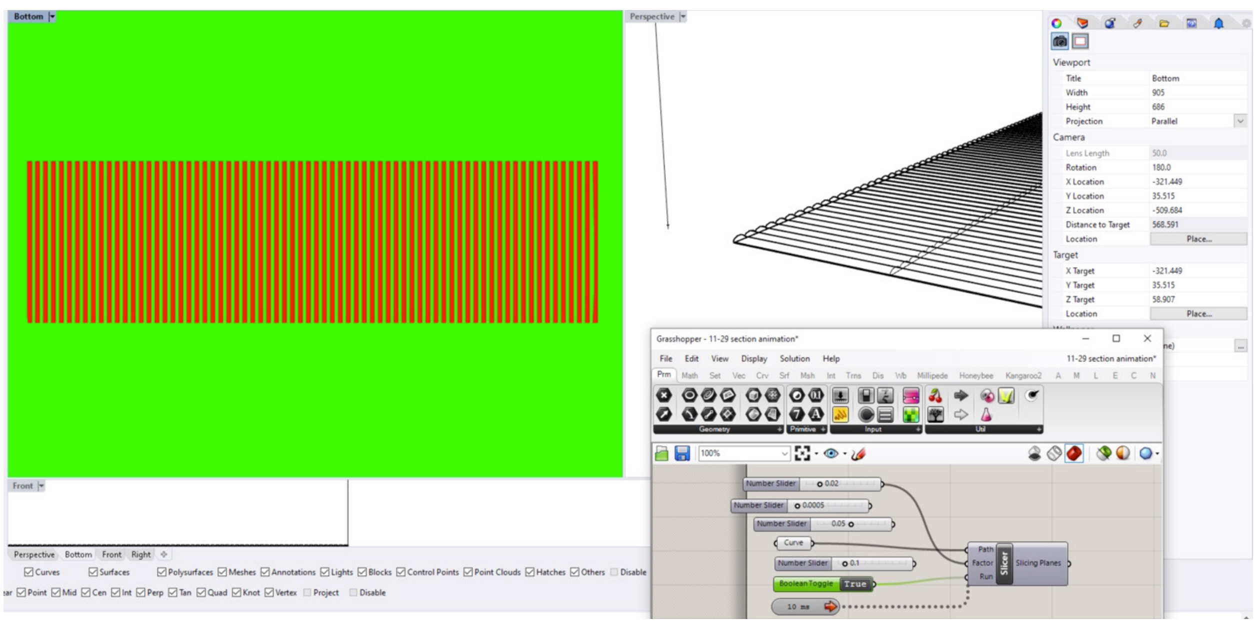


Figure 4-1 slicing tool using grasshopper. "Bottom" window shows the sliced section (red pattern); the "Perspective" window shows the 3D object to be sliced; the bottom right window is the grasshopper script.

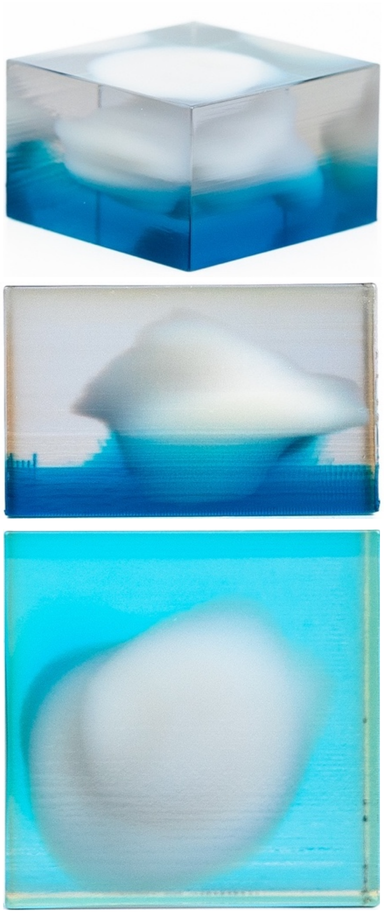


Figure 4-2 A "cloud" designed and printed by the voxel printing pipelin3, with "soft-touch" edge.

4.1.2 Voxel manipulation

The voxel information of this closed volume is recorded in each frame of the animation. The resolution of recorded video, slicing speed, and video frame rate determines the resolution of the volume in XYZ, respectively. This also allows us to edit the volume's shape, texture, and voxel characteristics by using video editing software such as Adobe Premiere (adjusting the speed, frame rate, and XY ratio of the video). Based on this methodology, we can also implement voxel printing of different internal shapes using layer overlaying, placing another volume inside one volume. We can also use existing algorithms of video processing software to manipulate each internal shape's characteristics, such as adding color transformation to the video layer of a specific volume to change its appearance or adjusting layers of the Gaussian blur algorithm to add physical textures like softness. This workflow makes it possible for us to control the voxel beneath the volume surface (Figure 4-2).

4.1.3 CMYK color separation

The slicing video saves all the data of the designed objects' voxel information, but the exported slice pictures are not ready to be printed on Stratasys J750 since Stratasys' voxel printing utility cannot directly decompose specific colors into CMYK (Cyan, Magenta, Yellow, Black) to simulate color characteristics. We invented a process to do the color separation, which shares a similar principle of traditional screen printing, except that each pixel of CMYKW (W refers to white) won't overlap like screen printing (Figure 4-3). To do it, we first restricted the exported colors in Photoshop's Color Index Table when compressing video into a gif (Figure 4-4) - by specifying the color index to match the colors available in the printer. After converting the array of gifs (generated in photoshop) to png. Files (Figure 4-5), each frame of the voxel information, can then be recognized and printed by Stratasys' voxel printing utility.

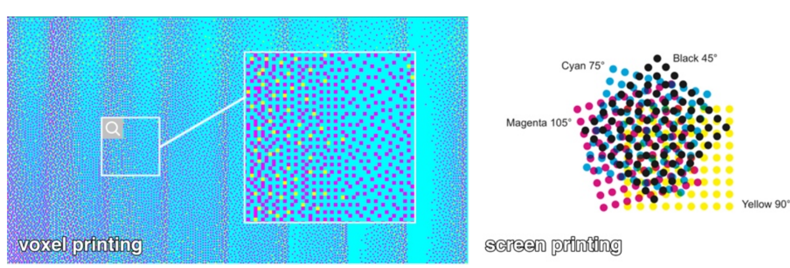


Figure 4-3 A comparison of color separation between voxel printing and screen printing

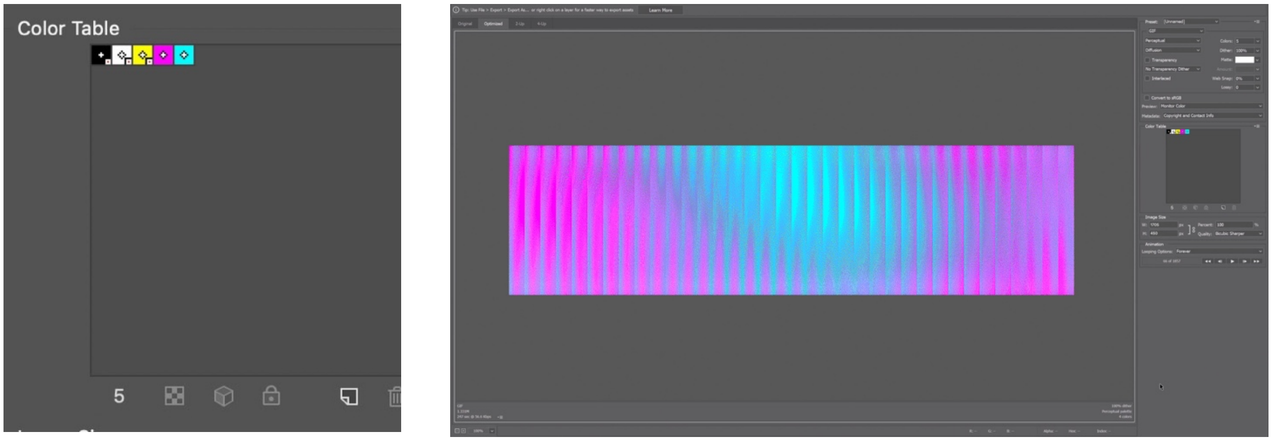


Figure 4-4 restricting CMYK information in Photoshop's Color Index Table when compressing a video into a gif.

Figure 4-5 png files of sliced volume, to be sent to the printer. See Appendix for the whole png. Array for printed objects.

4.2 Exploration of Lenticular Effect using Voxel Printing

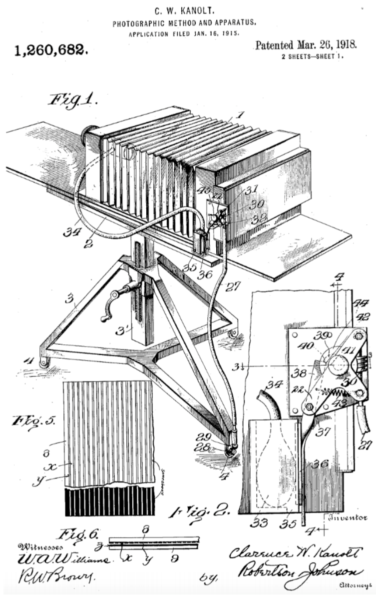


Figure 4-6 the first multi-view lenticular picture patented by C. W. Kanolt

Kanolt (1918) patented the first multi-view lenticular picture, which set the foundation of modern lenticular imaging. Today, lenticular printing always refers to a technology using lenticular lenses to produce images with depth illusion or to reveal independent images under different viewing angles (Weissman, 2018). Lenticular imaging is commonly applied in print technology, arts, advertisement, etc., for example, Figure 4-7 shows a typical lenticular card that reveals an image animation under different viewing angles.

Figure 4-7 A 3D lenticular card

The lenticular effect people can create, and the quality of optical aberrations is highly restricted by existing manufacturability in optical lens and printer resolution. Normally, the making of lenticular sheet and content images are separate and handled by different people. With multi-material 3D printing, we can design the optical lens together with the image content, experimenting with different shapes and depths of the lens, surface form, and even the transparency and hardness of the image content. At the product/object level, it is possible to apply the lenticular effect on any form, manipulating the optical properties of any object surface.

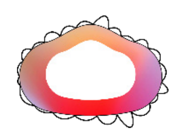
Traditional production	Multi-material 3D printing
	
Only applied in 2D printing	Can be applied in 3D object
Lens making and content making handled separately	Design lens and content simultaneously
Uniform lens geometry	Different lens geometry on one surface
Flat lenticular sheet	Flat or curved lenticular backplane
Image content on 2D paper	Can be 3D content
Linear viewing path	Non-linear viewing path which requires the individual lens to be designed with specific viewing angles to reduce the available resolution.

Table 4-1 Possible lenticular production with multi-material 3D printing comparing to traditional manufacture

4.2.1 Lenticular fundamentals and calculations

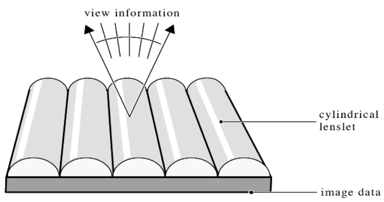


Figure 4-8 A lenticular panoramagram, published in "Autostereoscopic Displays and Computer Graphics" (Halle, 1997)

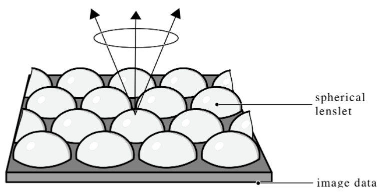


Figure 4-9 An integram, published in "Autostereoscopic Displays and Computer Graphics" (Halle, 1997)

Generally speaking, "lenticular" refers to a three-dimensional display using an array of long and narrow lenses to display three-dimensional information (Halle, 1997). This type of display is also called "lenticular panoramagram" as shown in Figure 4-8. A less common display type is the integral photograph or integram, which is made from spherical lenses instead of cylindrical ones to display a full parallax image. Unlike lenticular panoramagram, an integram (Figure 4-9) can display dynamic information both horizontally and vertically. However, in order to present more directional information, it sacrificed more spatial resolution, thus is less commonly used in lenticular imaging (Ibid).

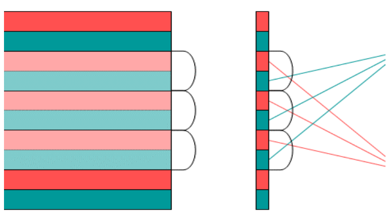


Figure 4-10 An illustration of how lenticular print works

Figure 4-10 shows a simple illustration of how lenticular panoramagram works: people see different parts of the interlaced image under the lenticular sheet from different viewpoints, due to light refraction. The two main purposes of lenticular images are 3D and dynamics. A 3D image reveals a three-dimensional scene by invoking stereopsis; A dynamic lenticular image displays independent images under different viewing angles (Weissman, 2018). To achieve a good 3D effect, a narrow-angle lenticular lens with a viewing angle from 15 to 44 degrees works best. For an optimal animation effect, a wide-angle lenticular lens with a viewing angle between 44 to 65 degrees works best (Lenstar, 2018).

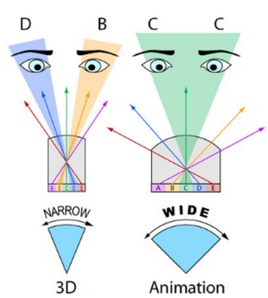


Figure 4-11 narrow-angle lenticular lens vs. wide-angle lenticular lens

Most calculations around lenticule geometry are based on getting the right range of the effective viewing angle, which refers to the angle to see the whole display content (α in Figure 4-12) and clearest image. This can be achieved by having the focal plane coincide with the backplane of the lens. In other words, with a given lens curvature and known refractive index of the lens, the lens thickness is determined; the same when the thickness is fixed, the lens curvature can be determined. In lenticular sheet manufacturing, with a given lenticule density, which refers to the number of lenticules per unit length, the viewing angle can be calculated.

However, in order to get the clearest image, this method sacrifices the maximum viewing angle – when observing the image at an angle that exceeds α, but still, within the lenticule's vignetting angle γ, the

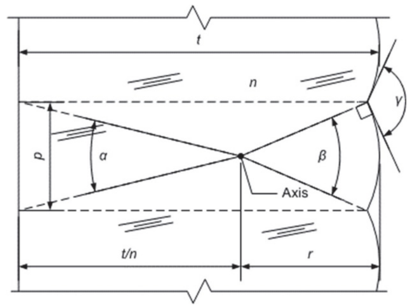


Figure 4-12 the geometry of a lenticule, published in Lenticular Imaging: Theory and Practice, page 434 (Weissman, 2018)

viewer will see the wrong image sequence which is under the adjacent lens. When working with dynamic lenticular effects on 3D objects, the viewing angle is extremely important due to varied surface curvature. **Therefore**, we proposed a new lens geometry calculation method that enables a maximum viewing angle by equating it to the lenticule vignetting angle γ. So that the extreme ray that enters from one edge of a lenticule will be refracted to reach the opposite edge of the image strip – the lenticular animation happens in the whole range of the vignetting angle instead of only in part of it. Our method leaves out the focal plane matching since we are mainly dealing with optical patterns and color strips instead of complicate content; its effect on content clarity is negligible when the lenticule thickness is tiny.

The following sections will briefly introduce the traditional method in calculating lenticular geometry and the common parameter settings in lenticular production. Extended from it, our method for lenticular calculation is then introduced.

4.2.1.1 The basics of lenticular calculation – the traditional method

This section is largely based on "Lenticular Imaging: Theory and Practice" (Weissman, 2018), where the basics of lenticular imaging and calculations are explained in detail. All the equations shown below are derived from the same book, which provides a reference for the calculation in section 4.2.1.2.

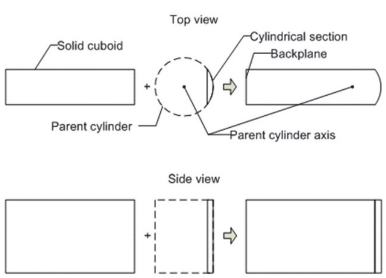


Figure 4-13 Plano-convex cylindrical lens geometry. Published in Lenticular Imaging: Theory and Practice, page 411 (Weissman, 2018)

A lenticular sheet consists of an array of identical lenticules. Each lenticule is made up of a thin cylindrical section and a solid cuboid, as shown in Figure 4-13 (Ibid). When looking at the cross-section of each lenticule, all rays emerging from a point O (Figure 4-14) will converge to the focal plane (Ibid).

According to "lens maker's formula" (Jenkins & White, 1957):

$$\frac{n}{s} + \frac{1}{s'} = \frac{n}{f}$$

and the relationship between focal length f and lens radius r (Ibid):

$$\frac{n}{f} = \frac{n-1}{r}$$

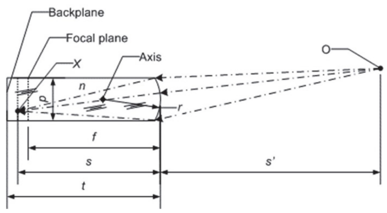


Figure 4-14 Fundamental optical characteristics of a lenticule. Published in Lenticular Imaging: Theory and Practice, page 420 (Weissman, 2018)

and the fact that lenticules are designed in a way that the focal plane coincides with the backplane (Weissman, 2018),:

$$\mathrm{t} = \mathrm{f}$$

we can get determine the value of r with given t and n, or the value of t with given r and n (Ibid):

$$\mathrm{r} = \frac{(n-1)t}{n}$$

or

$$\mathrm{t} = \frac{nr}{n-1}$$

Where:

Symbol	*Description*
t	*Lenticule thickness*
n	*Refraction index*
R_p	*Relative pitch*
α	*Viewing angle*
β	*Acceptance angle*
γ	*vignetting angle*
p	*Lenticule pitch*
r	*"radius of curvature" of the lens.*

Another important parameter in lenticules is relative pitch and can be defined by (Ibid):

$$R_p = \frac{np}{t}$$

The three key angles (α, β and γ) that affect lenticule optics can be derived by (Ibid):

$$\tan(\frac{\alpha}{2}) = \frac{R_p}{2}$$

$$\tan(\frac{\beta}{2}) = \frac{p}{2r} = \frac{R_p}{2(n-1)}$$

$$\gamma = \pi - \beta$$

The vignetting angle γ is the angle between the two tangents to the lenticules surfaces at the crevice between them. When viewing the lenticular from an angle larger than γ/ 2, there will be obscuration and the observer cannot see the full aperture (Ibid).

Another common parameter in the lenticular printing industry is the lenticule density ρ (the number of lenticules per unit length, commonly in inch). It is also called “lpi" - "lenticules per inch." The relationship between p and ρ is:

$$p(\mathrm{mm}) = \frac{25.4}{\rho(lpi)}$$

Figure 4-15 shows the characteristics of industrial lenticular sheets. It is noted that with a more curved lenticule, the viewing angle α is larger but the vignetting angle γ becomes smaller. The widest viewing angle a common lenticular sheet can achieve is around 60~70 degree, when exceeding the viewing angle but still within vignetting angle, the observer will see a wrong image sequence: for example, with the lens geometry shown in the last row, the angle people that can see the wrong image sequence is 117 degree (141-24), while the effective viewing angle (to see the correct image content) is only 24 degree.

t (mm)	*ρ* (1/inch)	*p* (mm)	*r* (mm)	*Rp*	*α*	*β*	*γ*
0.3	**100**	0.25	0.11	1.35	68º	97º	83º
1	**70**	0.36	0.38	0.58	32º	52º	175º
1	**40**	0.64	0.38	1.02	54º	81º	99º
1.2	**60**	0.42	0.45	0.56	32º	50º	130º
2	**40**	0.64	0.75	0.51	29º	46º	134º
4	**25**	1.02	1.50	0.41	23º	37º	143º
4	**20**	1.27	1.50	0.51	29º	46º	134º
6	**16**	1.59	2.25	0.42	24º	39º	141º

Figure 4-15 Characteristics of some common lenticular sheets. Published in Lenticular Imaging: Theory and Practice, page 471 (Weissman, 2018)

4.2.1.2 Our method – designing lenticule geometry that enables the maximum viewing angle

When applying lenticular effect on 3D objects, it is mainly about getting a dynamic lenticular effect other than stereopsis; this requires a large viewing angle. In order to get the maximum viewing angle, the full range of the vignetting angle should display the whole image sequence (full aperture). Geometrically, this means the extreme ray, which refers to the yellow line in Figure 4-16, enters from one edge of a lenticule will be refracted to reach the opposite edge of the image strip. Based on this theory, we can determine the relationship between r, p and t.

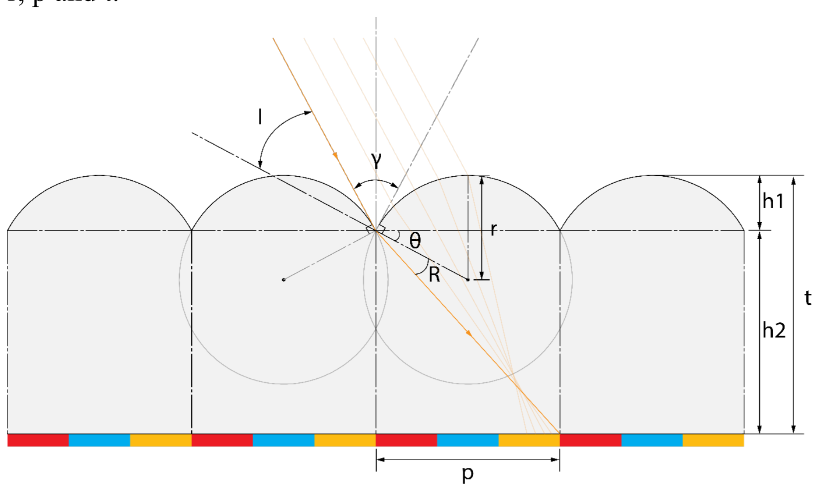


Figure 4-16 lenticule geometry explained with the extreme ray coming from the crevice between two lenticule

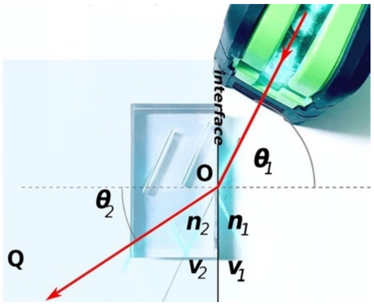


Figure 4-17 Measuring the refractive index of the printer material using a laser light

First, we calculate the refractive index of polyjet resin with a printed transparent block, according to Snell's Law of refraction:

$$n_{air}\sin\theta_1 = n_{resin}\sin\theta_2$$

$$\frac{n_{air}}{n_{resin}} = \frac{\sin\theta_2}{\sin\theta_1} = 0.642$$

$$n_{resin} = \frac{n_{air}\sin\theta 1}{\sin\theta 2} \approx 1.557$$

Then, based on the lenticule geometry in Figure 4-16, we can derive the lenticule thickness based on a given value of r and p:

$$r = \frac{p^2 + 4{h_1}^2}{8h_1}$$

$$\theta = arc\sin(\frac{r - h_1}{R})$$

$$I = 90 - 2\theta$$

$$R = arc\sin(\frac{n_{air}}{n_{resin}} * \sin I)$$

$$\lambda = \theta + R$$

$$h_2 = p * \tan\lambda$$

$$t = h_1 + h_2$$

$$\gamma = 2\theta$$

Where $p \leq 2r$,

Symbol	*Description*
t	*Lenticule thickness*
n_{air}	*Refraction index of air*
n_{resin}	*Refraction index of resin (lens)*
p	*Lenticule pitch, or width of each lenticular cell*
R	*Refraction angle of the extreme ray*
r	*Radius of curvature of the lenticule*
h_2	*Thickness of the substrate below the curved surface of the lens*
γ	*Vignetting angle*

Using the above formulas, we then validate different lenticular effects by adjusting the parameters of the control variables and apply those designed effects on the final product.

4.2.2 Lenticular effect validation, exploration and hypothesis

Based on the calculation shown in the previous section, we have a general concept of how the lenticule thickness, pitch, and radius relates to each other; and how to define one parameter based on the other two. In order to validate the equations and see how the three parameters could affect the lenticular content, we experimented several lenticule geometries with different printed grids (the resolution of the interlaced content), which includes:

For lenticular panoramagram (cylindrical arrays):

a) How lens curvature and thickness and content interlacing resolution affect lenticular observation
b) How the surface form of the content under the lens affects lenticular observation
c) When applying lenticular cylindrical arrays on the surface of a single 3D object, what effect it can create and what is the best geometry to display the desired image

For integram (spherical arrays):

d) How the sphere geometry and thickness affect lenticular observation with different content patterns
e) How the content shape (flat or voxel) under the lens affect lenticular observation
f) When applying spherical arrays on the surface of a single 3D object, what effect it can create and what is the best geometry to display the desired image
g) How would spherical lenses display when built on flexible material and deformed under pressure

4.2.2.1 Lens curvature and thickness testing with cylindrical arrays

In order to get a quick and clear result, the testing was conducted with ink printed paper and 3D printed lenses. We first tested the dynamic effect with two frames: color and shape changing from a red square to a blue circle; then three frames: from a red square to a blue circle to a yellow triangle. The cylindrical lens thickness was tested parametrically with an increase of ¼ lens radius for each iteration; the cuboid thickness was set to 1.5mm and 3mm, respectively. The image pattern was split by half, four times, six times, eight times, and 10 times respectively. The lens pitch was designed based on the column width of the printed grid.

<u>Two colors | two shapes</u>

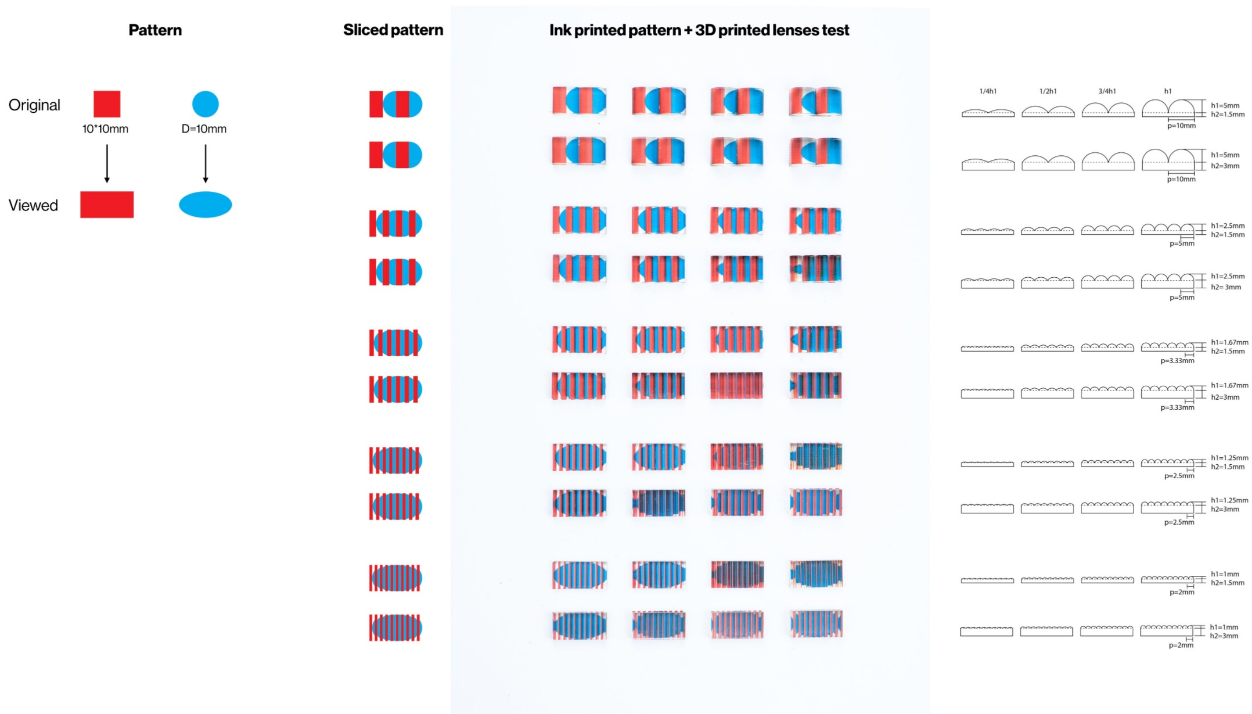


Figure 4-18 geometry diagram showing the original patterns and lens dimension in two pattern testing

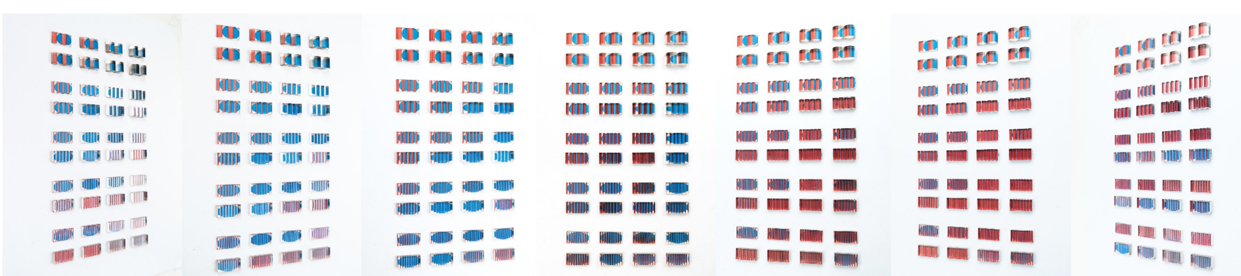


Figure 4-19 viewing printed lenticule blocks in different angle (2 color pattern), see Appendix 2 for high resolution images

Three colors | three shapes

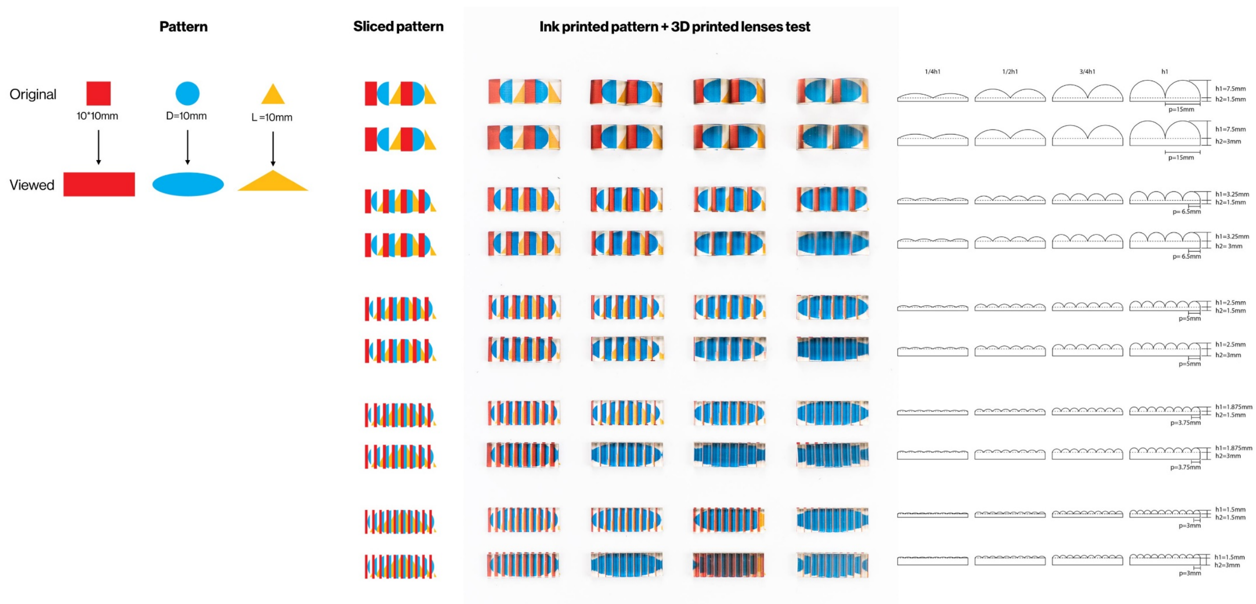


Figure 4-20 geometry diagram showing the original patterns and lens dimension in three pattern testing

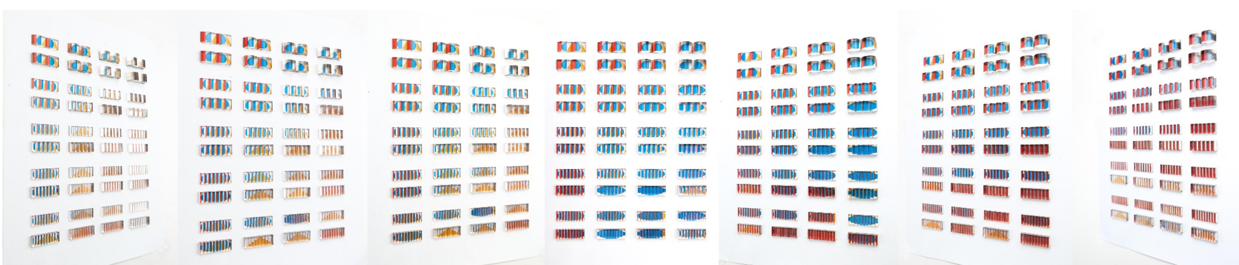


Figure 4-21 viewing printed lenticule blocks in different angles (3 color pattern), see Appendix 3 for high-resolution images

Key findings:

- The original pattern will be stretched by a factor of the number of views. For example, in the 2 shape-changing test, the viewed pattern was stretched horizontally by a factor of 2; in the 3 shape-changing test, the viewed pattern was stretched horizontally by a factor of 3. To make the viewed patterns the same as the original ones, all sequence images cells should be squeezed horizontally by a factor of 1/n before printing, where n is the number of views.

- Under the same cuboid thickness, a less curved cylinder lens gives a larger viewing angle, this means in order to see a full pattern change, one needs to look at the pattern from a fairly large and awkward perspective; a more curved cylinder lens reveals pattern change more rapidly, within a viewing angle of 40°.

- A larger lenticule thickness causes higher deformation on the original patterns; it would appear to be a resolution lost on the pattern's edge.

- When a lenticular sheet is observed from an angle that exceeds a certain value, it will display the pattern on the first image sequence again. Based on the theory discussed in the previous section, it is because when viewing from an angle larger than half of the viewing angle, people will see the image sequence under the adjacent lens.

4.2.2.2 Pattern content geometry testing with cylindrical arrays

In this testing, since the pattern surface is not flat, both the pattern content and lens block are printed with Stratasys J750.

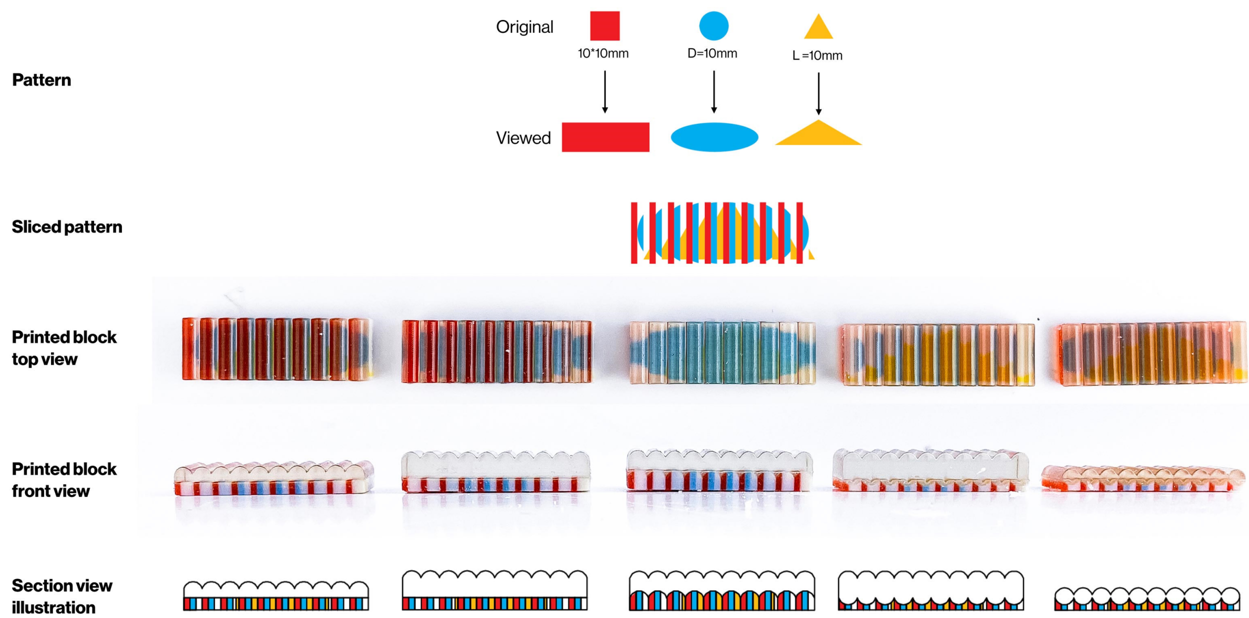


Figure 4-22 A illustration showing the lens and pattern content geometry in this test.

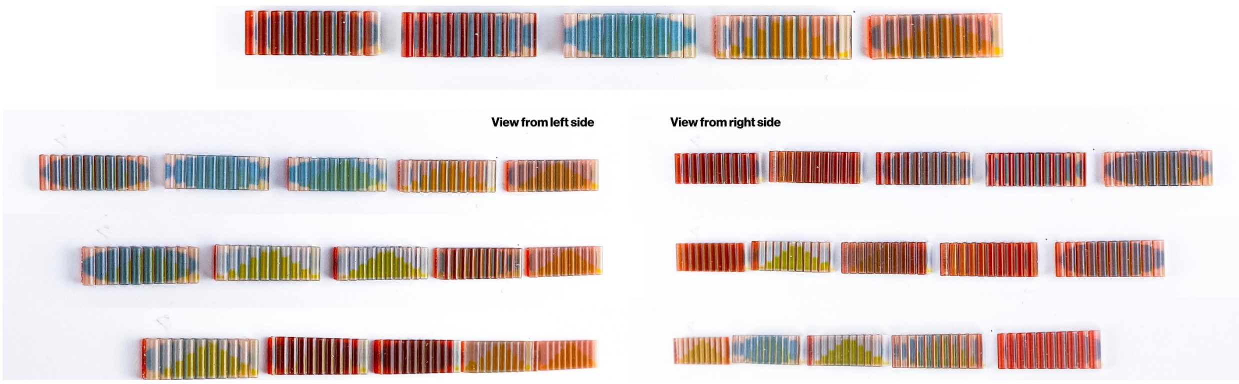


Figure 4-23 viewing printed lenticule blocks in different angles

Key findings:

- Compared to a flat pattern content, a raised content that follows the same curvature of the cylinder lens causes less deformation in pattern display.

- A concave pattern content causes more cross-talk between views, and the color boundary becomes more blurry.

4.2.2.3 Cylinder Lenticular arrays applied on the surface of a 3D object

The previous section gives a general idea about how lenticule geometry affects the 2D viewing result. This section explores the lenticular effect on 3D objects. First, a simple two color-changing content was tested on a 3D object with uniform section profile; second, three color-changing content and a simple line pattern was tested on the same shaped object, with a variety of lens geometry; third, three color-changing content was tested on a free form surface: the object was sliced vertically.

3D object with uniform profile, two-color testing:

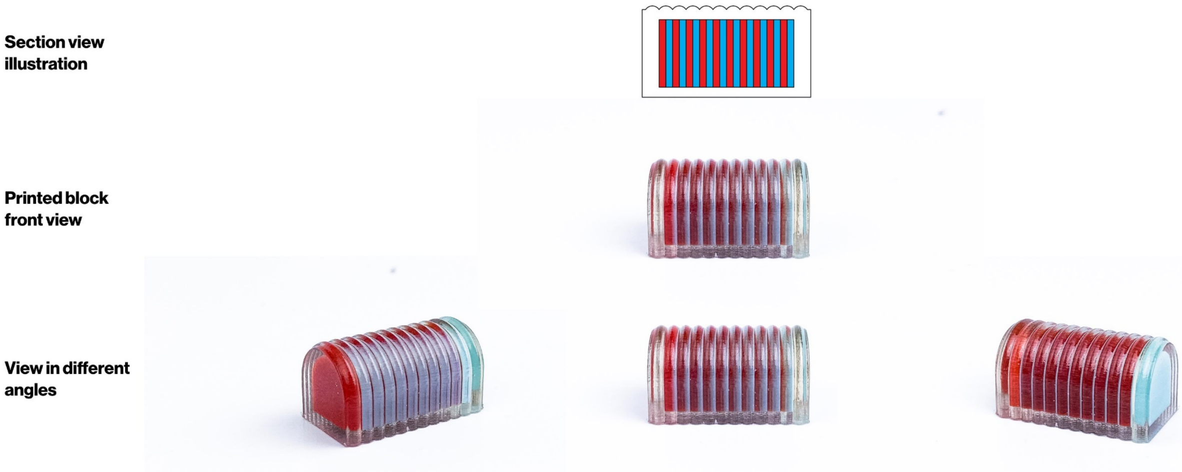


Figure 4-24 lenticular testing with two color changing content on an arched object

3D object with uniform profile, three-color, and line pattern testing:

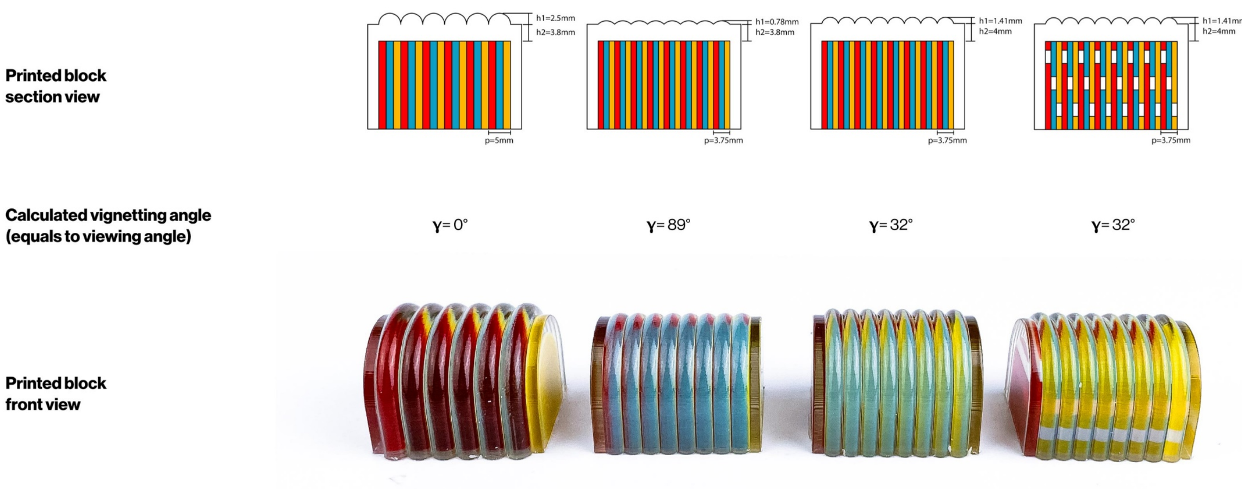


Figure 4-25 lenticular testing with three color-changing content and line pattern on an arched object, with various lens geometry

Figure 4-26 viewing printed blocks in different angles, see Appendix 4 for high-resolution images

3D object with a freeform surface, three-color testing:

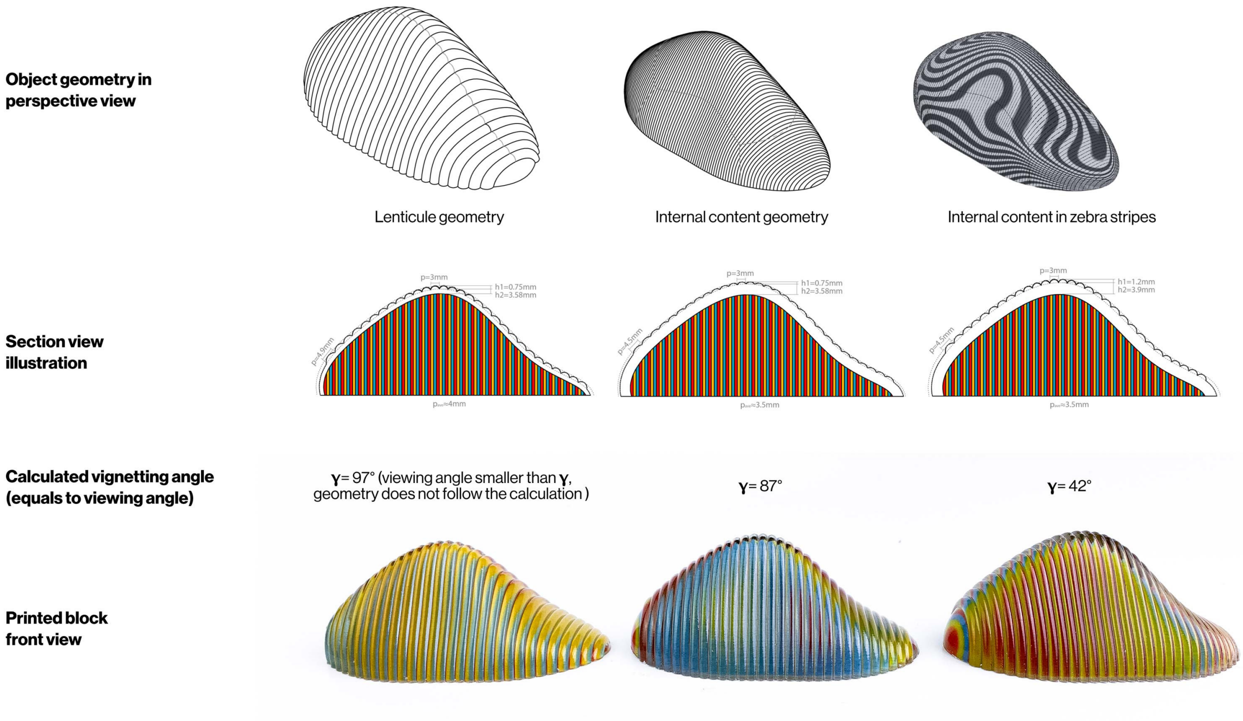


Figure 4-27 lenticular testing with three color-changing content on free form objects, with various lens geometry

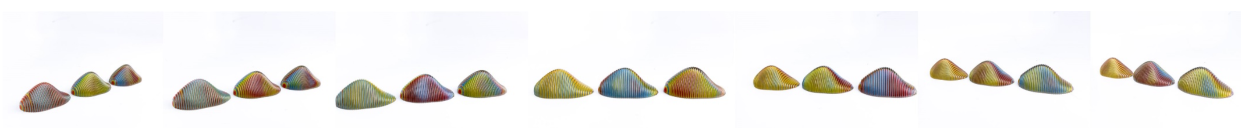


Figure 4-28 viewing free form objects from different angles, see Appendix 5 for high-resolution images

Key findings:

- Within the vignetting angle, which is equal to the viewing angle in our case, the viewer can see the correct image sequence from red to blue to yellow. When viewing beyond this angle, the viewer will see the image sequence again. With an extremely small vignetting angle - geometrically, it means the pitch equals to lens diameter - all three colors look mixed. With a tiny viewing angle change, people will see another color instantly.

- In a free form 3D object, this repeating color change was highly affected by the object geometry. From a fixed view angle, the lenticular could reveal all three colors, and because of the free geometry, the colors appear to be mixed and form new colors.

Different view angles will reveal different color content, even with a slight perspective change. The change in color and pattern looks fairly smooth as if looking at a digital screen playing an animation of the gradient loop.

- A discussion on why the color change is inconsistent across the surface:
  As shown in the section view of Figure 4-29, for an object with a flat surface, the viewing angle at each lenticule is the same when looking at the object from the same perspective. Thus, the color revealed from that perspective will stay the same for all lenticules. For an object with a free surface, the viewing angle varies along the curvature of each section profile even if the object is observed from the same perspective. With different viewing angles, the image contents showing through the lenticules appear differently across the surface.
  In order to eliminate the non-linear viewing path across the surface, future work could be adjusting the color content for each viewing angle in combination with the surface angle. So that from the same perspective, we can predict and create accurate content revealing across the surface.

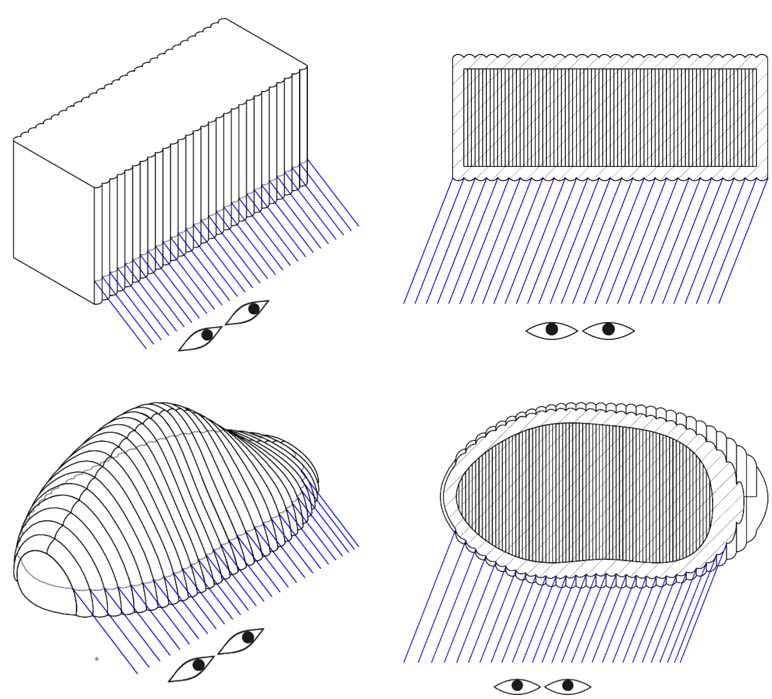


Figure 4-29 illustration showing light directions when looking from the same angle. Left two pictures are the perspective drawings, figures on the right side are the section views.

4.2.2.4 Sphere geometry and thickness testing with spherical arrays

A similar testing method was applied in integram with spherical lenses. First, the lens was designed with different spherical height, and there was a sharp transition between the spherical head and the cylinder bottom; second, a small fillet was added between each spherical head and the cylinder body; the third test uses lenses with relatively sharp heads.

<u>Spherical array testing_1</u>

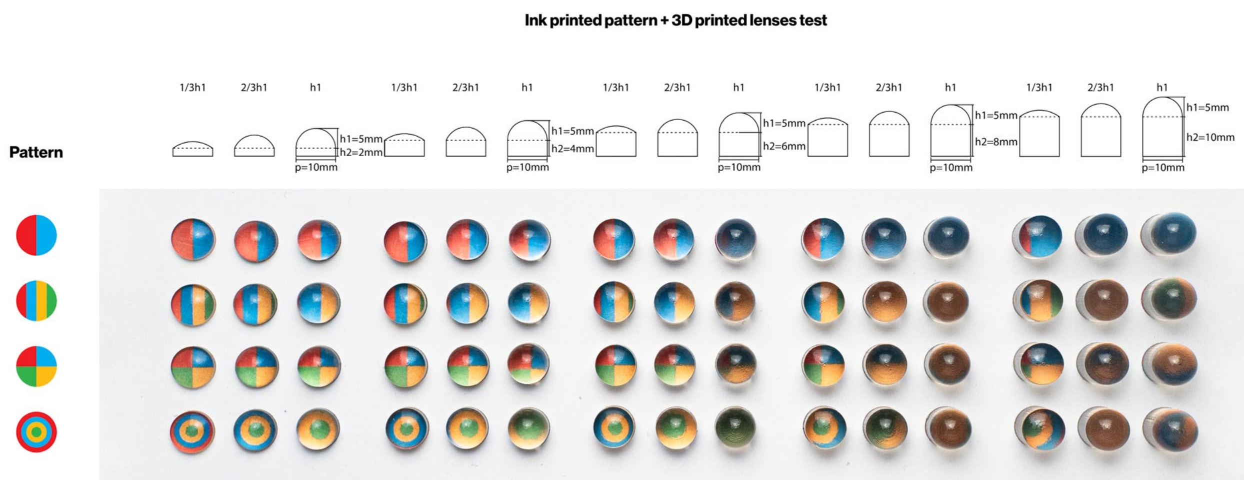


Figure 4-30 the original patterns and lens geometry in the spherical array testing_1

Figure 4-31 viewing printed lenticule blocks in different angles, spherical array testing_1, see Appendix 6 for a high-resolution image

Spherical array testing_2

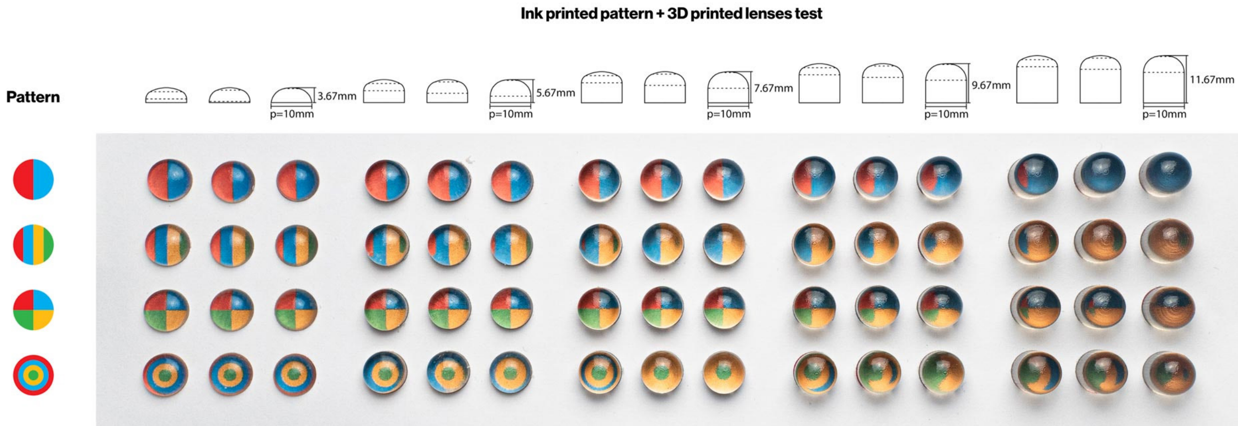


Figure 4-32 the original patterns and lens geometry in the spherical array testing_2

Figure 4-33 viewing printed lenticule blocks in different angles, spherical array testing_2, see Appendix 7 for a high-resolution image

Spherical array testing_3

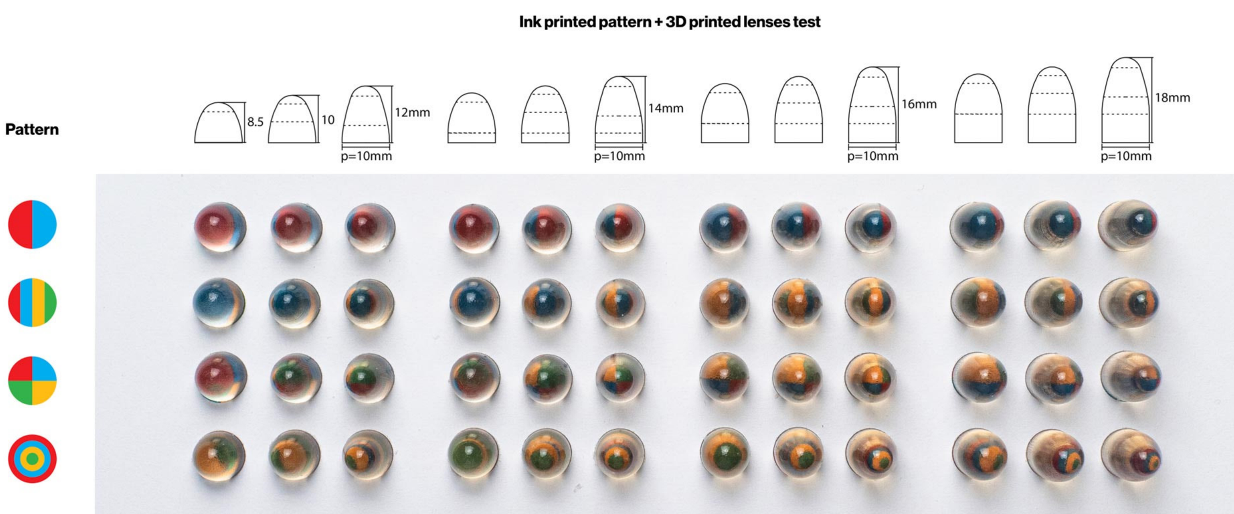


Figure 4-34 the original patterns and lens geometry in the spherical array testing_3

Figure 4-35 viewing printed lenticule blocks in different angles, spherical array testing_2, see Appendix 8 for a high-resolution image

Figure 4-36 crescent shaped pattern transition

<u>Key findings:</u>

- The content at the bottom will be "displayed" on the top only, leaving the lenticule body transparent; the larger the viewing angle is, the more portion of the lenticule body looks transparent.
- A less curved head surface displays less deformed patterns, which is closer to the original pattern at the bottom. When the curvature of the spherical head increases, there will be more color and pattern mixing, creating a smooth gradient transition effect.
- When the lens thickness increases, the pattern will be magnified more. It requires a bigger viewing angle to see the whole pattern.
- The pattern with concentric circles delivers the best result in smooth color mixing and transition: it can be viewed 360 degrees with color changing all the way.
- The lens geometry in spherical test_2 gives a special color transition effect, like a crescent. See Figure 4-36.
- The lens geometry in spherical test_3 makes the pattern "concentrate" more into the head.

4.2.2.5 Pattern content geometry testing with spherical arrays

In this test, both the pattern content and lenses are printed with Stratasys J750.

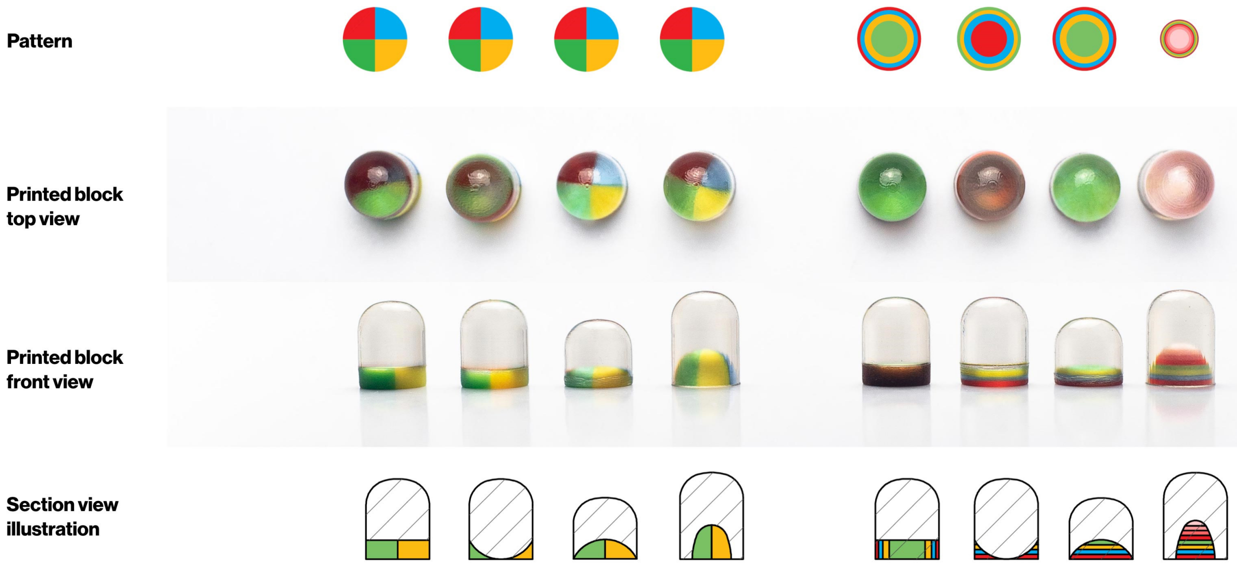


Figure 4-37 illustration showing the lens and pattern content geometry in this test

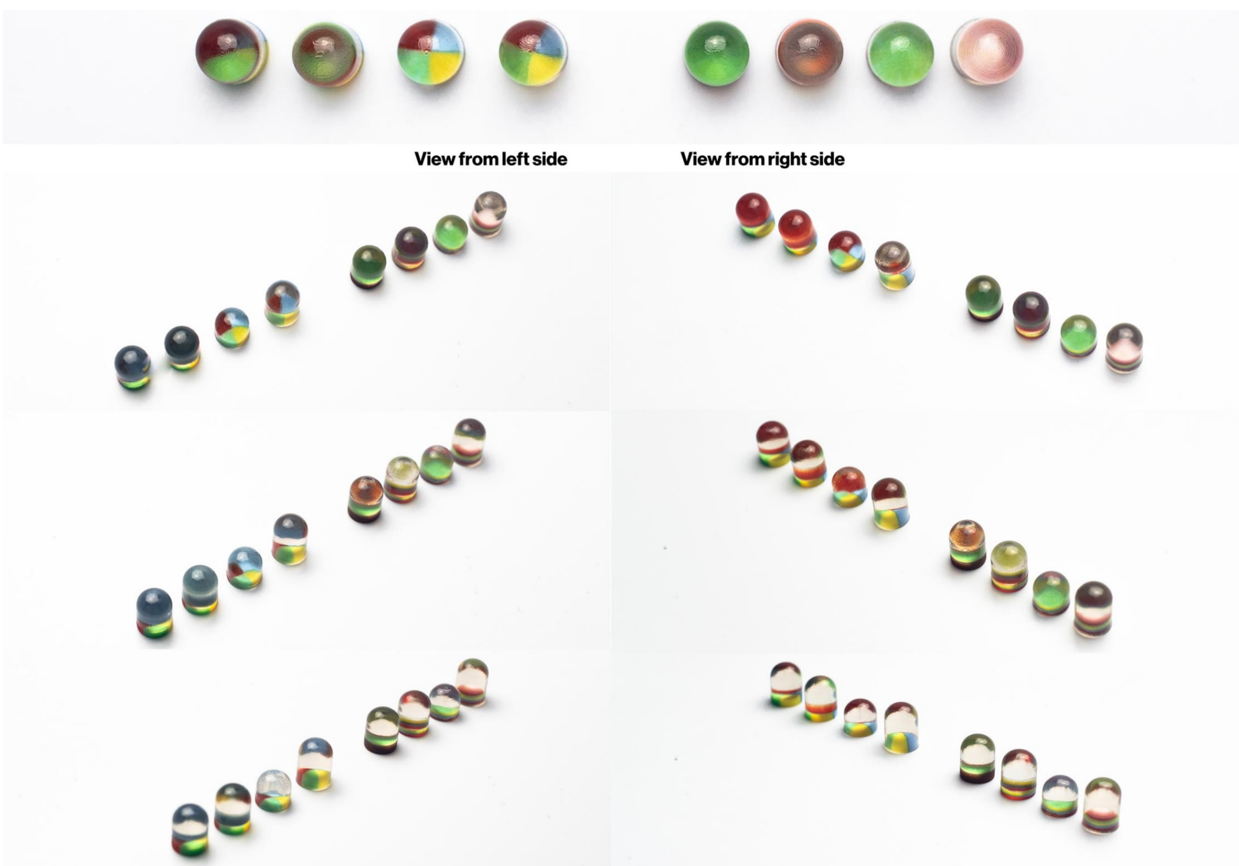


Figure 4-38 viewing printed lenticule blocks in different angles

Key findings:

- Compared to a flat pattern, a raised pattern gives a clear image display while a concave pattern shows more deformation through the lens. So if the wanted result is a smooth transition in color mixture, a concave pattern surface would be the optimal choice.
- Even the pattern content that does not fill with the full lens diameter, like the printed block shown in Figure 4-37 far-right, it will be displayed with full content width through the lens.
- A raised content can deliver more information as the surface area is bigger than the flat ones. However, the color will be mainly displayed on the spherical top with a fixed surface area. In order to see all the information designed in the content, a larger viewing angle is required.

4.2.2.6 Spherical lenticular arrays applied on the surface of a 3D object

In this test, we created a free form three-dimensional object and applied spherical lenticules on its surface. Different from the previous test in section 4.2.2.3, this time, we had the lenticules follow the UV-curves[3] of the object. The pattern content under the lenticule is a simple pie split into four parts, as shown in Figure 4-40.

[3] UV curves are the parameter curves that define the surface. Every three-dimensional location on a surface is described by an equation with two variables: U parameter and V parameter. (PTC, 2019)

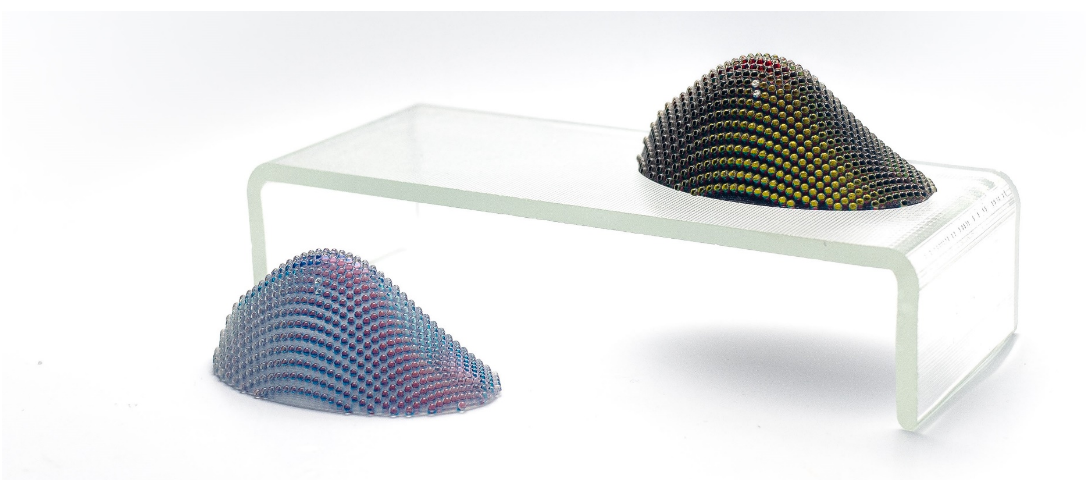


Figure 4-39 two free form objects with spherical lenticular surface

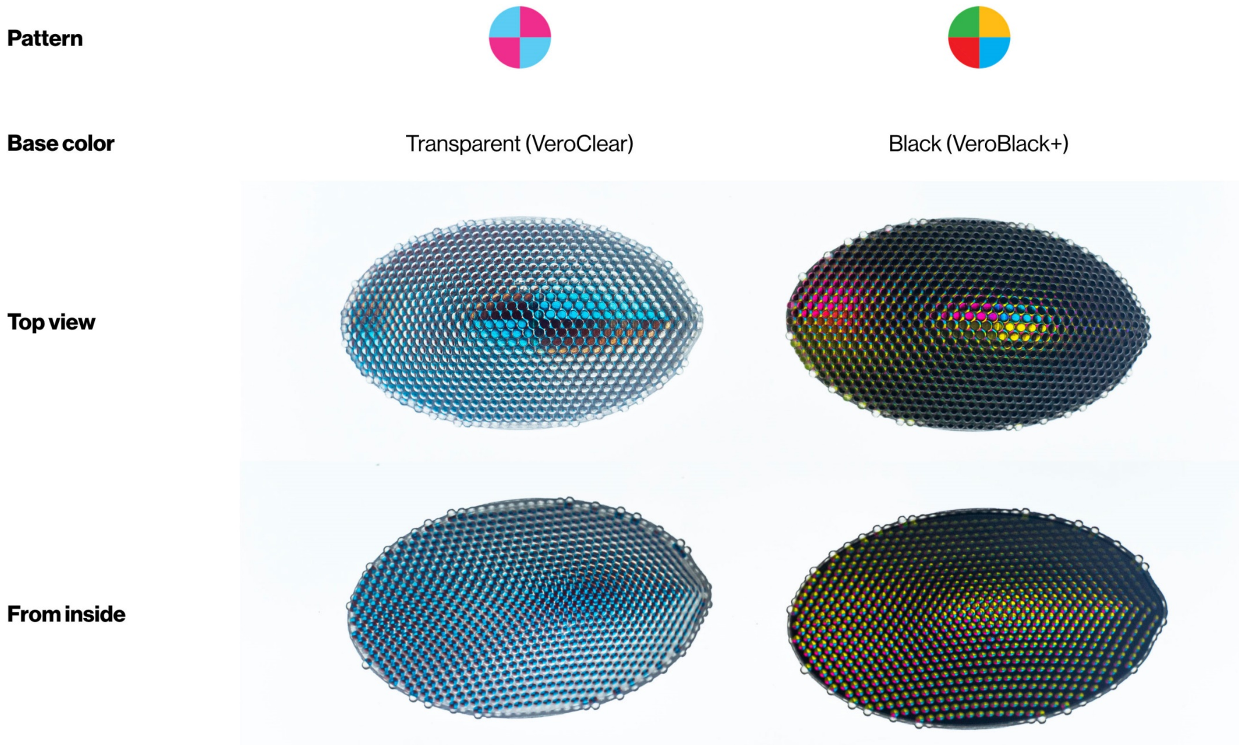


Figure 4-40 illustrations showing the pattern, top and bottom views of the objects

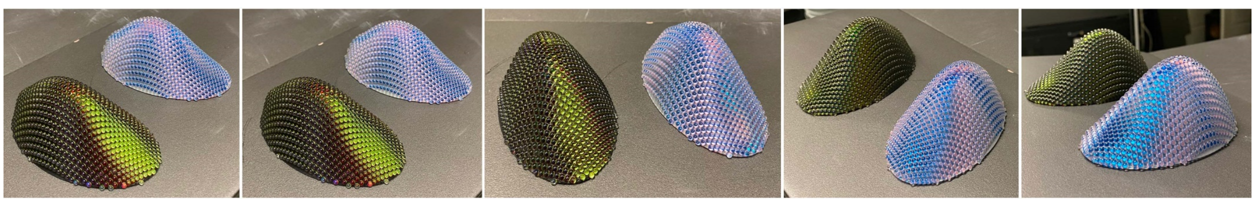


Figure 4-41 viewing the object from different angles (natural light source from top)

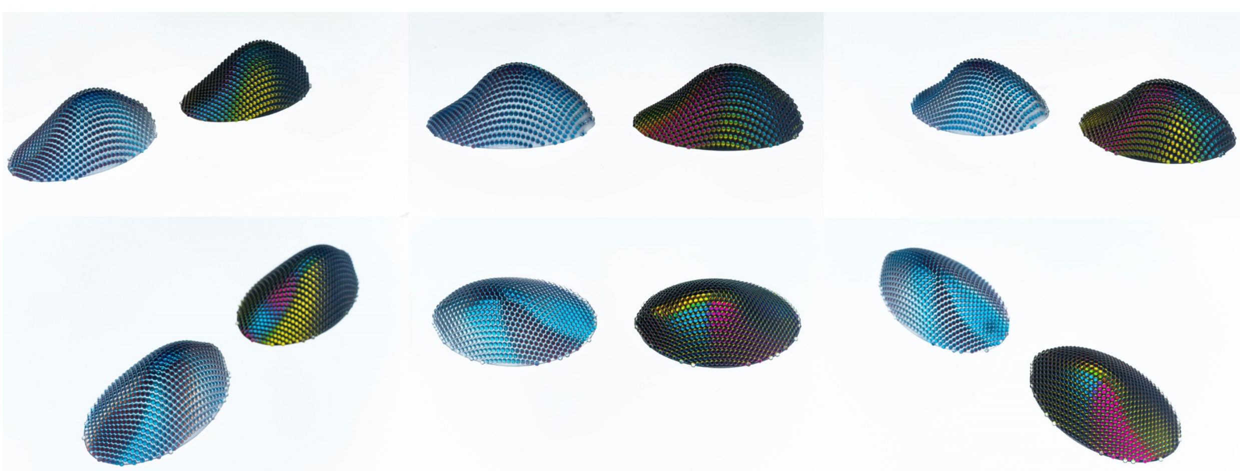


Figure 4-42 viewing the object from different angles (light source under the object)

Modeling process:

1) The locations of spherical lenses and patterns were generated based on the UV lines. The spherical patterns were projected onto the object surface.

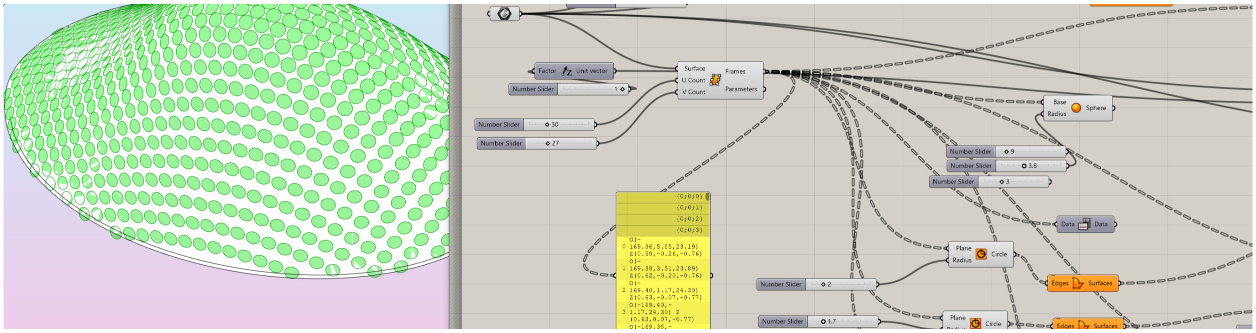


Figure 4-43 spherical lenticular on a free form object, modeling process step 1

2) The circular pattern was divided equally into 4segments on the surface body, using cutters aligned to the surface normal vectors. The data structure was cleaned up so that all the generated sectors are assigned into four separate data groups, based on the individual sector's relative location from clockwise directions on the circular pattern.

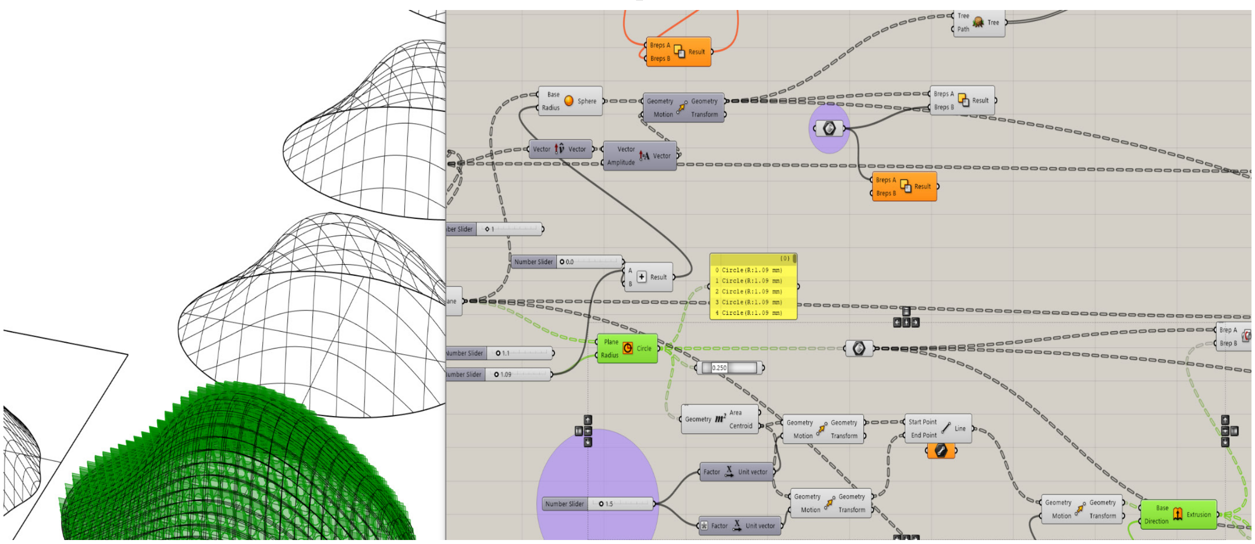


Figure 4-44 spherical lenticular on a free form object, modeling process step 2

3) Extrude the surface body with a certain thickness, extrude the circular sections, and Boolean with the surface thickness. The resulting geometry is the base body between lenses.

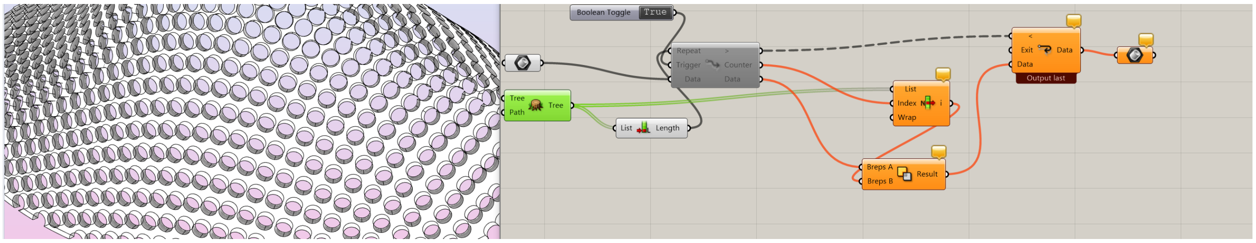


Figure 4-45 spherical lenticular on a free form object, modeling process step 3

4) Extrude all the sectors with a certain thickness, so that we can assign colors to individual groups in GrabCAD before printing.

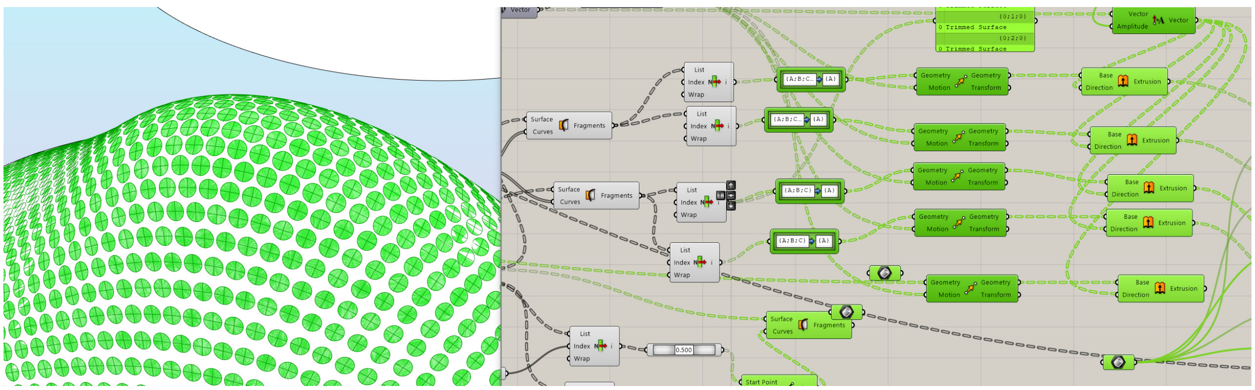


Figure 4-46 spherical lenticular on a free form object, modeling process step 4

5) Generate spherical lenses based on UV lines and move them along the normal of the object surface. Boolean the spherical lenses with the extruded object surface to form the whole lenticular surface.

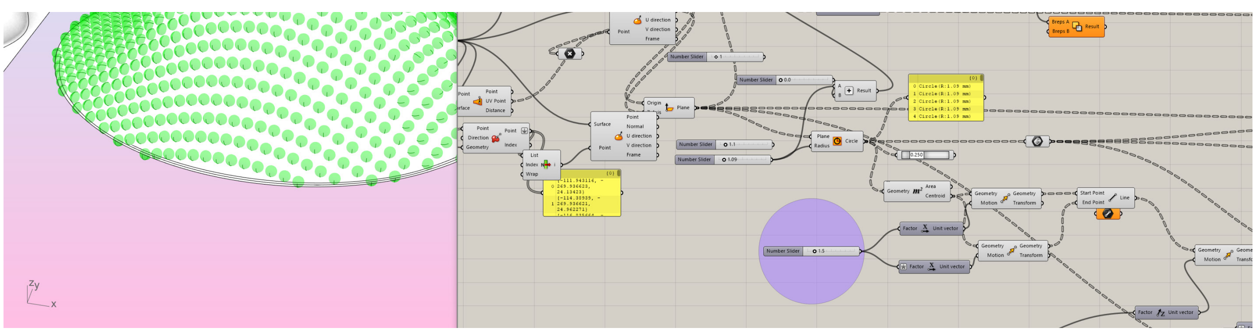


Figure 4-47 spherical lenticular on a free form object, modeling process step 5

Key findings:

- Although spherical lenticules allow viewing from all directions, similar to cylindrical lenticules, the color change is not consistent across the surface, and it's highly affected by the object geometry.
- From the top view, we can see that the object surface reveals four color segments that match the individual pattern under each lens. This is because the viewing angle varies along the curvature of the object. The lenses in each section share similar viewing angles from the top and reveal similar colors.

Future work:

- Another modeling process we can test out is to use a sphere packing algorithm to space the sphere more evenly across the free form surfaces.

4.2.3 Touch-sensitive material surface – surface deformation with lenticular visual effect

In this test, we printed the base surface with a flexible material (Agilus 30 Clear) and observed the visual effect when pressing and holding the object. When the object was deformed, the viewing angle toward each lenticule changed, creating a dynamic visual experience (Figure 4-48).

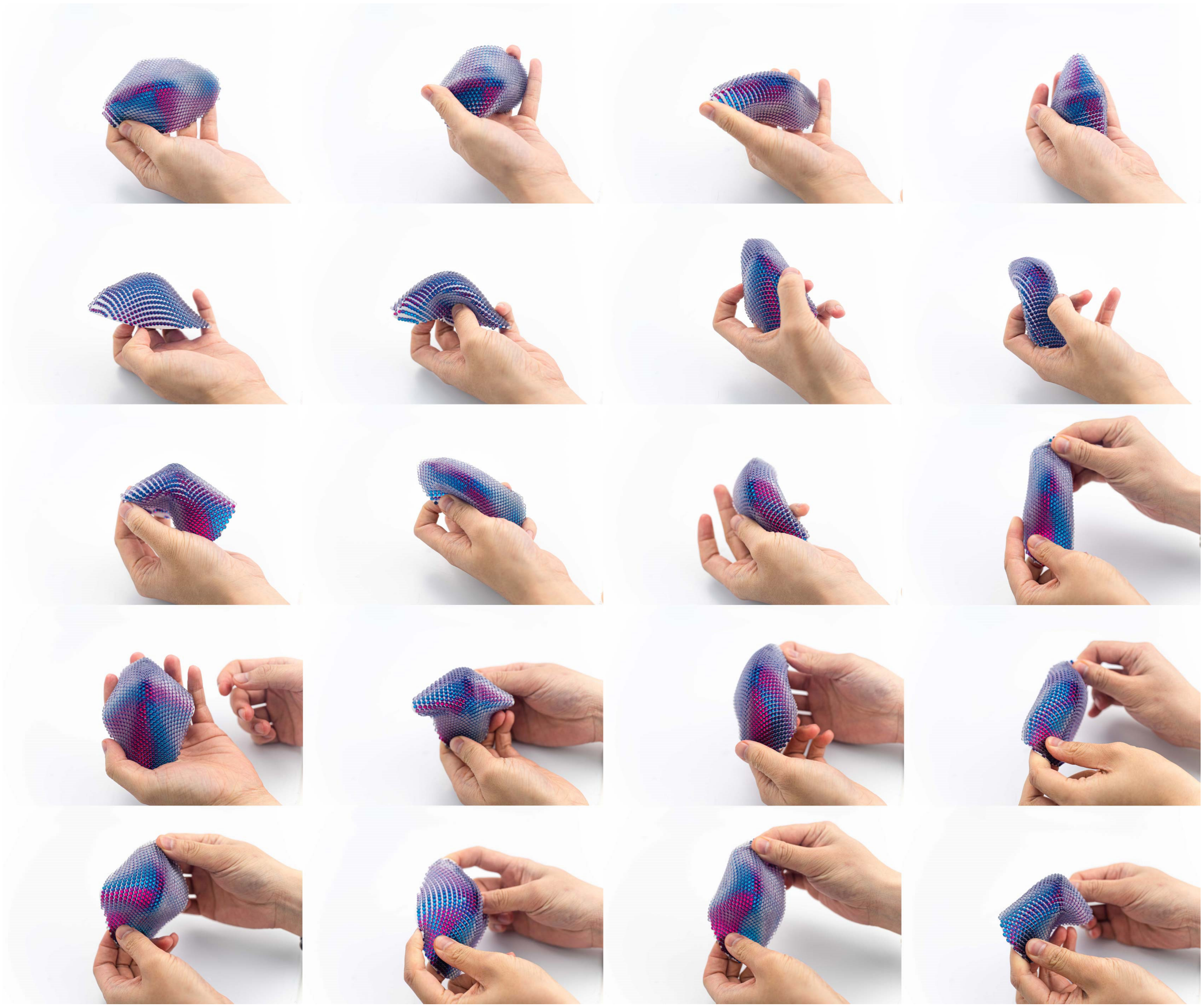


Figure 4-48 spherical lenticular material with user intervention (red and blue pattern)

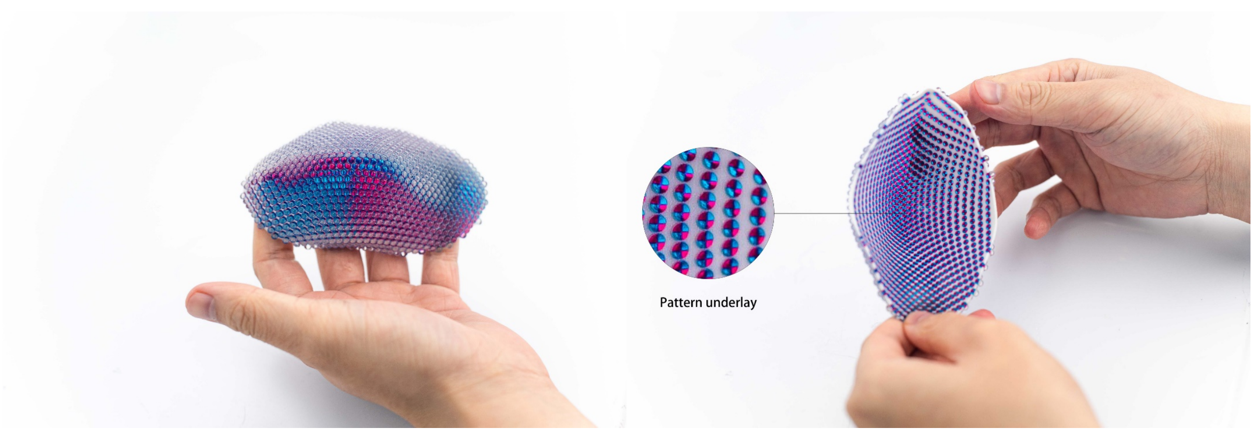


Figure 4-49 the top surface and inside of the free form lenticular object

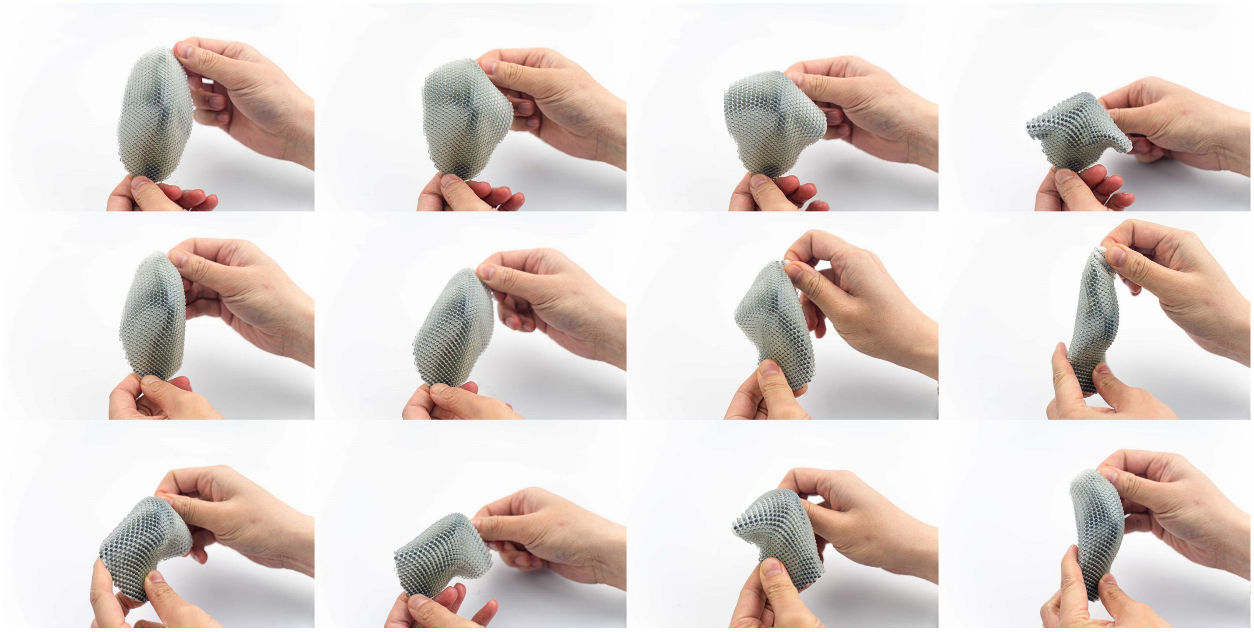


Figure 4-50 spherical lenticular material with user intervention (black and white pattern)

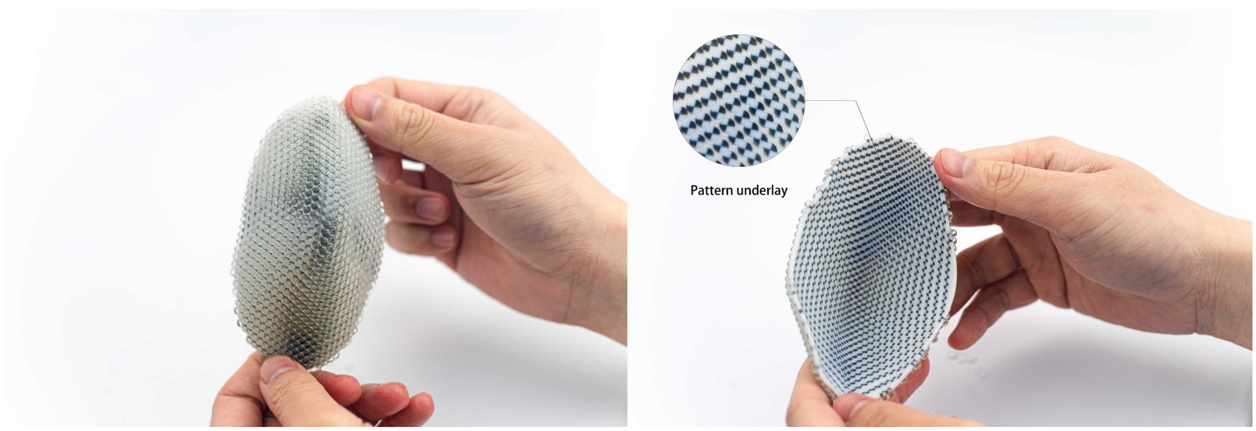


Figure 4-51 the top surface and inside of the free form lenticular object

Possible applications:

This touch-sensitive optical textile can be applied to any physical product interface that responds to user intervention without digital input. For example, a physical button revealing another color when pressed; an object showing a warning color or pattern when applied with a force that exceeds its maximum strength limit; or any artifact providing a dynamic user experience when being pressed.

4.2.4 Lenticular Effect on a 3D voxel printed object

In this test, we created lenticular lenses on a sophistic image content using voxel printing. Due to time constraints, the content is a two-dimensional image sliced to create a dynamic viewing experience. We will discuss the potential research direction combining voxel printing and lenticular effect in the next chapter.

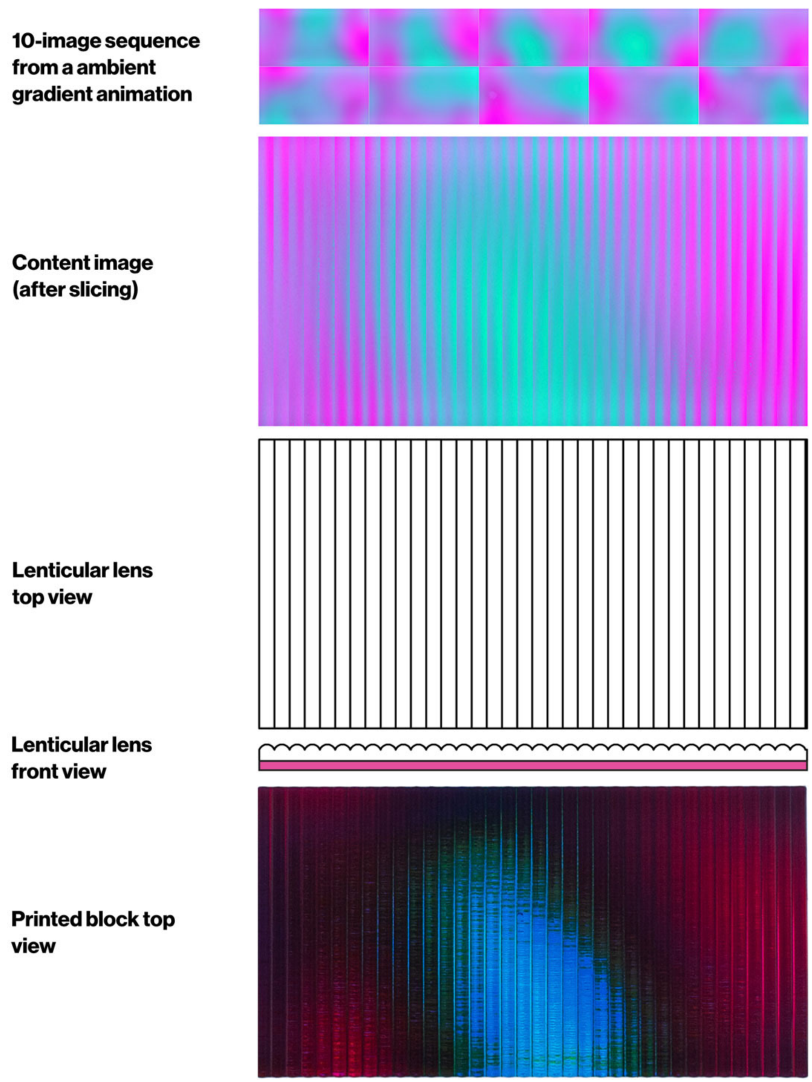


Figure 4-52 illustration showing the lens geometry and pattern content

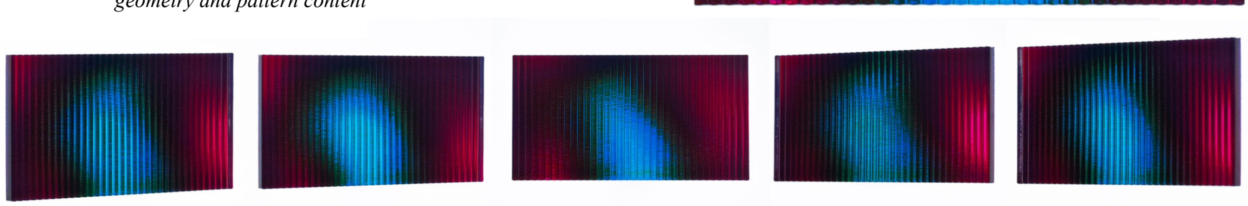


Figure 4-53 viewing the lenticular block from different angles

4.3 Applications and Products

In this section, we designed and prototyped three example objects as the proof of concept of my thesis, using materials with volumetric behavior that is both visually and functionally meaningful to the user. There could be more potential applications in other fields, such as packaging, fashion, furniture, installation, etc.

4.3.1 Minimal design with maximum information

"Minimalist", "minimal design" and "less is more" are one of the most common words designers hear all the time. The "minimal" features can refer to shape, graphic, colors, etc. In order to achieve this minimalism in product appearance, designers can either choose to deliver only the most essential information or embed product affordance within the product geometry. Volumetric material with optical effect offers designers a new approach to achieve minimalism by manipulating the light and delivering information only in designed viewing angles.

To prove the concept, we designed a "minimal perfume packaging" that only displays full text when viewed from a lower angle. We first tested on printed blocks with text information embedded below the lens, then applied the optimal geometry into the packaging design.

In the test, we assigned h1 value with 1mm (block 1), 0.5mm (block 2 3 4) and 0.25mm (block 5) respectively. The pitch distance was set to 3mm. The value of h2 in block 1, 3, 5 was calculated using our method in section 4.2.1.2, block 2 and 4 shares the same value of h1 and pitch with block 3, only the value of h2 in block 2 was reduced and in block 4, h2 was increased by half. The result was quite expected as we have previous experience in lenticular testing.

Key findings:

- A more curved lenticule gives a more rapid change in observed text with a smaller viewing angle. The text was deformed more, but it works better in hiding the text entirely from certain angles, as shown in block 1.

- When the lens gets thicker, as shown in Figure 1-5 block4, the text gets more stretched and deformed; the text revealing becomes more dramatic, with a tiny viewing angle.
- In order to get the optimal result and certain effect, the geometry calculation and print testing have to work together. In this case, the calculation will not tell how much deformation it might create or the best geometry to hide the text entirely. However, it can give a general idea of the right viewing angle, which is essential in this design.

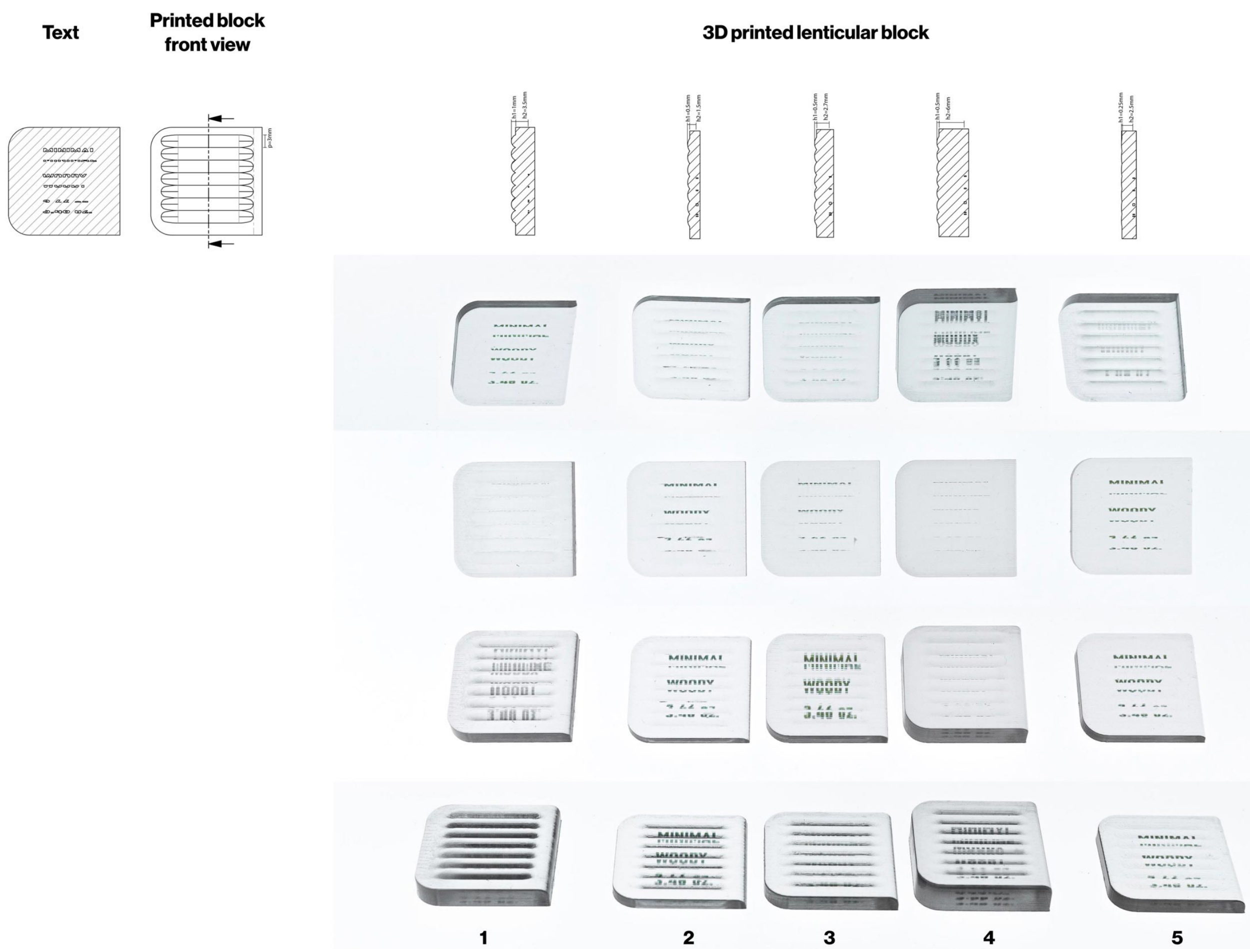


Figure 4-54 lenticular testing with text "MINIMAL WOODY 3.46 oz."

Figure 4-55 the product: a minimal perfume bottle with hidden text

Figure 4-56 minimal perfume bottle with hidden text

Figure 4-57 the side view of the perfume bottle

4.3.2 Reveal information that corrects user behavior

Another application is to embed certain information in the material interface for correcting user behavior. The free-formed pen shown in Figure 4-58 was designed with a lenticular window containing a red strip. During writing and looking from a recommended distance, the pen will display white in the lenticular section; if looking too close to the paper while writing, the pen reveals red. This color reminder could potentially prevent sight damage resulting from a long-term wrong sitting gesture.

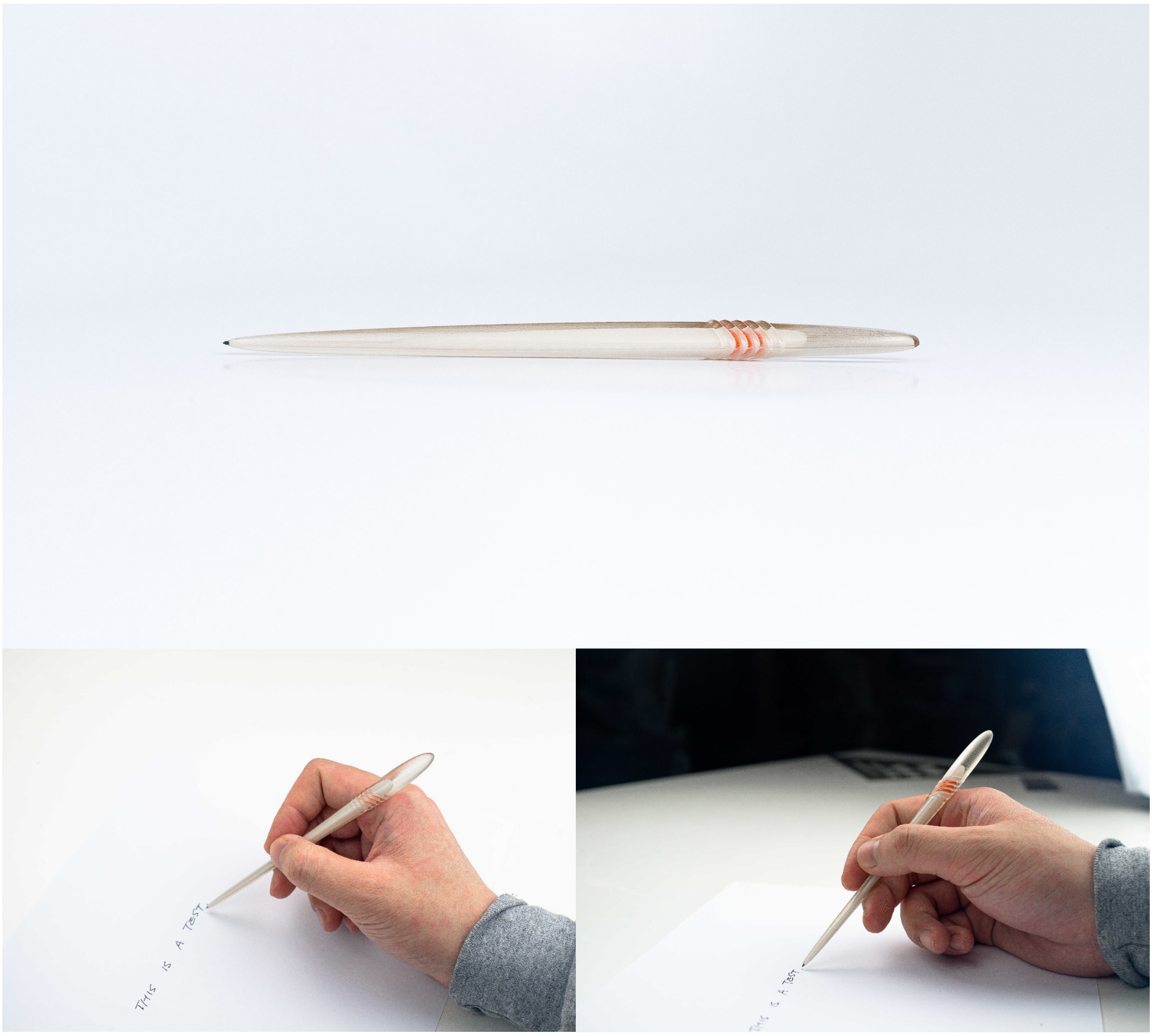


Figure 4-58 A pen designed to correct users' writing behavior

4.3.3 A lamp shell designed with optical textiles

Apart from the functional application, we designed an object with lenticular effect that is visually pleasant for the users. Optical textiles were applied on a highly complex surface object. This object was modeled with Rhino and Grasshopper (T-Spline).

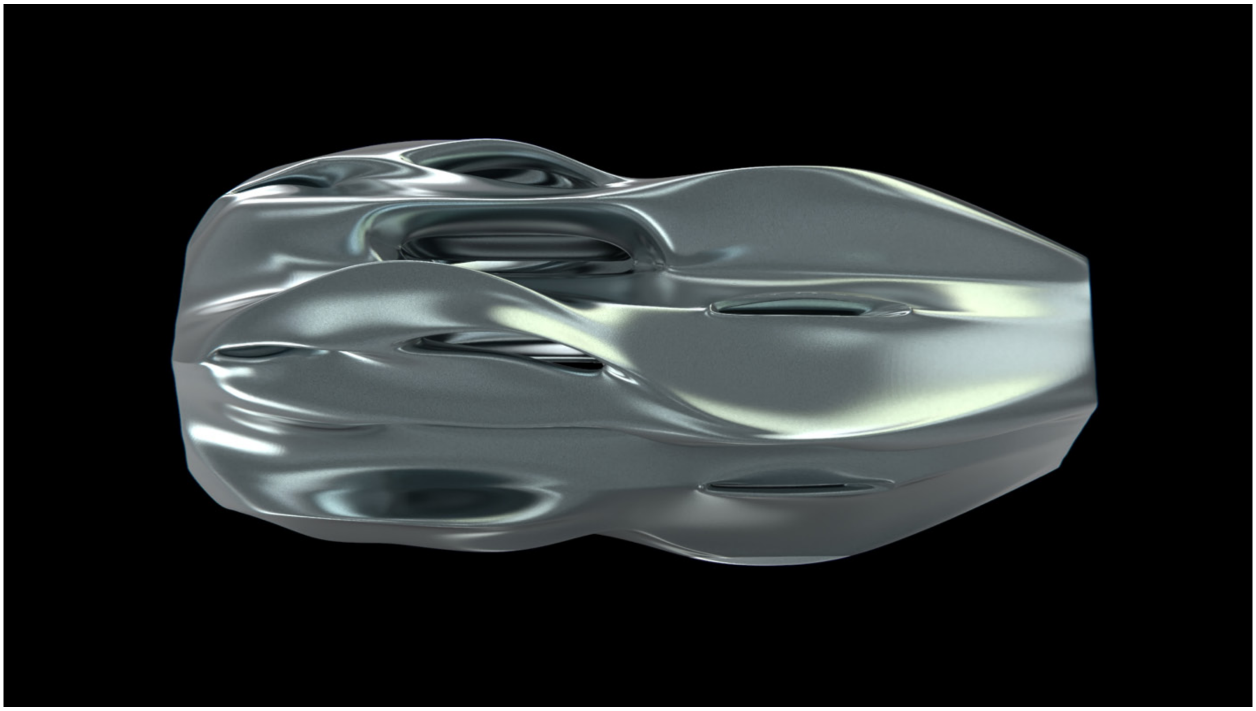


Figure 4-59 the original object form without lenticules applied (rendered front view)

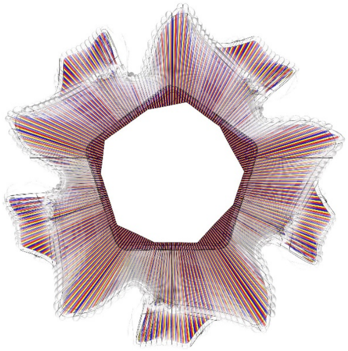


Figure 4-60 Model side view

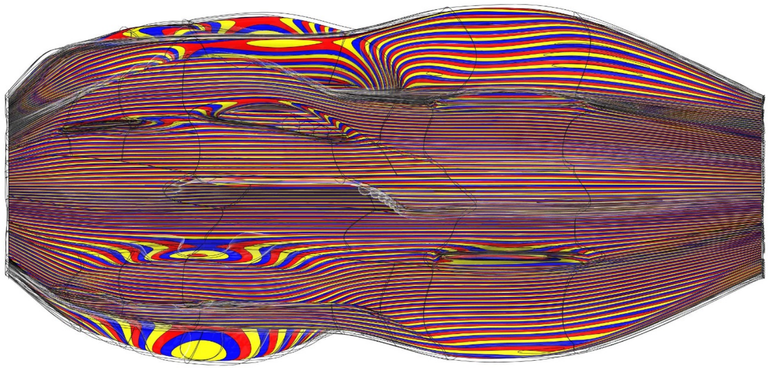


Figure 4-61 Model front view after lenticules and interlaced content applied

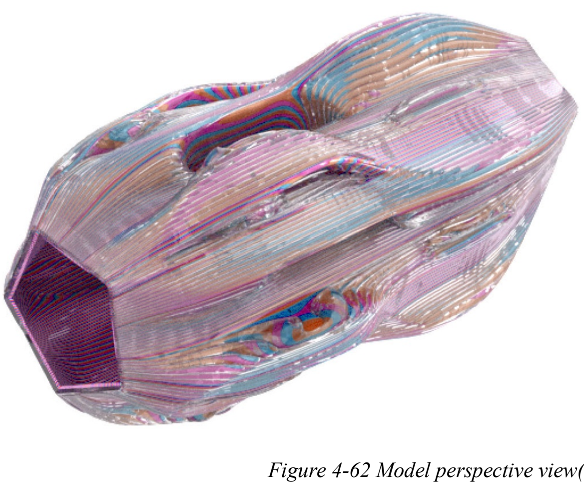


Figure 4-62 Model perspective view(rendered)

Figure 4-63 CAD modeling process illustration

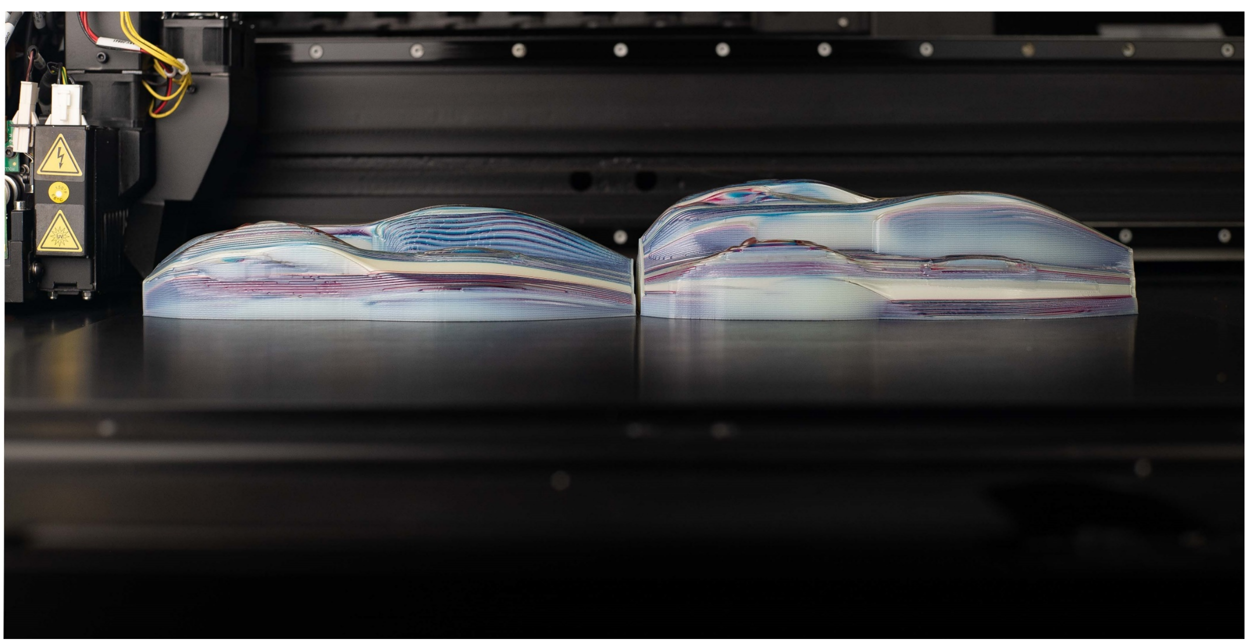


Figure 4-64 the printed models (by half) on Stratasys J750 tray

Figure 4-65 surface details of the lenticular artifact

Figure 4-66 the two half models of the designed object

Figure 4-67 viewing half of the object from different angles

Figure 4-68 viewing half of the object from different angles

Chapter 5
Conclusion

5.1 Contributions

Looking closer to this thesis, we discussed why industrial designers should think beyond the material surface and introduced the concept of volumetric material: a new material organization that responds directly to the user intervention or the environment. We conducted a series of comprehensive tests on volumetric material with lenticular effects, 3D printed by Stratasys J750. We analyzed the relationship between lens geometry and optical effect through observation and calculations. Based on those findings, we created some material samples of optical textile and touch-sensitive textiles that display dynamically via user intervention. We designed and printed three objects that apply volumetric material (optical textiles) to achieve certain functionality.

From a macroscopic point of view, we envisioned the future of product/object design with multi-material 3D printing: the design of material, including textiles and finishing, should be smoothly integrated into the form and function design. We embraced the freedom of creating matters from meta-level and producing materials with properties that cannot be achieved conventionally. We proved that material could display by itself, by bringing "digital-liked" material into reality. We integrated simple color separations with an optical lens to create dynamic color gradients, which can be applied in any object surface.

5.2 Future Work

My thesis is the very first step towards the broader topic of volumetric material in the product field. Referring back to section 3.1, we mainly discussed the view-based dynamic display under optical property manipulation and touch-sensitive material under mechanical property manipulation, there are many other directions this research can go as shown in section 3.1.

Under the lenticular testing, we can go deep in each section. For example, when applying lenticule with cylindrical arrays on a 3D object, we can change the slicing orientation to have the lenses align with the UV curves. We can test out different color mixtures and ratios and determines the relationship between pattern geometry and lenticular effect. We can also design the lenticule in a way that each lenticule has a unique viewing angle from the same perspective – so that we can even quantify the overall lenticular effect with regards to the lens geometry. When applying lenticule with spherical arrays on a 3D object, we could also test different content patterns such as concentric circles and increase the number of colors to be mixed under each lens.

The flexible material we create in section 4.2.3 looks like an animal's skin with unique surface reflexivity. More research could be carried out in designing and mimicking nature materials with special texture and surface details.

Additionally, we could create and develop a pipeline that enables designers to apply the desired optical effect on any 3D object or free form surfaces. Or even apply lenticular effects on a voxel printed object.

There are some technical barriers to be tackled too. For instance, for an object with a complex surface, it is hard to trace the UV lines and create lenticular lenses along these curvatures. Like the design shown in section 4.3.3, the lenses can get twisted and deformed along the UV curves. Some of the areas can not be covered with lenses. Secondly, in order to achieve a desired lenticular effect, the lenses were printed with a relatively large scale, compared to traditional lenticular sheets. This is because the current printer accuracy cannot reach the one traditional lens manufacturers have. The lens would not be perfectly smooth to reflect light correctly. Thirdly, when working with a free form surface, there will be lots of supporting material under the lenticular lenses. This "jelly-like" supporting material is hard to remove entirely and could affect the overall optical effect. However, we believe shortly with the development and wide-spread use of multi-material 3D printing, all these problems could be solved to some extent. By then, volumetric material would become common materiality in industrial design and any other design industries.

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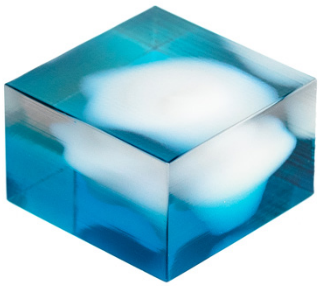
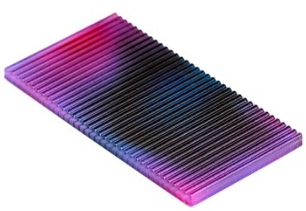
List of figures

Appendix

1. Sliced imges for voxel printing

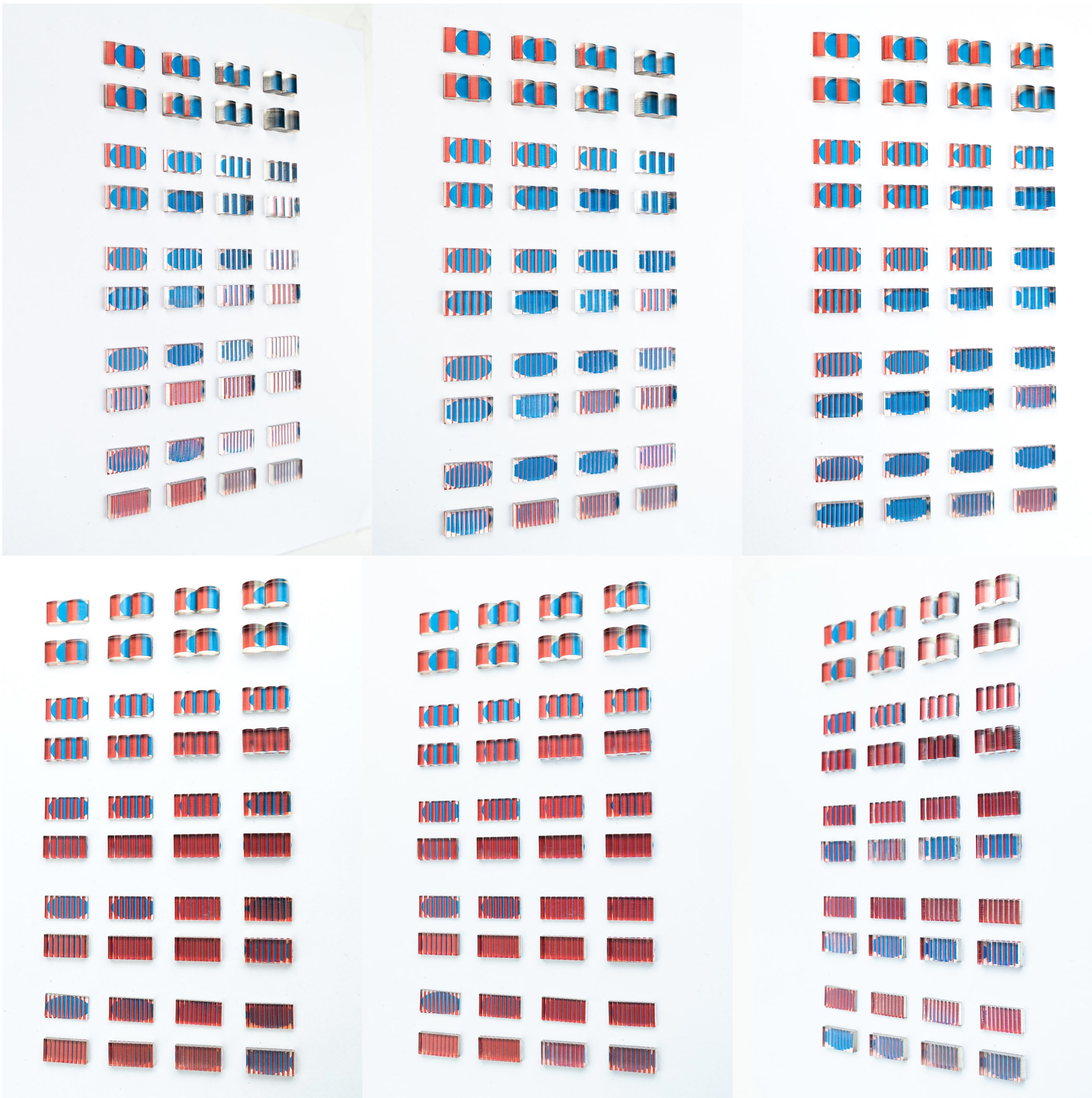


Appendix Figure 1 Part of the png. An array of the "cloud" model for voxel printing



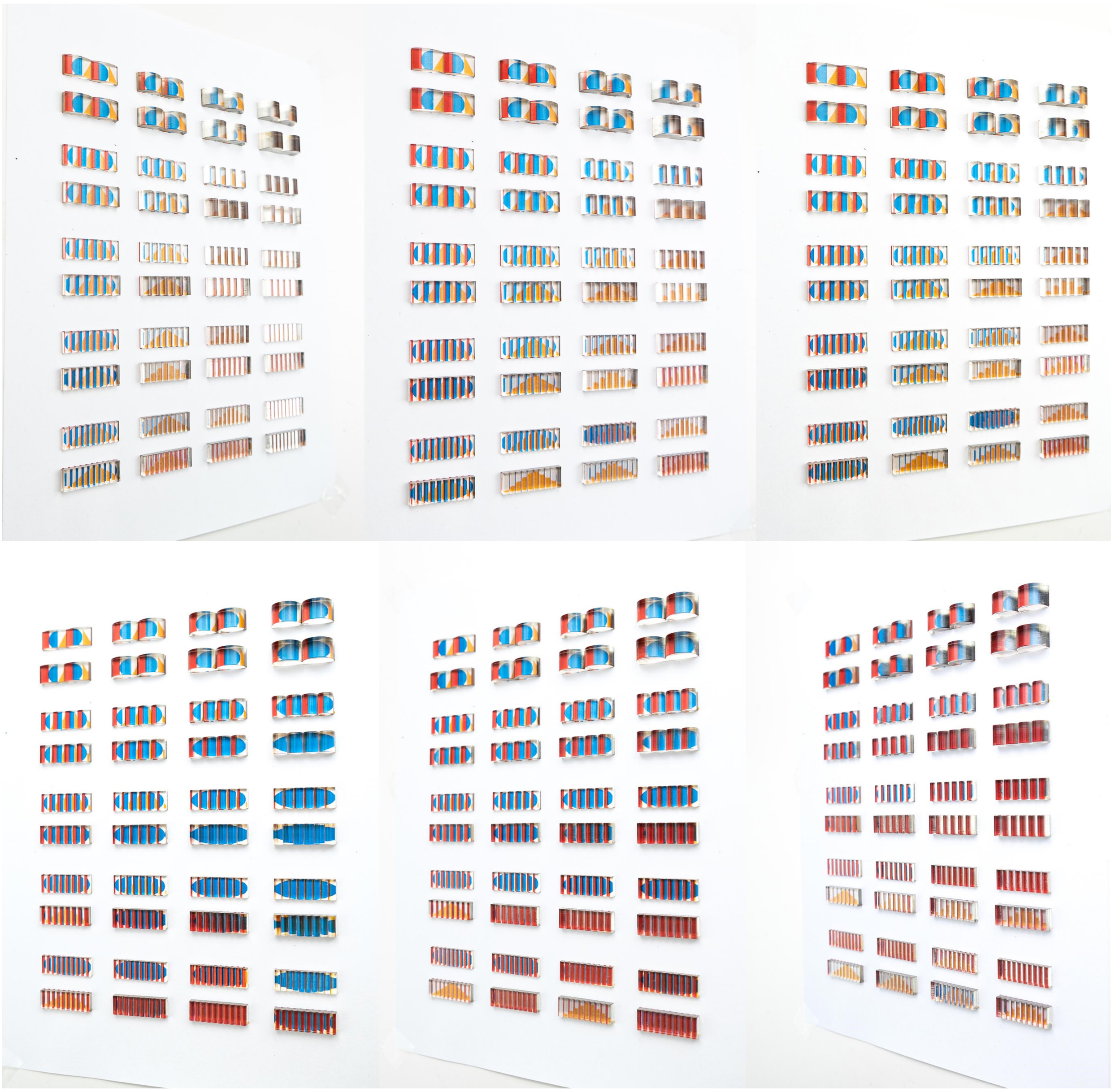
Appendix Figure 2 png. An array of the lenticular model for voxel printing

2. Cylinder lenticule testing, 2 colors | 2 shapes



Appendix Figure 3 viewing lenticular blocks in different angles

3. Cylinder lenticule testing, 3 colors | 3 shapes

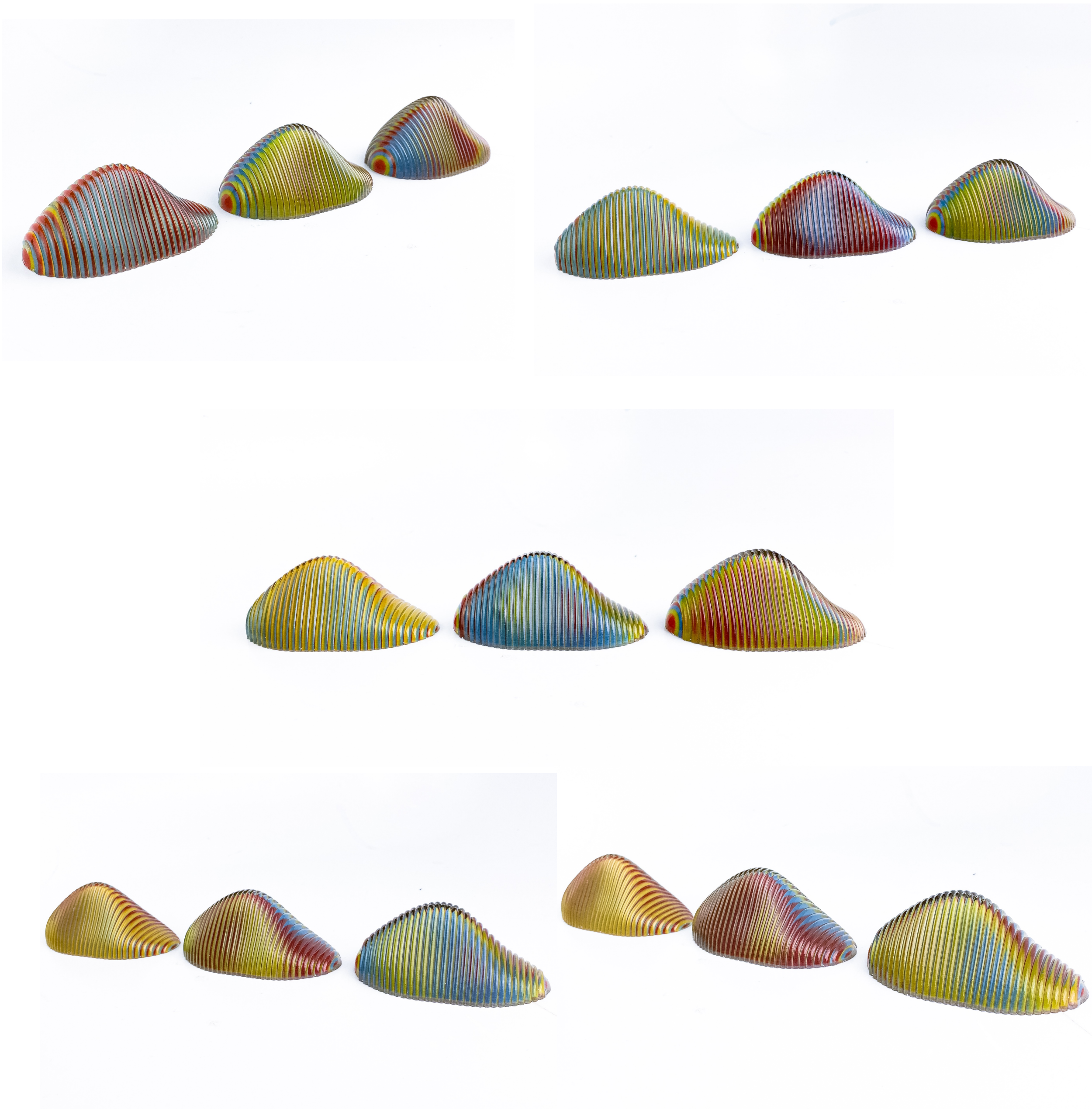


Appendix Figure 4 viewing lenticular blocks in different angles

4. Cylinder lenticule testing on 3D object with uniform profile, 3 colors + line pattern

Appendix Figure 5 viewing lenticular objects in different angles

5. Cylinder lenticule testing on freefrom 3D object, 3 colors



Appendix Figure 6 viewing lenticular objects in different angles

6. Spherical array testing_1 (the other half of the figure is in the next page)

Appendix Figure 7 viewing spherical lenticular blocks in different angles

Appendix Figure 8 viewing spherical lenticular blocks in different angles

7. Spherical array testing_2 (the other half of the figure is in the next page)

Appendix Figure 9 viewing spherical lenticular blocks in different angles

Appendix Figure 10 viewing spherical lenticular blocks in different angles

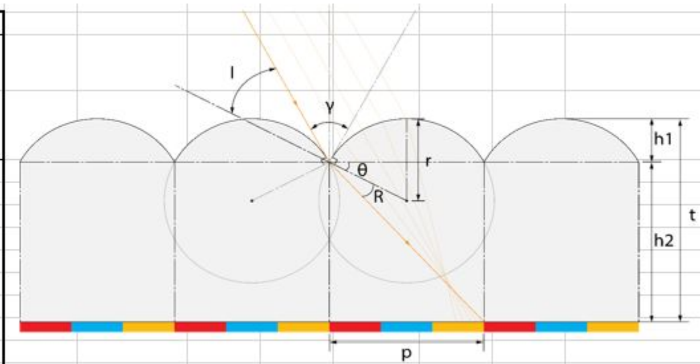
8. Spherical array testing_3 (the other half of the figure is in the next page)

Appendix Figure 11 viewing spherical lenticular blocks in different angles

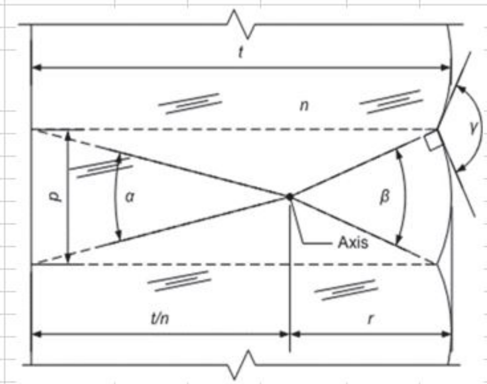
Appendix Figure 12 viewing spherical lenticular blocks in different angles

9. Excel table for lenticular calculations

Our method										
Parameters	**h1**	**p**	**r**	**θ**	**I**	$\frac{n_{air}}{n_{resin}}$	**R**	**λ**	**h2**	**γ**
Equations			$r = \frac{p^2 + 4{h_1}^2}{8h_1}$	$\theta = arc\sin(\frac{r - h_1}{r})$	$I = 90 - 2\theta$	0.642260758	$R = arc\sin(\frac{n_{air}}{n_{resin}} * \sin I)$	$\lambda = \theta + R$	$h_2 = p * \tan\lambda$	$\gamma = 2\theta$
4.2.2.3 test	2.5	5	2.5	0	90	0.642260758	39.96060583	39.960606	4.189643236	0
	0.78	3.75	2.643605769	44.82537894	0.349242125	0.642260758	0.224303696	45.049683	3.756509087	89.651
	1.41	3.75	1.951675532	16.11366827	57.77266346	0.642260758	32.90947652	49.023145	4.317402623	32.227
	1.2	3.5	1.876041667	21.12202138	47.75595724	0.642260758	28.38917144	49.511193	4.099594902	42.244
	0.75	3.5	2.416666667	43.60281897	2.794362055	0.642260758	1.794290961	45.39711	3.548855525	87.206
	0.75	4	3.041666667	48.88790956	-7.77581912	0.642260758	-4.985074353	43.902835	3.849667262	97.776
perfume test	1	3	1.625	22.61986495	44.7602701	0.642260758	26.88766983	49.507535	3.513484206	45.24
	0.5	3	2.5	53.13010235	-16.2602047	0.642260758	-10.36003339	42.770069	6	106.26
	0.5	3	2.5	53.13010235	-16.2602047	0.642260758	-10.36003339	42.770069	3	106.26
	0.5	3	2.5	53.13010235	-16.2602047	0.642260758	-10.36003339	42.770069	1.5	106.26
	0.5	3	2.5	53.13010235	-16.2602047	0.642260758	-10.36003339	42.770069	2.775120828	106.26
	0.25	3	4.625	71.07535558	-52.1507112	0.642260758	-30.47396134	40.601394	2.571437618	142.15
pen	0.5	2	1.25	36.86989765	16.26020471	0.642260758	10.36003339	47.229931	2.162068022	73.74



Traditional method										
Parameters	**r**	**n**	**t**	**p**	R_p	**α**	**β**	**γ**	**h1**	**h2**
Equations			$t = \frac{nr}{n-1}$	$R_p = \frac{np}{t}$		$\alpha = 2arc\tan(\frac{R_p}{2})$	$\beta = 2arc\tan(\frac{p}{2r})$	$\gamma = 180 - \beta$		
4.2.2.3 test	2.5	1.674	6.209198813	5	1.348	67.9599402	90	90	2.5	3.7092
	2.64	1.674	6.565869522	3.75	0.956080528	51.09935493	70.69299586	109.307	0.78	5.7859
	1.95	1.674	4.847336558	3.75	1.295041086	65.84777249	87.70422313	92.295777	1.41	3.4373
	1.88	1.674	4.659486276	3.5	1.257434758	64.31657766	86.01838602	93.981614	1.2	3.4595
	2.42	1.674	6.002225519	3.5	0.976137931	52.03113448	71.81944616	108.18055	0.75	5.2522
	3.04	1.674	7.554525223	4	0.886356164	47.80374299	66.65257937	113.34742	0.75	6.8045
perfume test	1.63	1.674	4.035979228	3	1.244307692	63.77593497	85.41877991	94.58122	1	3.036
	2.5	1.674	6.209198813	3	0.8088	44.03681605	61.92751306	118.07249	0.5	5.7092
	2.5	1.674	6.209198813	3	0.8088	44.03681605	61.92751306	118.07249	0.5	5.7092
	2.5	1.674	6.209198813	3	0.8088	44.03681605	61.92751306	118.07249	0.5	5.7092
	2.5	1.674	6.209198813	3	0.8088	44.03681605	61.92751306	118.07249	0.5	5.7092
	4.63	1.674	11.4870178	3	0.437189189	24.66117909	35.93827948	144.06172	0.25	11.237
pen	1.25	1.674	3.104599407	2	1.0784	56.66709235	77.31961651	102.68038	0.5	2.6046



Appendix Figure 13 Excel chart for lenticular calculation