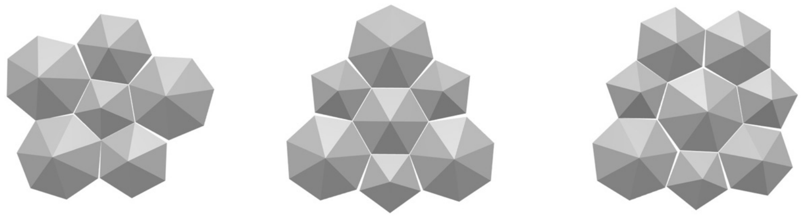
Un/Folding Form

A Unified Strategy for Making and Visualising in 3D



Kris Henning - Master Thesis by Composition - 2011
Victoria University School of Design, Wellington New Zealand

Un/Folding Form

A Unified Strategy for Making and Visualising in 3D

by
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Abstract

This thesis project "Un/Folding Form" is a design investigation that explores the transition between the virtual representation and physical fabrication of folded forms. Un/Folding Form refers to a unified strategy for making and visualising in 3D. Un/folding was a method used to explore the notions of form, space and structure and to develop an adaptable approach to mediate between the virtual and physical world.

Designers who make and visualise in 3D need methods that allow for the prototyping of virtual designs in order to experience them physically. The development of a unified strategy that assists in closing the gaps between virtual representation and digital fabrication improves the designer's understanding of the process of making, leading to more creative and resolved outcomes.

This research suggests that there are methods that can transition seamlessly between the virtual representation and physical reality of folded forms. The final composition presented in this thesis is a demonstration of this notion of working towards a seamless digital process of making. The 3D Portal can be used to assess the 'seams' between the virtual and the physical and validate a methodology for making and visualising in 3D.

In order to arrive at a unified strategy, the folding and unfolding of surface geometries was first explored through a series of physical experiments. These geometries were then 3D modelled and the surfaces manipulated digitally in order to create patterns for digital fabrication and physical reconstruction. The virtual representation of these folded designs was then investigated within a 3D stereoscopic projected environment. This involved the use of software to explore design interfaces to create immersive visual representations of physical forms. These series of experiments involved a process of moving back and forth between the virtual environment and physical form with the aim of moving closer towards a seamless transition between the two. This methodology was tested with the making of a final composition 3D Portal: a gateway to the virtual world and a play on the inter-relationship of 3D visualisation and its corresponding physical form. Thus, the focus of this thesis is twofold: to create an understanding of the process and evolution of design using folding as a technique; and to develop a methodology for designing a work using the folding technique.

Contents

Introduction

Un/Folding Form is an investigation that identifies a strategy for designers to embrace complex geometric forms and facilitate the interlinking of 3D visualisation techniques with manufacturing processes. The research in this thesis seeks to create an understanding of the process and evolution of design using folding as a technique and to develop a methodology for designing a work using this technique.

The methodology for making and visualising in 3D is an iterative process which commences with the making of folded forms that can be manipulated digitally, visualised in 3D, unfolded into 2D cut patterns, and reassembled in a physical form. The research questioned how the virtual and physical mediums used in this project could be integrated to develop a unified strategy for designing and interacting with form and space in 3D.

Designers who make and visualise in 3D need methods that allow for the prototyping of virtual designs in order to experience them physically. Designers may seek to prototype fragments of a virtual design or the entire design itself to gain a more in-depth understanding of their design during the conceptual and development phases of their work. An iterative approach between physical form and the virtual environment informs the design process and leads to a more holistic understanding and uninhibited view of the final design outcome.

"Digital practises have the potential to narrow the gap between representation and building, affording a hypothetically seamless connection between design and making." (Iwamoto, 2009, p.4).

Prototyping and physical exploration of design can be investigated using physical folding, digital fabrication and 3D immersive environments, but it is the interlinking of these mediums that reveals gaps in which new opportunities can be explored. The development of a design methodology that assists in closing the gaps between virtual representation and digital fabrication, will also present strategies that aid the designer throughout the development process.

In this research, strategies for folding and unfolding are explored through a series of physical and virtual experiments addressing the main elements of this research: the properties of physical folding, manipulations in 3D modelling software, visualisation in 3D immersive environments and digital fabrication with CNC machines. The crossover between these approaches supports the design of a final composition for this thesis.

Un/folding is a process used in this thesis as the means through which to transition between physical form and virtual space. Folding to crease, bend, shape and flatten surfaces is an experimental work in progress: transformative and forever evolving (Vyzoviti, 2006). Physical folding geometries can be represented as physical coordinates on a flat sheet of material as well as digital coordinates in 3D space.

The folding and unfolding of surface geometries are explored through a series of experiments which seek to identify a form suitable for further development: one that can be 3D modelled and manipulated digitally, and can translate into the virtual environment. The design and development of folded forms in this research was guided by concepts including geometry and pattern, as well as biomimicry. These are introduced in the background section of this thesis.

The virtual representation of these folded forms is developed further and investigated within a 3D stereoscopic projected environment. 3D immersion provides the opportunity to visualise complex geometrical forms and surfaces. The prospect of immersing ourselves in spaces and exploring form at the human scale is an advantage available with 3D stereoscopic projection.

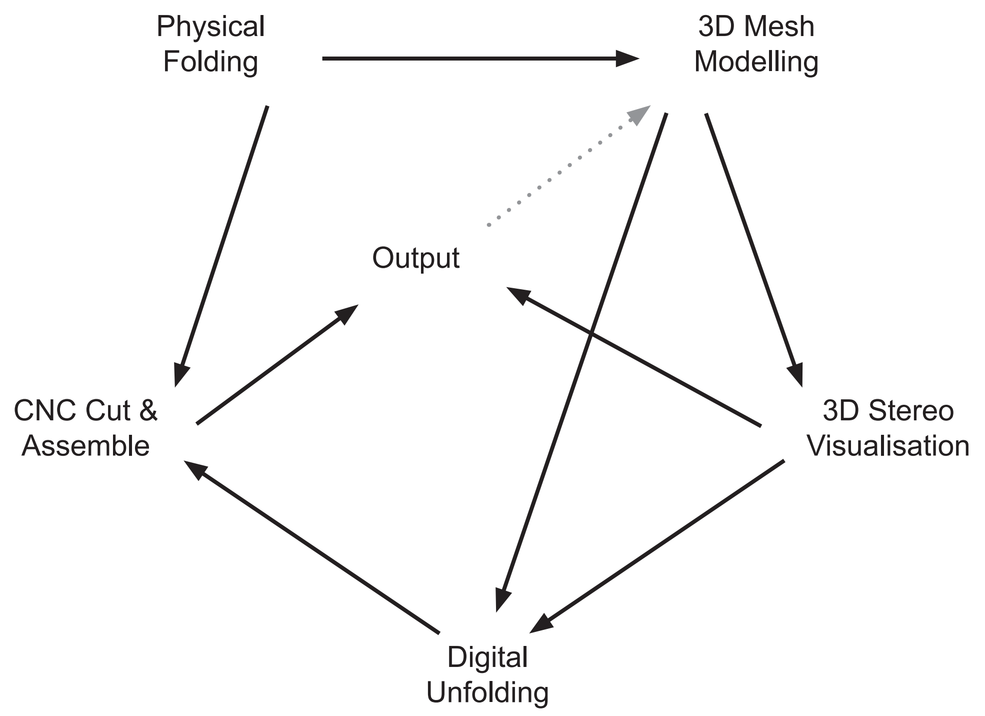
The virtual environments are explored in this research after the experimental stage 'Digital Manipulations' as a way of defining the forms that will enter into the virtual space. The digital manipulations stage encompasses 3D modelling, and the manipulation of surface geometries to create forms and spaces that can be unfolded. This is explored simultaneously with digital fabrication, involving the unfolding, patterning and cutting of physical sheet materials.

The digital forms are unfolded into patterns, in effect creating a visual road map of the original processes that shaped its formation. This map can be used as a pattern in which to develop a flat 2D net. These patterns are laid out on flat sheets of material and physically fabricated through the use of CAD/CAM software (computer aided design and computer aided manufacture) and CNC machines (computer numerical control). The cut out shapes are then manually reassembled to create a physical structure of the design that had previously been represented virtually.

The design interfaces used to create the immersive visual representations of the physical forms are developed with the use of computer software, "Blender" and "Pepakura". Blender is a tool for the modelling of 3D objects and allows for the warping of surface geometries. Pepakura is software that allows for the unfolding of a 3D form, the division of its surfaces, and the nesting of these shapes into a pattern for export for digital fabrication.

While the first stage of un/folding is the starting point for the creation of physical forms, thereafter it is a process of moving back and forth between the virtual environment and physical form. The interlinking of 3D immersive environments and digital fabrication techniques brings this design process closer towards a seamless transition between the physical and the virtual.

The unified strategy was tested with the making of a final composition the 3D Portal: a gateway to the virtual world and a play on the inter-relationship of 3D visualisation and its corresponding physical form. The 3D Portal demonstrates a way in which physical forms and virtual spaces can be combined to create an interactive experience for the designer and the audience and validate a methodology for making and visualising in 3D.



Method

Mediums for Investigation.

The research method used to develop findings for this thesis was conducted through design experimentation. This method incorporated the inclusion of five distinctive mediums for investigation: • Physical Folding - an investigation of form through a series paper folding experiments.

• **3D Mesh Modelling** – an investigation of 3D mesh modelling techniques to create virtual objects using Blender.

• **3D Stereoscopic Visualisation** - an investigation of visualisation techniques for the viewing of objects and spaces in 3D environments

• **Digital Unfolding** – an investigation of unfolding and pattern nesting for digital fabrication.

• **CNC Cut & Assemble** – an investigation of the use of CNC cutters to fabricate shapes for manual reassembly.

Each of these mediums is an activity or process that was explored both independently and together in order to identify areas of potential intersection. This thesis groups these mediums into three distinct stages of experimentation, and a final design stage. Each of the three experiment stages, or Chapters, explores different avenues of the cross-over between the virtual and physical components of this project:

• **Physical Folding** - The properties and qualities of folding paper and modular components.

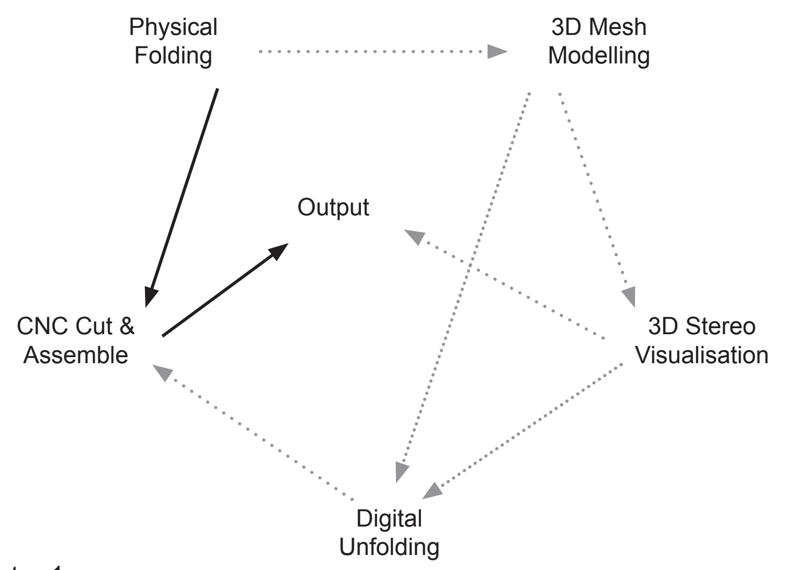
• **Digital Manipulations** - The use of 3D modelling software to create folded and unfolded forms.

• **Immersive Environments** - The process of analysing form, space and structure within 3D stereoscopic environments.

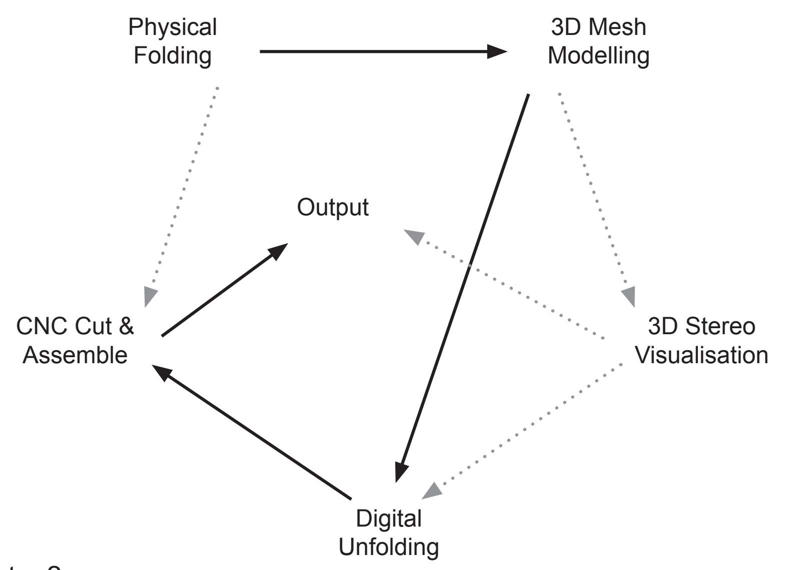
Each of the experimental stages is a way in which to develop design solutions that will allow for the crossover between the virtual and the physical. This crossover guides the direction of the design development and is indicated in each of the diagrams on the right. Each stage forms a foundation for the final chapter and the output of the thesis:

• **The Final Design** - A composition consisting of a design installation and an interactive 3D experience.

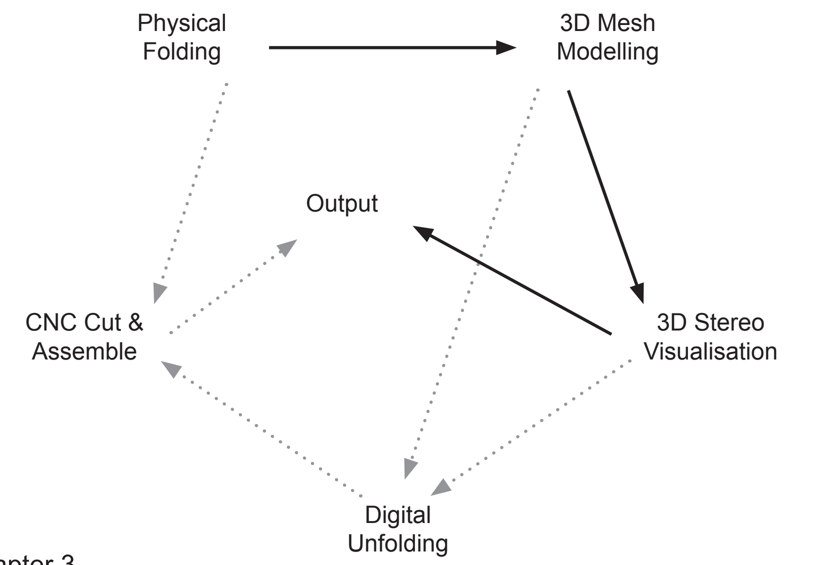
The final design stage is an assessment of the integration of each of these three stages and their resulting combination. The design outcome is a 3DPortal that is both a physical space to inhabit, as well as a 3D virtual experience to watch. It is a demonstration of the integration of design mediums and a direct interlinking between physicality and virtuality. It is a test of the unified strategy developed in this research.



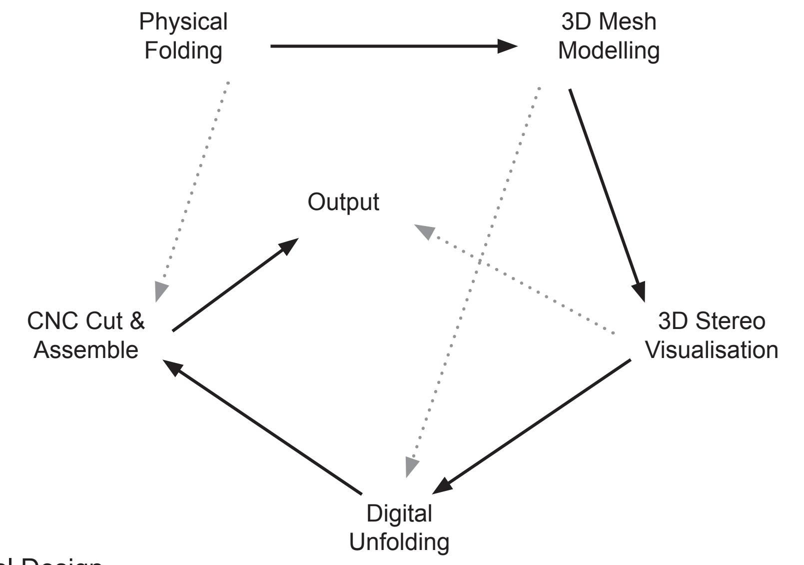
Chapter 1
Physical Folding



Chapter 2
Digital Manipulations



Chapter 3
Immersive Environments



Final Design
3D Portal

Background

The interlinking of design processes for visualising and fabricating in 3D are developing areas of research in the design field. Iwamoto in her book Digital Fabrication: Architectural and Material Techniques, documents the rise of digital fabrication and explores the use of digital design and manufacturing for form, spatial and perceptive effect (Iwamoto, 2009). Through the interlinking of visualisation and fabrication techniques the designer can gain a more in-depth understanding of the processes of making.

Increasingly today technologies are available for creating seamless transitions between virtual models and physical form. The gap between representation of a model and its construction can be narrowed through the use of digital technologies.

> *"As with any design process, there are invariably gaps among the modes of making. And, as with all tools of production, the very techniques that open these investigations have their own sets of constraints and gear particular ways of working"* (Iwamoto, 2009, p. 4).

While various techniques, such 3D modelling, laser cutting, CNC milling, and 3D immersive environments have advantages and disadvantages, their integrated use can assist in working towards a seamless transition between the virtual and physical world. Such methods of transitioning between the virtual and physical open up new opportunities for meeting functional design requirements and allow the designer to gain a greater understanding of their design during the conceptual and development phases of their work.

The mediums used in this research to transition between the virtual and the physical are: physical folding, 3D modelling, 3D stereoscopic immersion, unfolding, and CNC cut and assembly.

The experiments which use these mediums can be broadly contextualised within the following four major areas:

- Geometry, Pattern and Folding
- Digital Fabrication
- Visualisation of Form and Space
- Biomimicry and Organics

These contexts guide the use of the mediums, frame the research within an aesthetic approach, and direct the decisions on un/folding for exploration within 3D stereoscopic environments.

Geometry, Pattern and Folding

The exploration of geometry and pattern is one of the central themes that run throughout this thesis. Geometry *"is a process that reveals patterned organisation and formation of spatial systems"* (Hanson-Smith, 2000, p.24). There are certain geometries and patterns that a person feels innately connected to because of the prevalence of these patterns in the world around us. Patterns appear in all natural structures and the same pattern often appears frequently and builds upon itself. Nature chooses to order itself in a harmonious and proportionate manner, for example, like the swirls on a sea shell.

Many artists, designers, architects and engineers recreate these geometries and patterns in their creative endeavours. For example, Buckminster Fuller built geodesic domes by redefining the spherical shape as a pattern of triangles or hexagons in order to provide both lightness and structural stability. Andrew Kudless drew inspiration from mathematics and the processes of natural biological systems in his Manifold Project, which used a mathematically generated homey-combed pattern on a walled surface to create an irregular curvature. The pursuit of the natural is also shown through the work of Heron and de Meuron, and in particular the de Young Museum in San Francisco's Golden Gate Park (Fraser, 2008, pp. 68-69). This context is the aesthetic perspective in which we can view the geometries created within this project. As Fontenelle, a writer and poet, has said:

> *"The geometric spirit is so bound up with geometry that it cannot be disentangled and carried into other fields. A work of morals, of politics, of criticism, perhaps even eloquence, will be finer, other things being equal, if it is written by the hands of a geometer."* (Quoted in Abas and Salman, 1994).

In nature as elsewhere, beauty is expressed through harmonious proportions. A good example of this can be seen in the tessellated geometries of patterns in Islamic art (Abas and Salman, 1994). "Tessellations are collection of pieces that fit together without gaps to form a plane or surface" (Iwamoto, 2009, p. 36).

> *"It has been appreciated since antiquity that beauty arises if and only if the constituent parts of a structure are harmoniously proportioned in relation to each other and in relation to the whole. Beautiful patterns have to be based on some form of inner logic of proportions."* (Abas and Salman, 1994, p.18).

For this research, it was important to understand the principles of this inner logic as a means of interpreting folding geometries. For example, in Leonardo Da Vinci's Vitruvian man, the circle, square and triangle have a direct relationship to the body. A well proportioned person's feet and hands will fit within the circle arced around the central point of our body, the navel. Similarly, the Fibonacci sequence and its correlating golden rectangles define the position of the joints throughout the human body and, for example, the petals of a flower (Melchizedek, 1999). This is a testament to the beauty that exists in nature and the harmonious proportions that it creates.

Throughout this thesis geometry and patterns are used as a means through which to explore the topology of a surface. Easton+Combs' work emphasised the importance of surface as the focus of their design investigation (Techman, 2008). Eisenman also explored the topological qualities of the form, but moved beyond the geometries of folds to the way in which folds could be used to incorporate dynamism (Payne, 2008).

The act of un/folding is used in this thesis as a way in which to explore geometry not in a formulaic manner but in a hands-on physical process. *"Folding is a process that involves changes that extend the geometrical properties of an object while preserving its topology"* (Terzidis, 2003, p.45). In contrast, unfolding is a term used to denote the process of opening, spreading out or extending something that has been folded. They can be understood as a complementary unified pair, where one operation owes its existence to the absence of the other.

In 1993 Greg Lynn suggested new approaches to design which would produce a *"more fluid logic of connectivity"* through folding to produce curvatures (Lynn, 1993). Because of its accuracy and simplicity, folding and unfolding can contribute to the understanding of complex geometrical shapes (Terzidis, 2003, pp. 49-51). It is the position of this thesis that through geometry, patterns and the process of un/folding, we can develop a greater understanding of the relationships between forms, spaces and their inhabitants.

Digital Fabrication

Today it is difficult to imagine design without the use of computers. They are used at every step of the of design process from conceptual design to construction. For example, Frank Gehry began using Computer Assisted Design (CAD) in the late 1980s to develop and test the constructability of the systems used in the Disney Concert Hall. In the 1990s other projects also used digital techniques, such as William Massie's use of formwork to make concrete moulds, Bernard Cache's surface manipulations, and Greg Lynn's waffle typologies.

3D modelling, visualisation, structural analysis and file to factory production are just some of the digital practises employed by designers.

> *"Digital fabrication is often one of the final stages of this process, and it is very much what it sounds like: a way of making that uses digital data to control a fabrication process."* (Iwamoto, 2009, p.5).

Designers seeking to embrace these processes to design and build projects themselves, understanding that it is "a mode of inquiry whose method of making ultimately forms the design aesthetic." (Iwamoto, 2009, p.4). In this research it this design aesthetic that will reveal itself through the act of both physically folding and digitally unfolding.

Digital fabrication particularly suits the folded form. While folding has a long history in craft-based practices, it takes on a new dimension with digital fabrication (Iwamoto, 2009, p. 63). Iwamoto/Scott's In-Out Curtain is an example of the combination of traditional origami paper folding and digital cutting techniques to produce designs not possible through the use of only one of these techniques alone. Digitally driven design processes and new manufacturing processes open up new possibilities for designers (Kolarevic, 2000, p. 117].

Visualisation of Form and Space

Geometry and pattern were the driving force for the design of the folded forms, which were developed for digital fabrication. These were in turn visualised, analysed and interpreted within 3D stereoscopic immersive environments.

A range of different studies have sought to explore 3D spatial environments as a way in which to assist the design process. These include the design of *"infotainment"* systems in automobiles (Althoff et al, 2003), collaborative virtual prototyping (Zheng et al, 2006), and Virtual Reality software for use in small to medium enterprise manufacturing (Kuenzler & Iseli, 2004). In this research, facilitating the development of organic geometrical ideas required the use of 3D immersive environments that would allow for greater interactions and understandings between the designer and their design.

Visualising organic forms with 2D screens and renders is often difficult because the surfaces are inherently more complex and hence more difficult to interpret than traditional shapes. For example, looking at a cube from one vantage point, we only see three sides, but because we are familiar with modern rectangular shapes, it takes little deduction to realize the orientation of the three remaining sides. In comparison, an organic surface would require multiple vantage points to understand the true nature of the form. The intention in this research was to embrace forms that would make the most of the capabilities of 3D immersive environments, and therefore not limit the developed geometries to simplistic surfaces typically associated with folding.

In order to better understand the form and space of complex geometries, the notion of visualisation, coupled with a methodology of making physically, is important because folding is an experimental process (Vyzoviti, 2006). To some extent, our 3D stereoscopic environment presents the opportunity to investigate folds as a virtually tactile experience. Stereoscopic visual feedback in an immersive virtual reality environment assists the user in gaining a much better understanding of 3D shape geometry (Hua et al, 2005, p. 2).

Along with the relatively recent mainstream acceptance of 3D technologies in our Cinema, the scientific community has also dived into a world that would allow for more engaging experiences. Emerging facilities such as the Allosphere at the California NanoSystems Institute, University of California, have developed a fully immersive 3D display environment with open source software. The educational institute provides scientists, engineers and of course designers the opportunity to explore their work within a totally unique space.

> *"Visualizing, hearing and exploring complex multi-dimensional data provides insight that is essential for progress in a number of critical areas of science and engineering, where the amount and complexity of the data overwhelm traditional computing environments. The need for richer and more compelling visualizations continues to receive attention as a US national science priority."* (Kuchera-Morin, 2011).

As a scientific instrument, the fully immersive AlloSphere is a tool for gaining insight and developing bodily intuition about spaces in which the body cannot enter.

Biomimicry and Organics

As indicated earlier, many of the forms existing in nature leave behind traces of their geometry, their symmetry and patterns of their life cycle. The notion of Biomimicry is one of the central reasons for why the forms, surfaces and structures developed in this research look the way they do.

> *Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these design and processes to solve human problems, e.g., a solar cell inspired by a leaf. … It introduces an era based not on what we can extract from the natural world, but on what we can learn from it."* (Benyus, 2002, p.iii).

Biomimicry is being used to adopt more organic, natural, and sustainable systems for research and development. When those adopting the concepts of biomimicry look at forms and materials, they are hoping not just to copy nature but to understand the principles behind nature's success, and apply those successes elsewhere. A good example of embracing natural systems can be seen with the self assembling attributes of a crystal. The final shape of a crystal is not due to some predetermined overall design. It happens because the molecules naturally come together in a lattice, and as the crystal grows, it results in faceted shapes. More complex molecules will assemble into more complex shapes. Similarly the biologist Thompson in his 1961 book On Growth and Form, used geometry to describe and analyse the cellular form and organic growth (Terzidis, 2003).

In the example given in the geometry and pattern section above, the Fibonacci sequence was highlighted as a good indication of how biological principles are seen in the world around us. It is the role of biomimicry to interpret these principles in a light that provides functionality as well as form. Throughout this research emphasis is placed on the formal attributes of nature and less so on its functionality. Modularity and adaptability are explored in order to achieve a design aesthetic that looks organic. Whereas biomimicry concentrates on the functionality of the object or structure, the focus of organics is on its spatial and aesthetic attributes.

The aim of incorporating the concepts of biomimicry is to frame the method of making as a process that is adaptable enough in scope to allow for the prototyping of designs that are outside the normal considerations of architects and designers. For example, there may be a need for internal spaces within walls that are not inhabited but are vital to the sustainability and functional necessities of the structure (such as solar energy production).

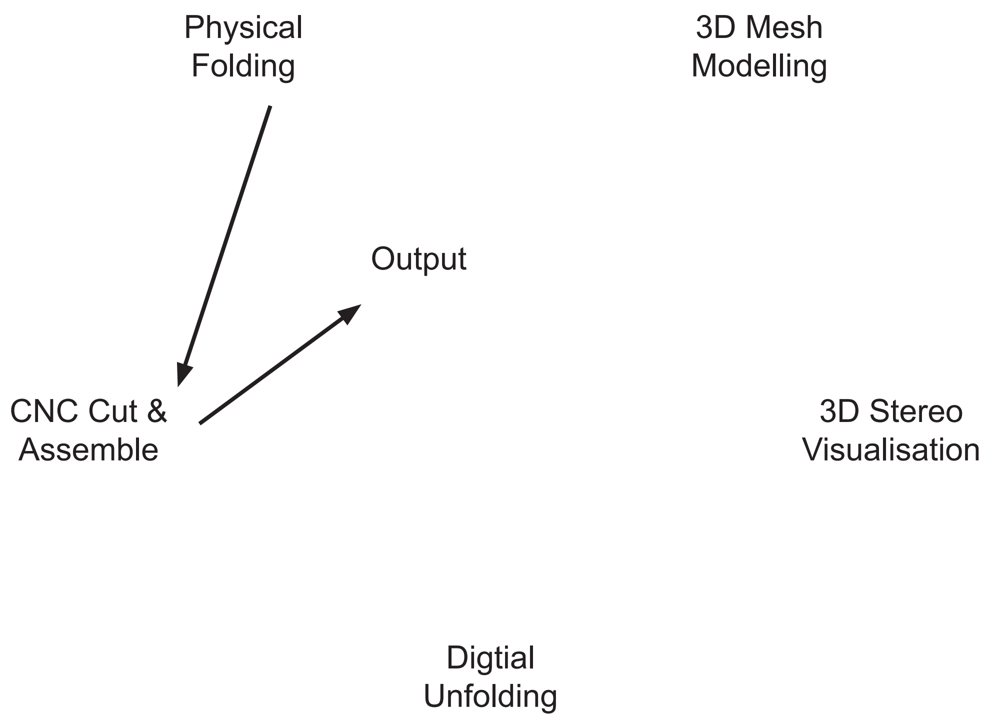
The construction of the Eden Project (a greenhouse in Cornwall, UK, emulating a natural biome) drew from the structural forms and solutions found in nature and employed fabrication techniques modelled on the silk of a spider (Pawlyn, 2011). In the future, the requirements of scientists and engineers incorporating nature's principles may be more inclined to embrace the prototyping of physical structures with methodologies that are versatile enough to accommodate a variety of complex geometrical forms. Simultaneously the need for advanced visualisation techniques are needed to design, develop and analyse the functionality of these structures and spaces.

Physical Folding

This first stage of the project presents a series of paper folding experiments that explore paper as a medium to investigate the design of surfaces, forms and structures. Through these experiments, a number of folding strategies were investigated to identify folding concepts that would aid in the translation into 3D modelling software. The purpose was to identify folding strategies that would lay the foundation for further development within the next stage of this project, Digital Manipulations.

Some of these experiments were investigated as concepts that could be directly applied for a design output. The notion of an output is addressed at this early stage because paper folding provides a versatile opportunity for conceptual development. In this case a wide range of folding concepts could be explored that define forms and surfaces that would be suitable for the final design phase. The constraints addressed while working with the physical medium would help to define the scope in which designs are applicable for an output, while simultaneously suggesting a strategy for translation into 3D modelling software.

As indicated in the diagram on the right, CNC Cut & Assemble acts as the means through which to achieve an output from the physical processes of folding. This medium is important throughout this research because surfaces, forms and structures must be able to be fabricated and constructed physically. While the use of CNC fabrication is not evident in each of the subsequent experiments, the aspect of assemblage was an important frame of reference.



Introduction

The physical, virtual and theoretical act of folding is the context for an existing field of extensively researched and developed ideas, many of which are encompassed in art, design, architecture, engineering, science and mathematics. With the physical use of folding, many designers are consistently pushing the boundaries of what the medium can both represent artistically and offer functionally. Whether it is a wonderfully crafted origami crane or sophisticated collection of transformable tessellations, the folding of sheets of material is a medium that has universal appeal and its applications have withstood the test of time (Lang, 2009). In this physical folding stage, the purpose of the research was to establish an understanding of the design processes that could assist with the development of strategies for virtual modelling.

Un/folding can be used as both a physical and virtual process to cross between one dimension and another, which is one of its most important qualities. A flat 2D sheet of material can be folded into a 3D form. When the 3D form is unfolded, it reveals an inscribed geometry that traces its creation, helping us to recreate the way in which it would be made. The pattern itself informs the transformation from folded to unfolded and the sequence in which it occurs. This was the reason un/folding was chosen as the means through which to aid in the translation between virtual and physical making.

In contrast to origami, in which artists define the art as a process of working with a single sheet of paper and without cutting or gluing, in this research, the opportunity to diverge from the rules that define origami is embraced by introducing methods that explicitly explore the cut-line and fastening techniques. More specifically, these techniques involve cutting and removing material from paper and using tape and glue to reconnect the open edges. It follows, that these next folding experiments investigate the opportunity to create larger surfaces by cutting and connecting surface geometries together. A recurring theme throughout the following experiments was the investigation of folding patterns that were inherently modular in their configuration and explored the notion of the component as one of many. This was in conjunction with identifying a folding methodology that was complex enough in its geometry to suit a wide range of applications, yet compelling enough in its simplicity to be adaptable for a range of functional opportunities.

The objective was to develop a surface geometry that could be modelled in 3D software. Once a suitable physical geometry was found, its limits were analysed as the means in which to enter into the virtual and return to physicality. This revealed several opportunities that were appropriate for further development.

Some initial strategies for investigation are indicated on the right. Rather than describing the formal characteristics of the end result, the focus is on the process and understanding the origin and the evolution of the object. Each of the strategies for investigation aid in the development of concepts that can be outputted throughout the design process, with the objective of creating a unified design strategy for mediating between virtual and physical forms.

Strategies for Investigation

• Investigate the transformations of folding 2D sheet materials into 3D forms.

• Investigate the economy of folding as a means of minimising assembly times.

• Investigate the scale of a component as a constraint for physical inhabitation.

• Investigate geometries as a means of developing an organic beauty that draws upon the principles of nature.

• Investigate symmetries and asymmetries of folding geometries as a means of achieving flexibility or rigidity of a surface.

• Investigate collapsibility as a theme for introducing adaptability to a folding surface.

• Investigate folding as a method of creating strength and structural integrity.

• Investigate a variety of pattern configurations and arrays of undulated surfaces.

• Investigate the constraints of surface thickness and material hinges.

• Investigate the translation of the physical properties of folding into computer software.

• Investigate the opportunities of using CNC machines for the digital fabrication of folding materials for assembly.

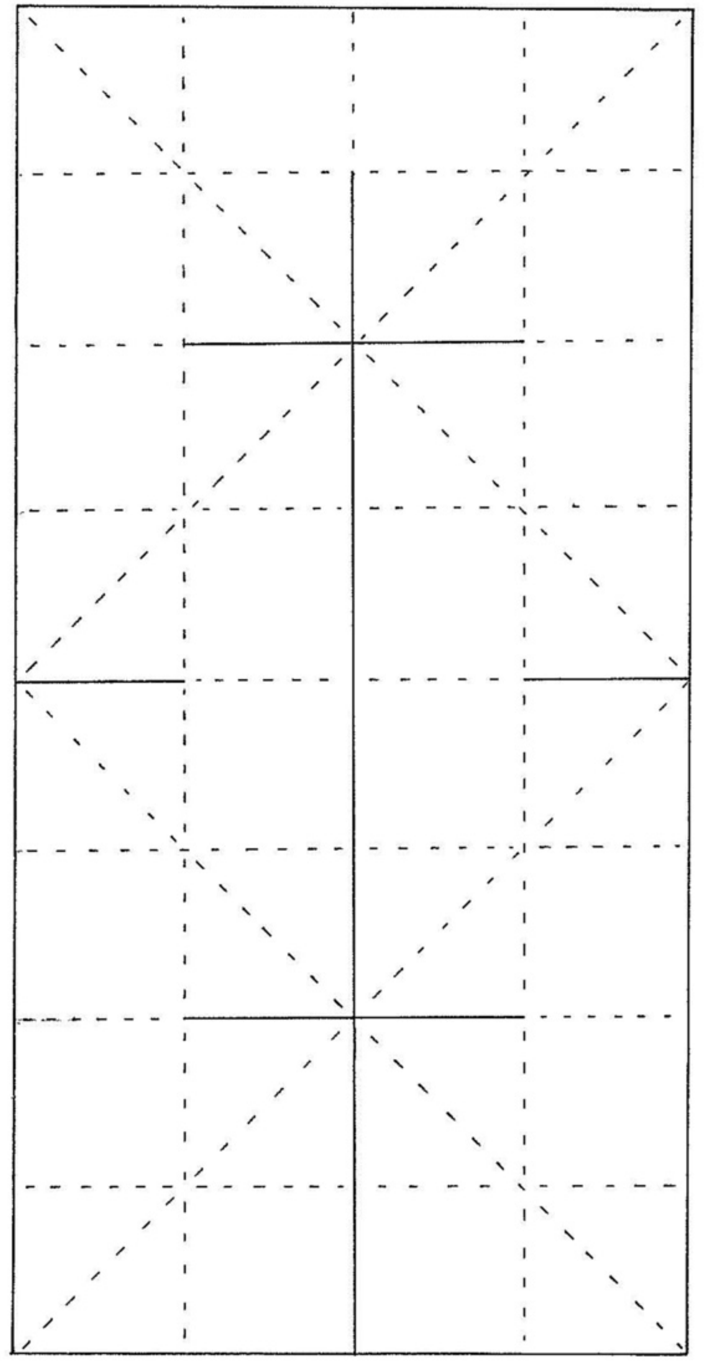
Flat Packing

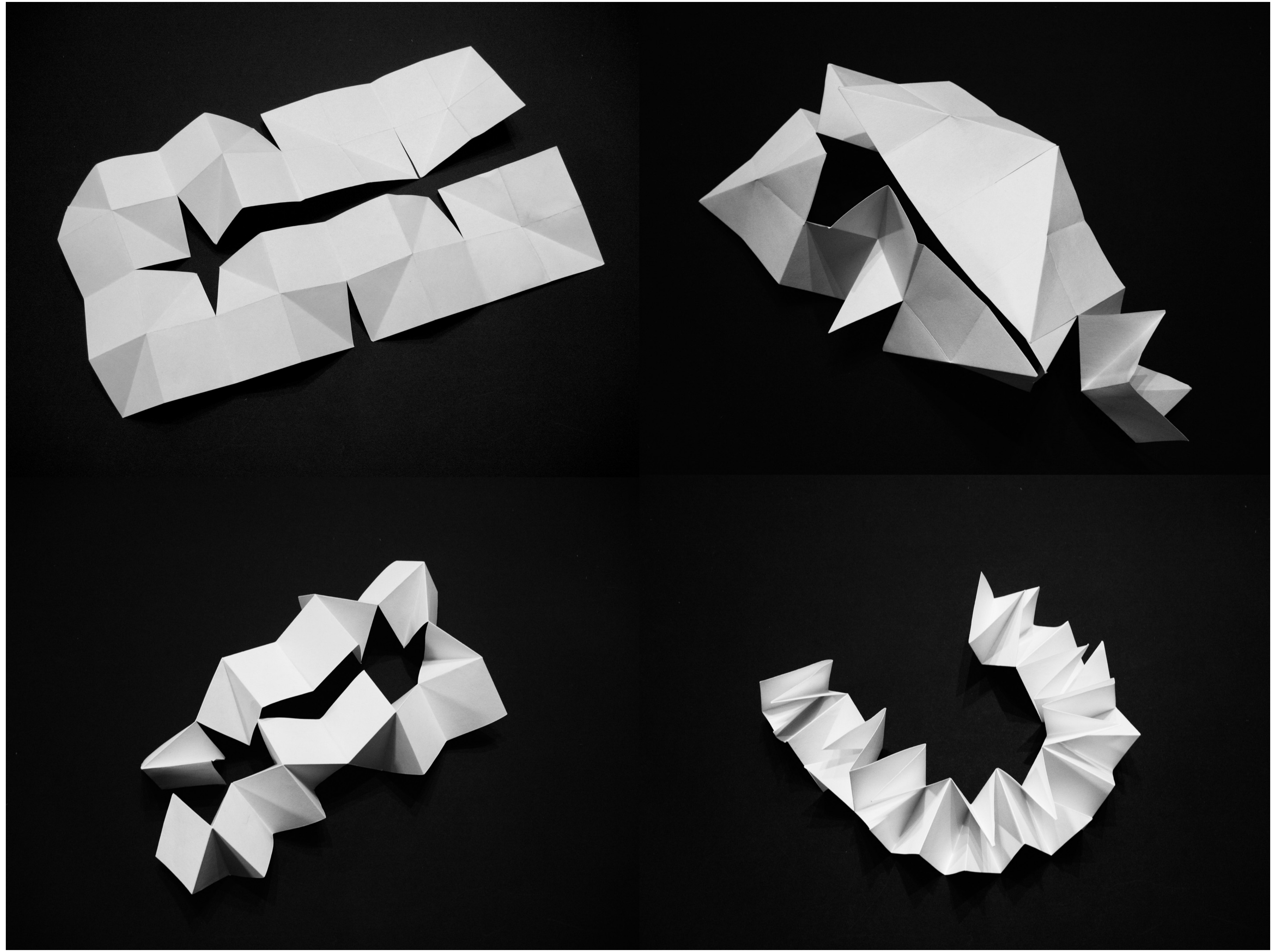
Folding Experiment 1.

This experiment explored the concept of expandability and collapsibility with a surface geometry that could fold into a flat sheet. When investigating these concepts, factors such as transportation, storage, and the flat-packing of pre-assembled components are considered as a distinctive feature of folding designs. A collapsible form would extend the life of a prototype, and allows for greater ease of transportation and storage.

In this experiment the dimensions of 1.2m x 2.4m sheet is represented. This dimension will be the standard sheet material size used with the CNC machine at final stages of this project. The concept of transformation was explored here through a concertina design. The sheet was first divided into equal segments and then the material is cut in a manner in which each surface never folds over itself more than once. This means that regardless of surface thickness the sheet material would always be able to fold flat without deforming.

Giving an object the ability to expand and contract is limiting in its possibilities for unique forms and spaces, and also reduces the ease of transition into the digital medium. However, the notion of transformable surfaces has many appealing features that if thought through rigorously, are attractive for development because they allow people to adapt designs to their own needs.



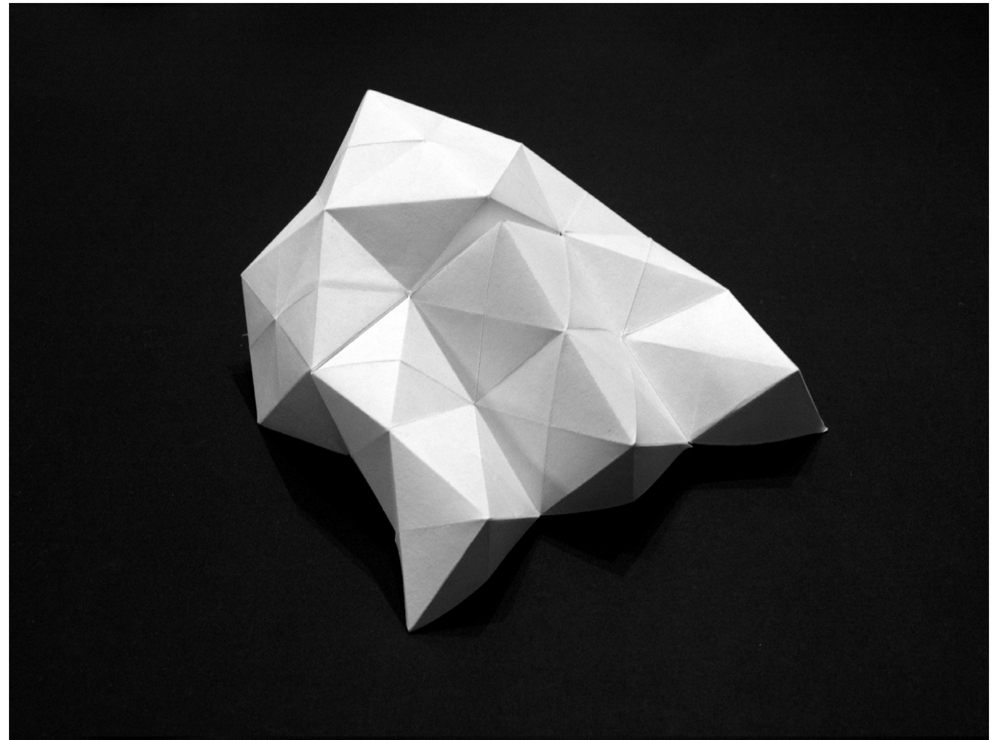


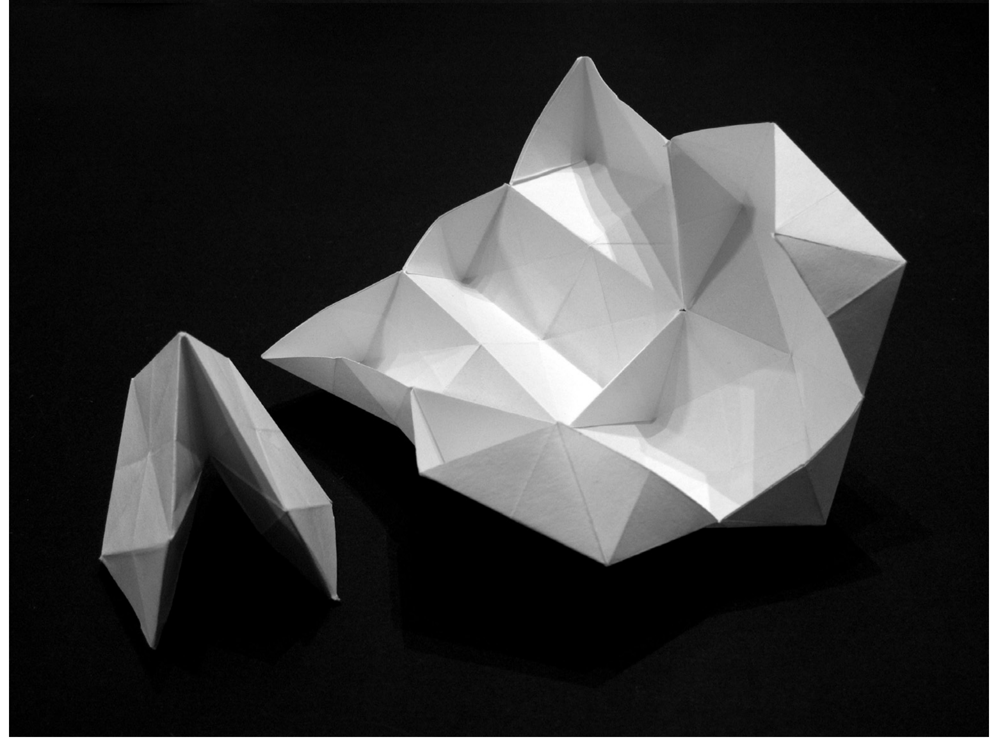
The Deployable Shelter

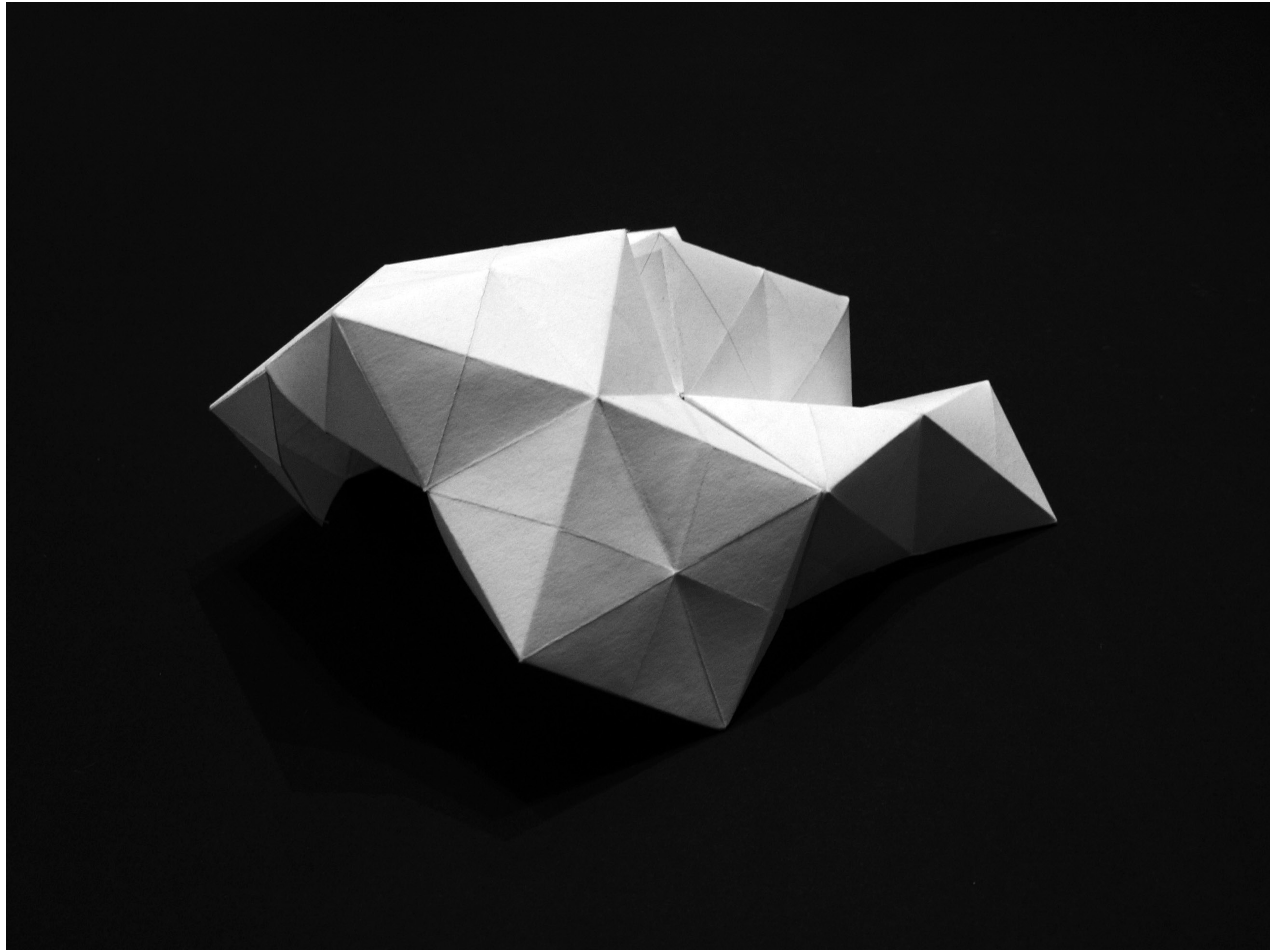
Folding Experiment 2.

This experiment demonstrates the opportunities of using folding as a process to develop expandable and collapsible structures. It was a practical attempt at applying the previous experiment's folding geometries into a form that created a context for ongoing experiments. In this case, “The Deployable Shelter” introduces the notion of scale as an important aspect for this research. The surfaces, structures and spaces developed within each stage of the research are intended to envelop their inhabitants and create spaces for them to occupy. In this design, the scale of a person is approximately the 2/3rds the height of the structure and has similarity to a large tent. It is composed of 6 identical folding components that independently fold flat and are then ‘popped open’ and assembled into a structure.

Within the architectural and design fields, a deployable structure is typically associated with design solutions that drastically reduce on-site assembly times. This is in comparison to the traditional approach of on-site construction. A deployable structure also exhibits strong potential for volume savings and reduction of mass during transport. Such structures are usually light weight, inexpensive and designed for efficiency. For these reasons folding materials are an ideal medium in which to investigate expandable surfaces and structures.





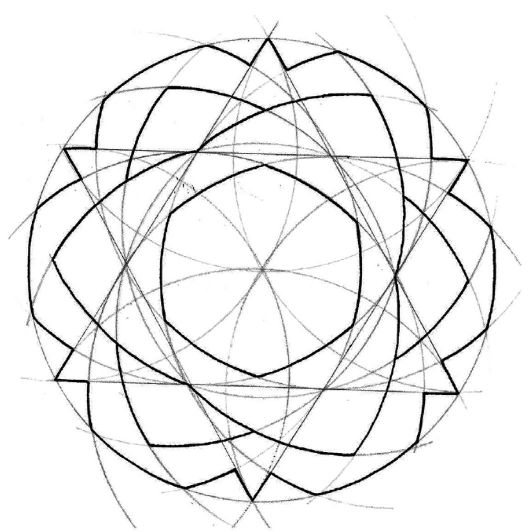
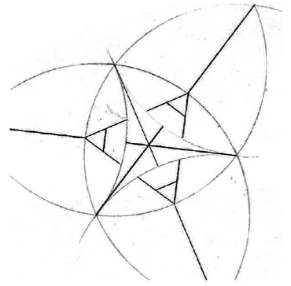
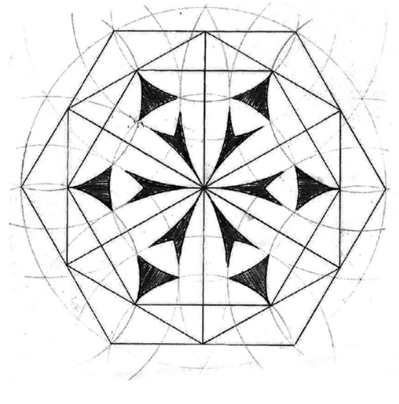
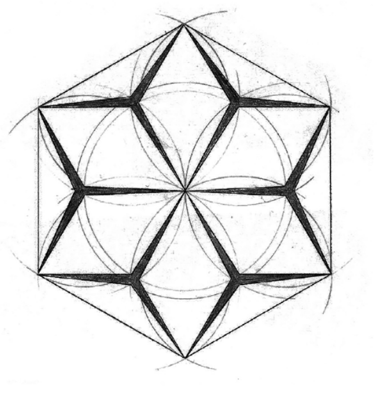
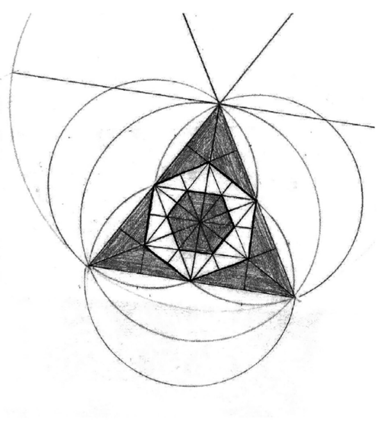
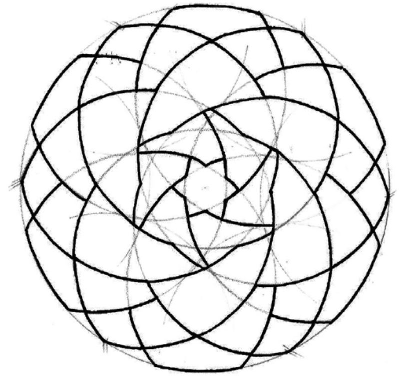
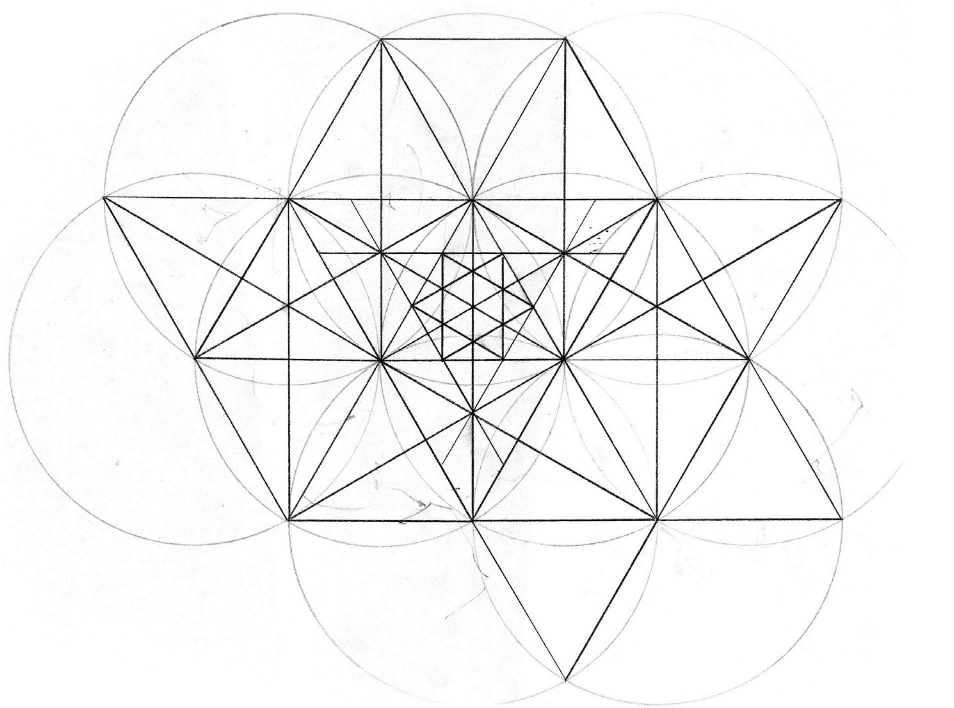
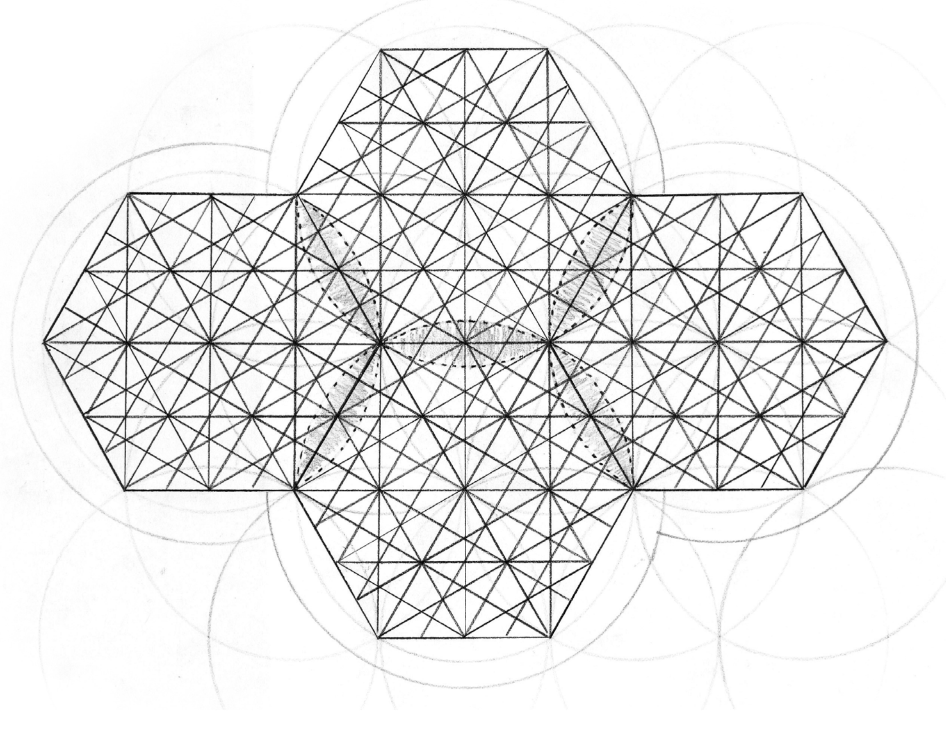
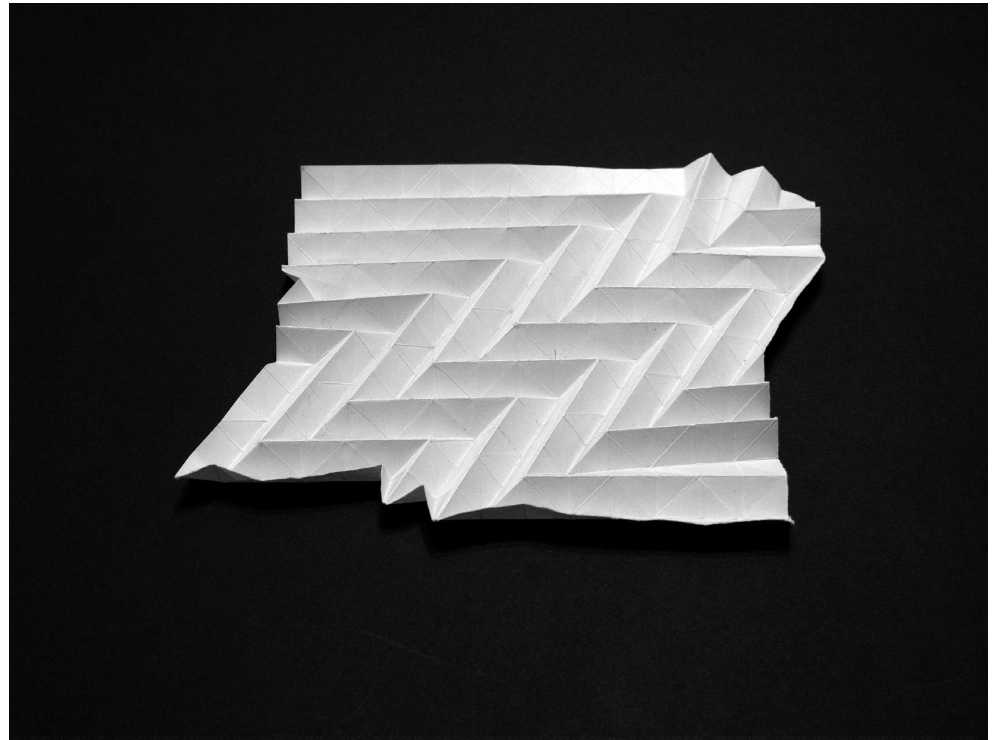
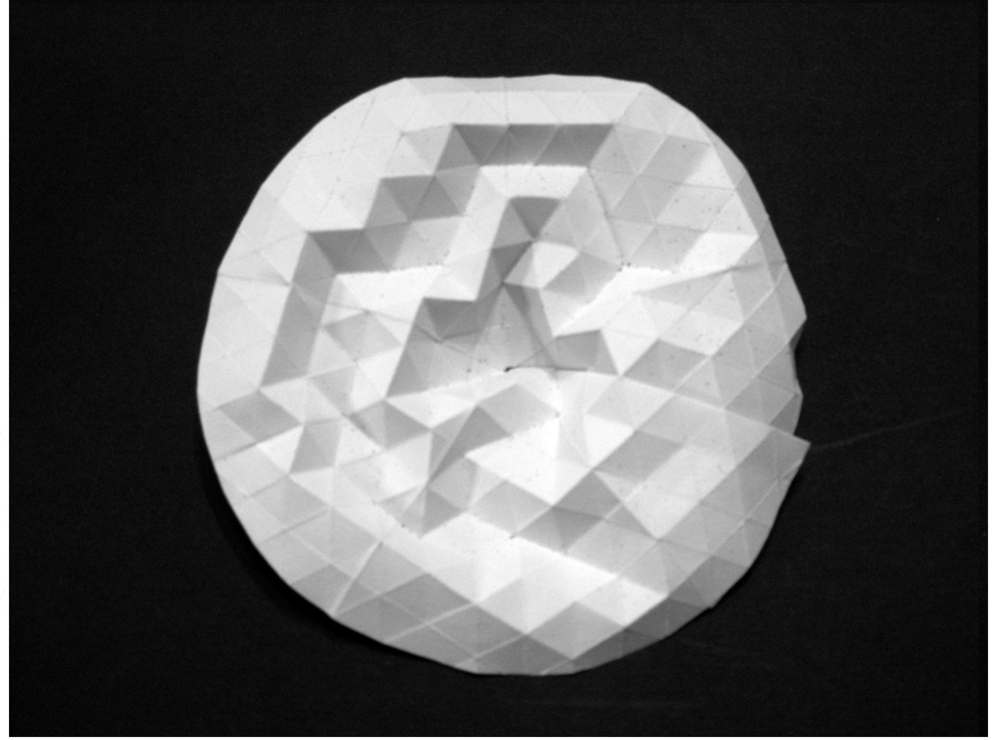


Three-Fold Geometry

Folding Experiment 3.

In this experiment a series of compass drawings were drawn to better understand the potential for the circle as a shape to define the making of geometries for ongoing exploration. First, a circle was drawn and the circle's radius marked consecutively along its arc. This divided the circle six times, and is commonly called three-fold geometry, as you would fold three times to divide into six segments, or six-fold geometry, as it has six axis of symmetry. These compass drawings explore the way in which intersecting lines can be used to determine points along a line. The points then become new centres in which to make more circles, and then these can be used to create straight lines for folding.

While these patterns are two dimensional, they inherently express a three dimensionality. The patterns represent a drawn blueprint in which three dimensions can be encoded within the flat plane. In the experiments on the far right crease patterns have been folded to create an evenly faceted surface and an uneven form. The latter is achieved by folding parts of the surface over itself so that a greater degree of deviation is available between each of the mountain and valley folds. This folding under and over of material is an excellent method in which to create form from flat 2D sheet material, and was explored further in subsequent experiments.

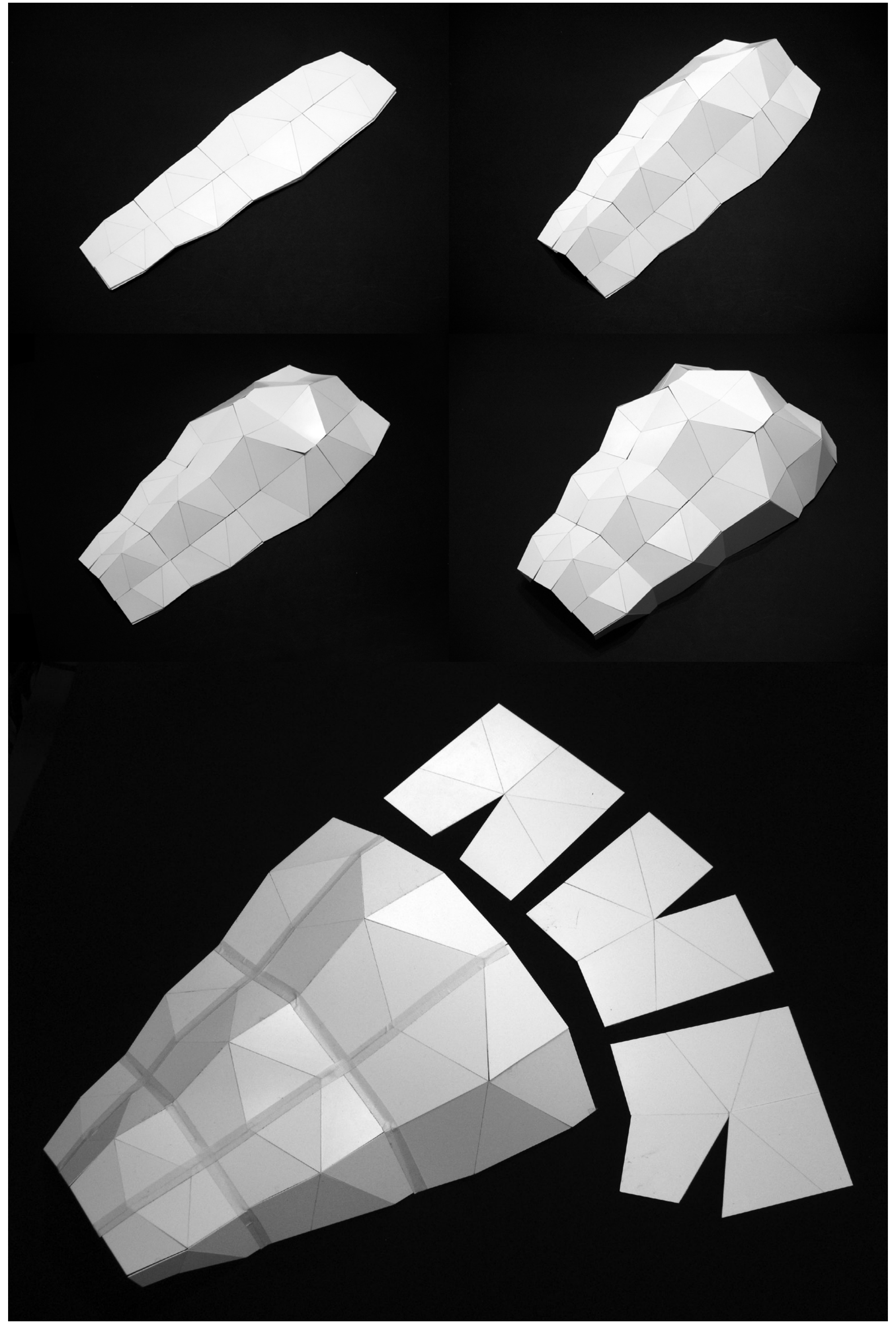











Symmetry

Folding Experiment 4.

This experiment explored the symmetries of 3D components and the opportunity to collapse an array of these components into a flat object. In this experiment a set of three-fold geometries developed in the previous experiment were applied within the frame of a square. The square was divided into six equal segments, and a two degree angle between each is segment is removed. Each segment then had 58 degrees from the square's centre. This results in 12 degree of lost surface information or a 3.333% reduction in surface area. The larger the percentage of surface area removed, the greater the pitch of the cone.

The four images on the top right show a model going from a flat-packed surface to an expanded structure. The image on the bottom right is the expanded structure accompanied by a set of flattened designs before each of the edges has been connected. This was an exploration of symmetry in the sense that each of the components is identical and then composed together to create a 3D form. The advantage of them being symmetrical is that they will retain flexibility and collapsibility when composed together in an array. This is a result of each segment being the same size, meaning they would mirror themselves and fold flat into one facet. Different sized components are possible by altering the edge length along only one side. This means that the design can retain its symmetry and its flexibility, while allowing for more options in the design of customizable forms.

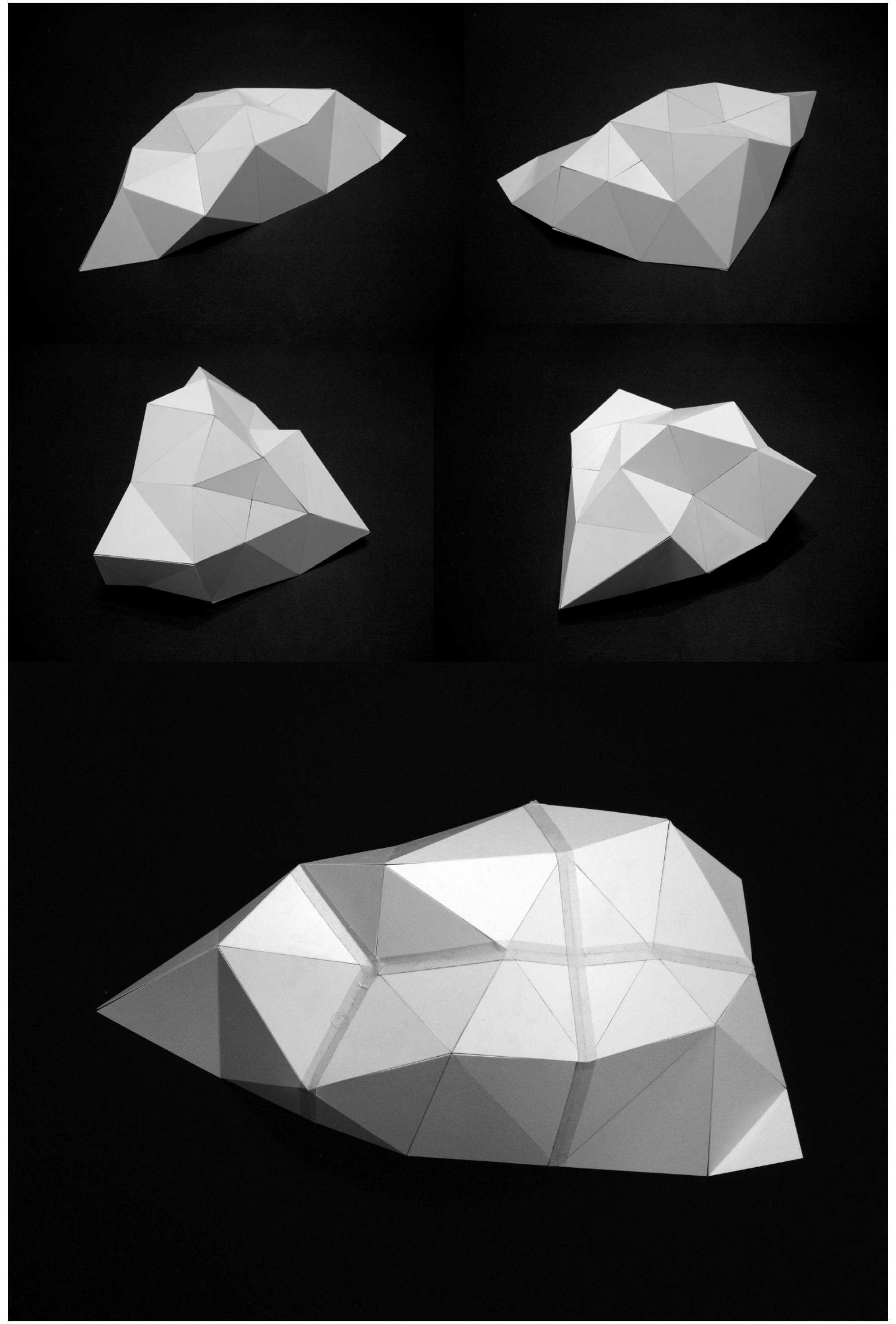


Asymmetry

Folding Experiment 5.

This experiment used similar components to the previous experiment, the difference being that the central point of each square was moved to create an asymmetrical component. As a result, each of the segments becomes a different shape, yet the components retain identical edge lengths and consequently still connect together in a wider array. The less symmetrical each component becomes, the less flexibility the components have as a whole, therefore adding strength to the structure . Because each component doesn't mirror the others, the structure cannot collapse in on itself. In this way, there is a trade-off between flexibility and stability that is relevant when considering concepts such as a locking structural assembly.

When compared with the previous experiment one can clearly see the symmetry and the structure of the object created when the components are connected. This means that one doesn't have to overly analyse the form in order to understand it as a readable surface. In contrast, the asymmetrical structure appears more difficult to interpret. In the images on the right, the same object was photographed several times, with the surface manipulated into slightly different positions. Even with multiple views there is no clear understanding of the variety of configurations in each of the components. For this reason this experiment directly relates to the requirement of involving 3D stereoscopic environments to better understand asymmetries in relation to folding designs and their structures.



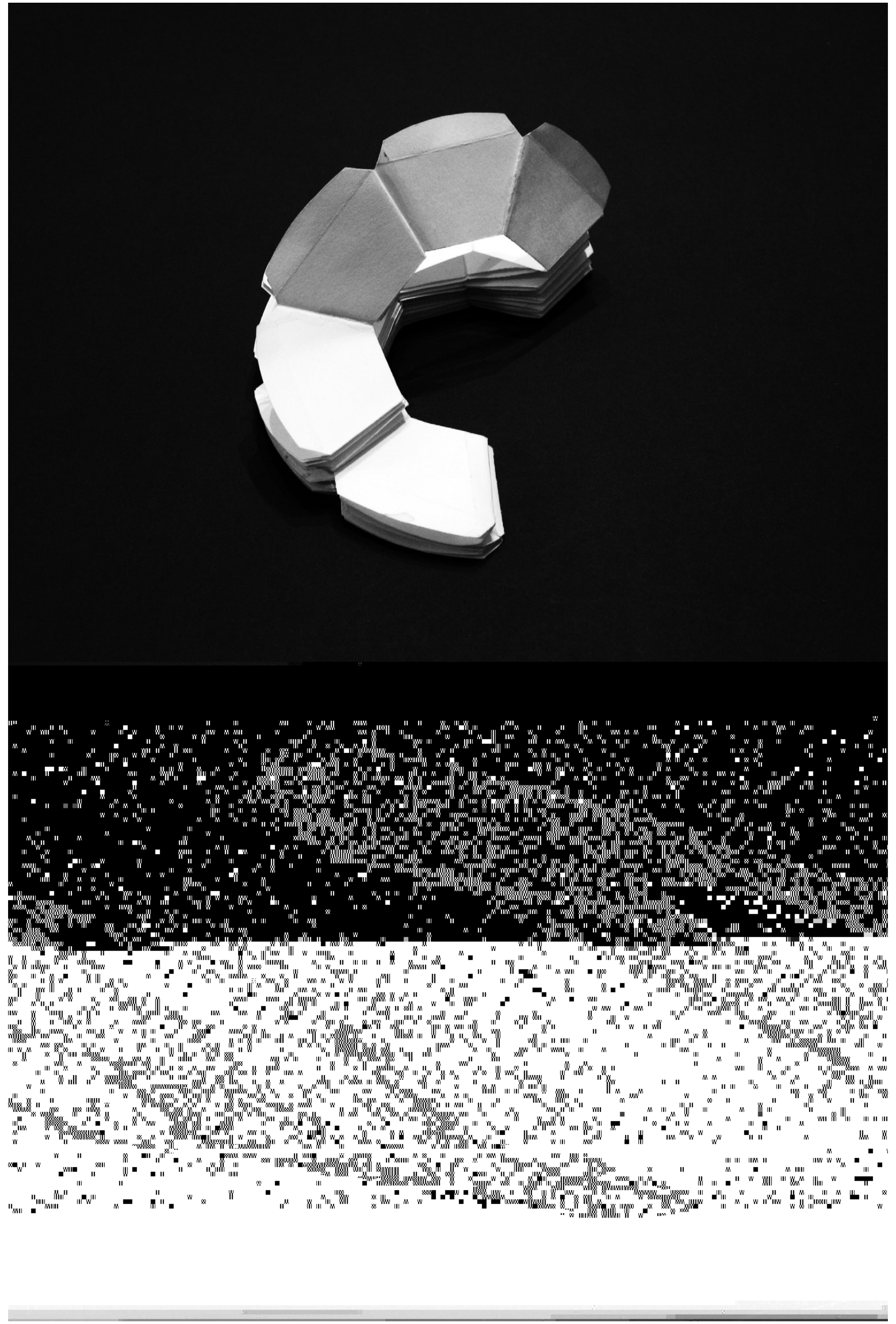
Deployable Surface

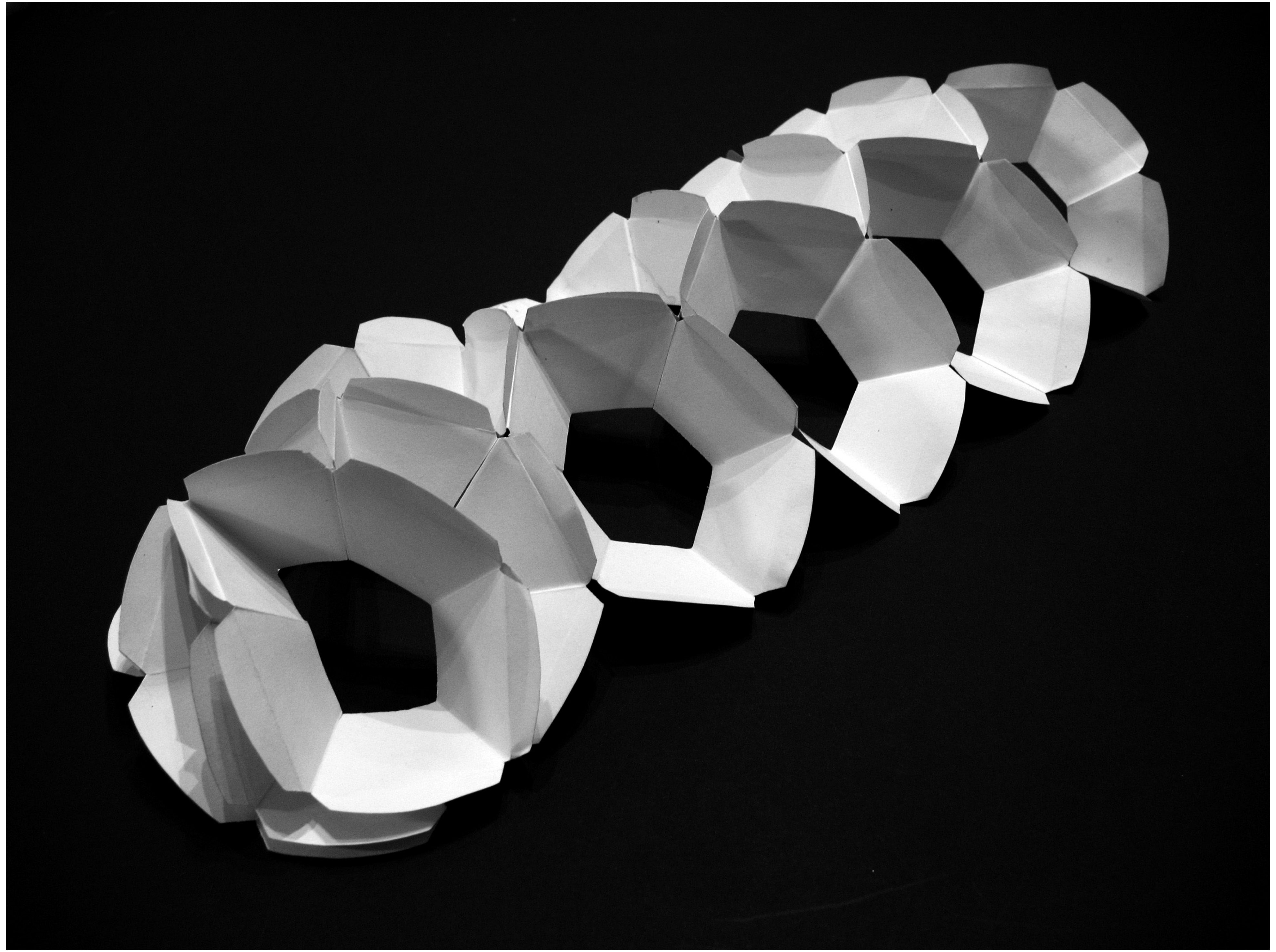
Folding Experiment 6.

This experiment focused on a geometry that could unfold from a flat 2D surface into a 3D form. It explored the notion of expandability and collapsibility with the opportunity to use this form as a structure for use throughout the ongoing experiments.

The idea originated from the subdivision of the circle to create a cone and experiments with how a flexible geometry could create a flat packing shape. A series of flat folding hexagons were connected together with each pattern made from 3/4ths of a circle or 6 of 8 segments. Because each face is identical it is able to collapse into itself and therefore the form can be flattened. An interesting finding is that folding on the short edge of the surface creates greater thickness for folding over itself than when it is folded flat on its long edge. This illustrates the need to build and experiment with shapes during the conceptual stages of design development.

As a deployable surface, this experiment could extend into a variety of applications if applied at an architectural scale. From the perspective of this research however, it is perhaps less relevant for ongoing development because the shapes' features are only useful when the applications are determined. This results in a form that does not provide the versatility to be used as a design component for ongoing development in digital stage of this research.





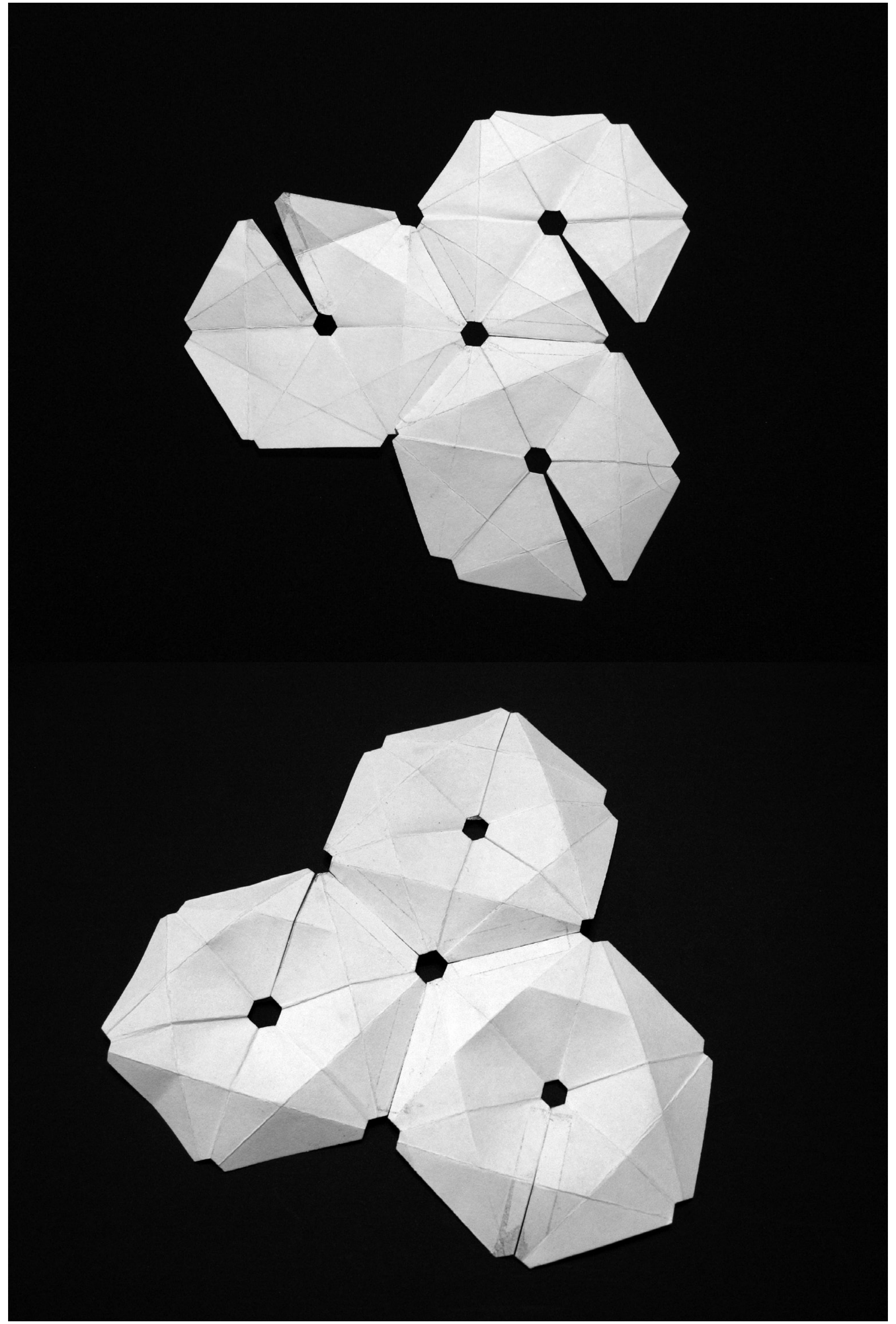
The Fold's 'Pop'

Folding Experiment 7.

In this experiment, thin slices of material were removed from the material's surface to create 3 shallow conical components. The notion of the 'pop' action is explored as an opportunity to provide structure to a component and simultaneously provide the means in which to fold the shape flat. The pop is defined as the movement when the fold goes from a valley through itself into a mountain fold. This is illustrated through the use of an interior fold within the middle of each of the hexagon's segments. This mid-fold provides structural stability for each of the individual components, while still providing flexibility on account of its symmetry throughout each segment.

The smaller the degree of material removed from each segment, the easier it is to pop in and out without tearing any of the fold hinges. Holes are added in the centre of the cone to make it easier for the surface to pop in and out. The larger the holes, the easier it is to pop between a concave and convex form.

The greatest weaknesses within the component array are the connection edges between each component. This is a result of there being no structural folds locking the shapes into a fixed position. The notion of locking these components together with folds and additional surfaces was explored in the following experiment.



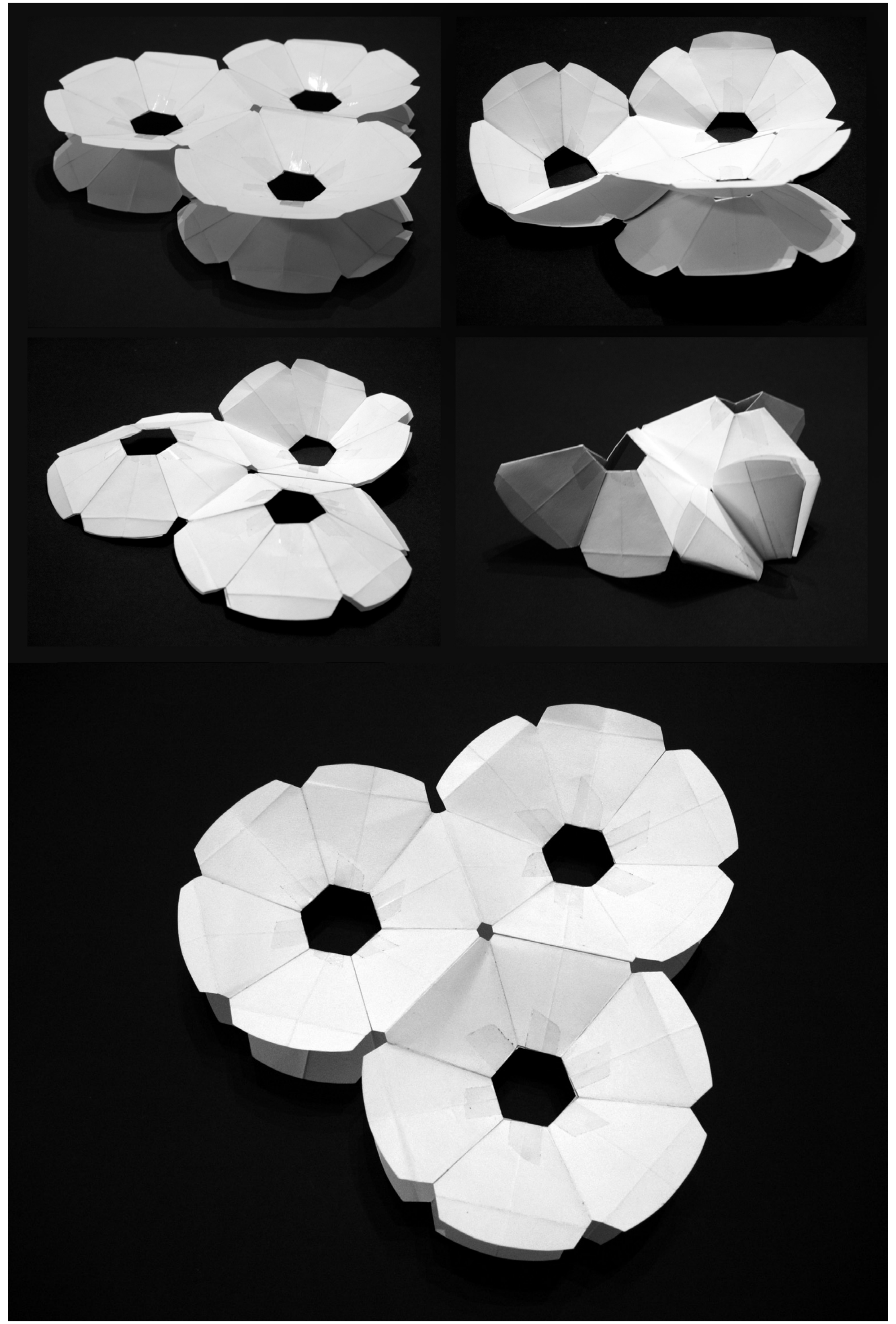
The Double 'Pop'

Folding Experiment 8.

This experiment explored surface collapsibility with a folding geometry that retains its structural integrity when connected around its central edges. In this example six components were attached together to form a dual surface. The under surface is a mirror of its top surface and as such can be folded in on itself.

The model has the same amount of angle separation as the preceding experiment, except with larger holes for greater flexibility of movement. The top image demonstrates the process of folding the form from its deployed state into its collapsed state by popping the concave form of itself into its convex mirror. This can be done with one component at a time or all of them together. In its deployed state, each component is structurally tied together into a fixed position. Comparatively, it is much stronger and more rigid than the previous experiment, and yet still retains elements of flexibility and collapsibility. In its flat state the modules pack together in a similar fashion as the deployable surface in folding experiment 6.

This was an appealing experiment for further development as the notion of a dual surface is a excellent strategy to triangulate a surface and therefore add strength and stability. However, the form of the model is similar to the deployable surface in that it is a defined output and its features are not as easily translated into a digital medium.



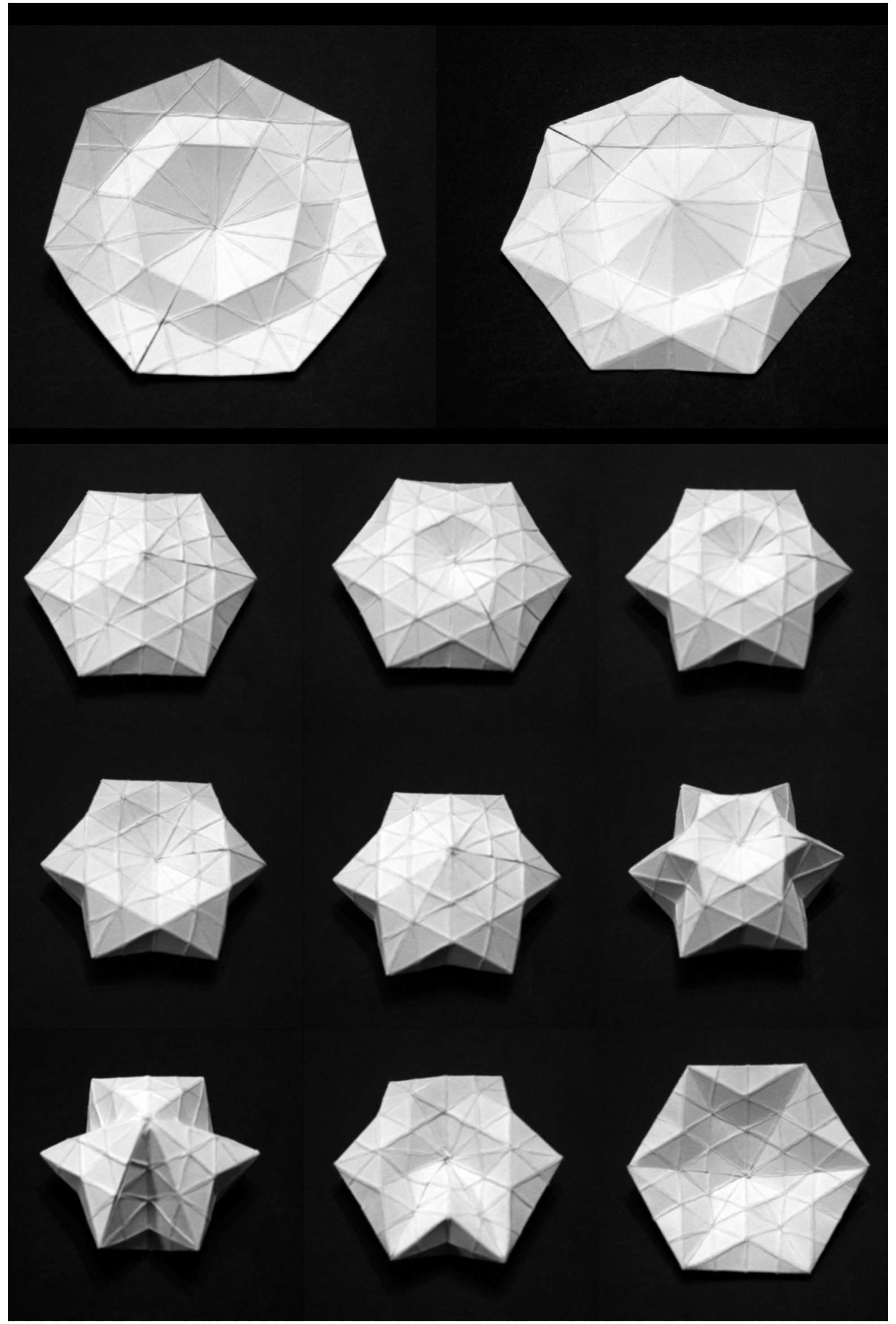
Surface Subdivision

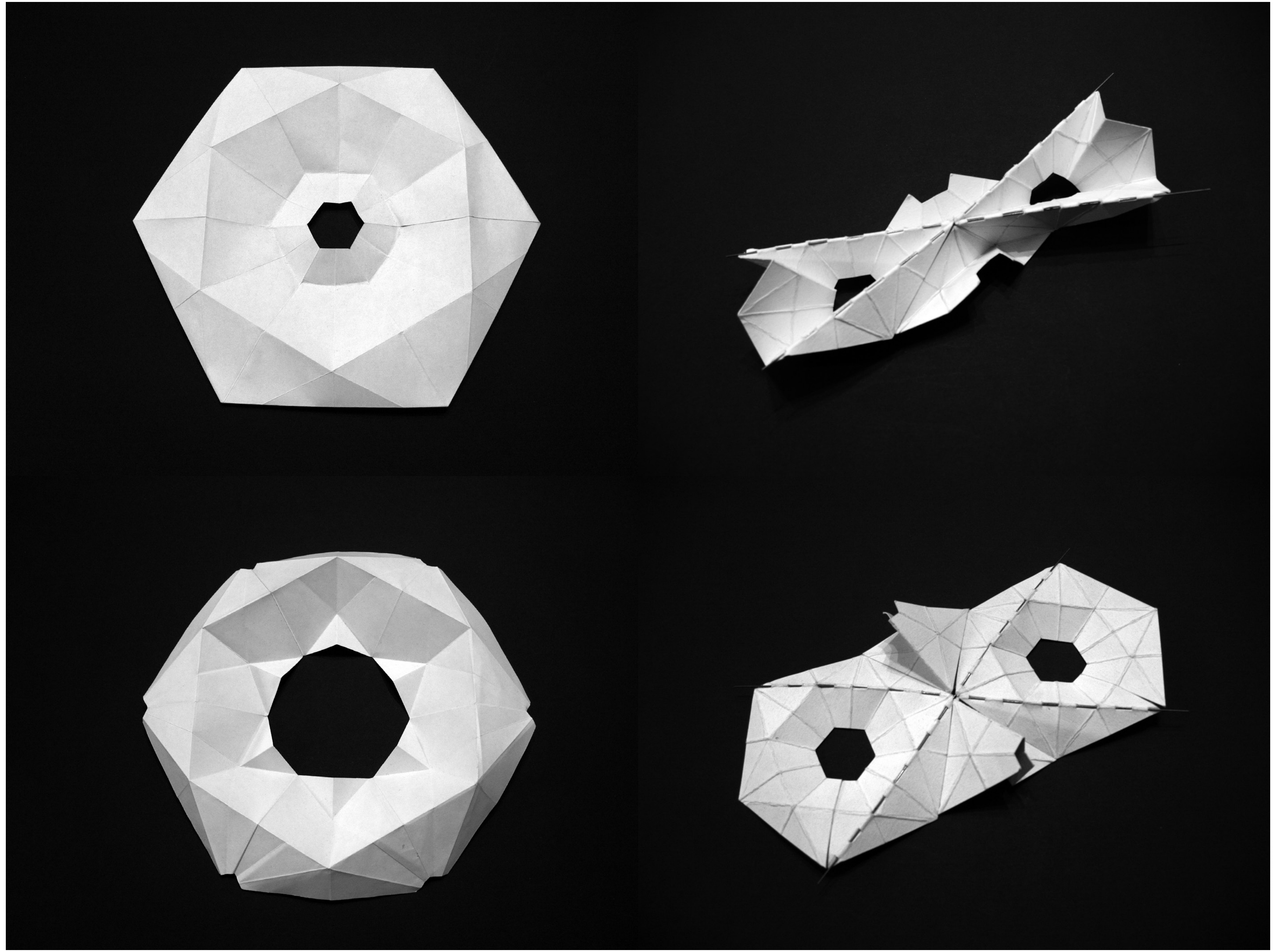
Folding Experiment 9.

These folding experiments demonstrate the variety of 3D tessellations that can be developed by subdividing the surface through folding. This was achieved with a development of the mid-fold discussed in the previous experiments. A greater number of surface subdivisions results in a wider variety of fold configurations. It also provides the opportunity to define a greater diversity of folds applied to both the manipulation of the 3D form and its structural integrity.

The pattern in the models illustrated in the above right was divided two times. In comparison, the series of nine component variations on the bottom right was constructed with a pattern that had been subdivided three times. The edges of the model have been folded inwards to create a 3D form, and in this case, were manipulated into a form with at least nine different configurations. The only opportunity to connect the shape with identical modules was on the points of the hexagon. While this does not allow for a homogeneous surface, it does allow for a wider variety of asymmetrical variations within each component. This would provide the freedom to explore curvature within an entire array of modules.

The experiments illustrated on the far right utilised a wire frame threaded through two components to fix the form within a single mode of transformation. In its expanded state the fold is used to lock the wires into a fixed position. When the folds are popped inwards, the form will fold flat. This experiment illustrates the opportunity to use these folds as structural elements, while still retaining surface collapsibility.





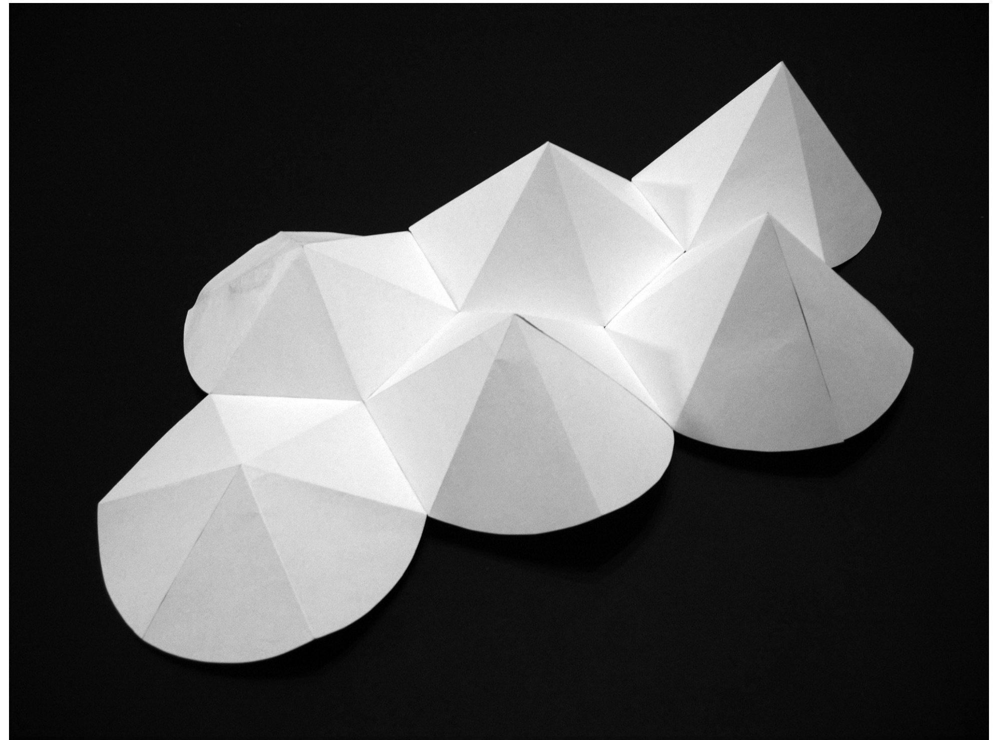
Conical Subdivision

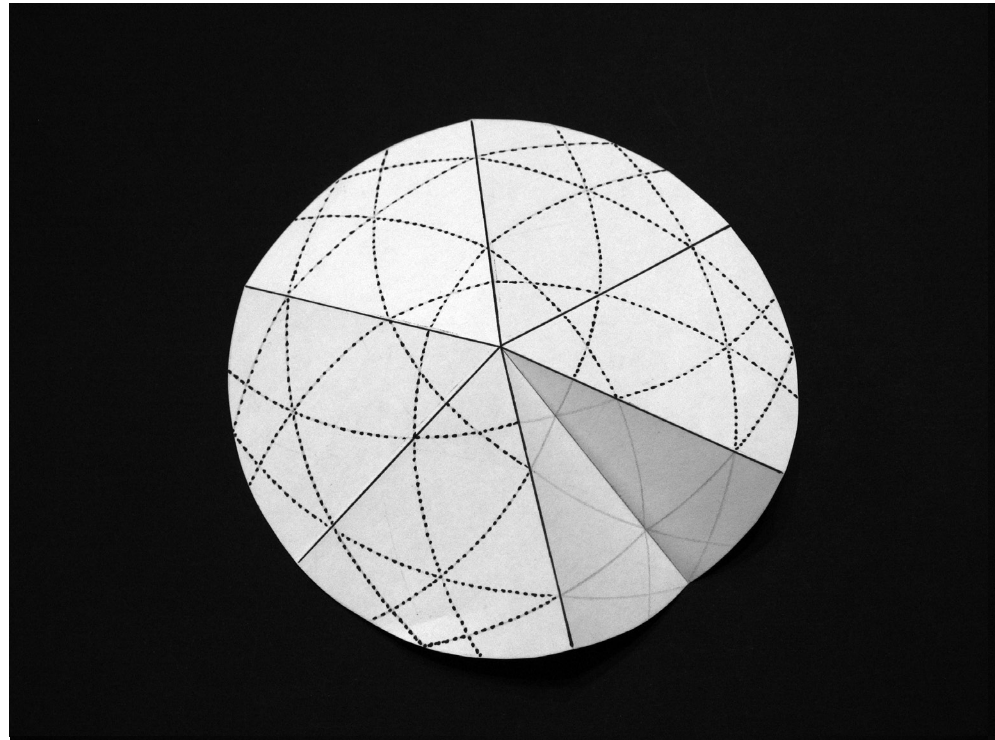
Folding Experiment 10.

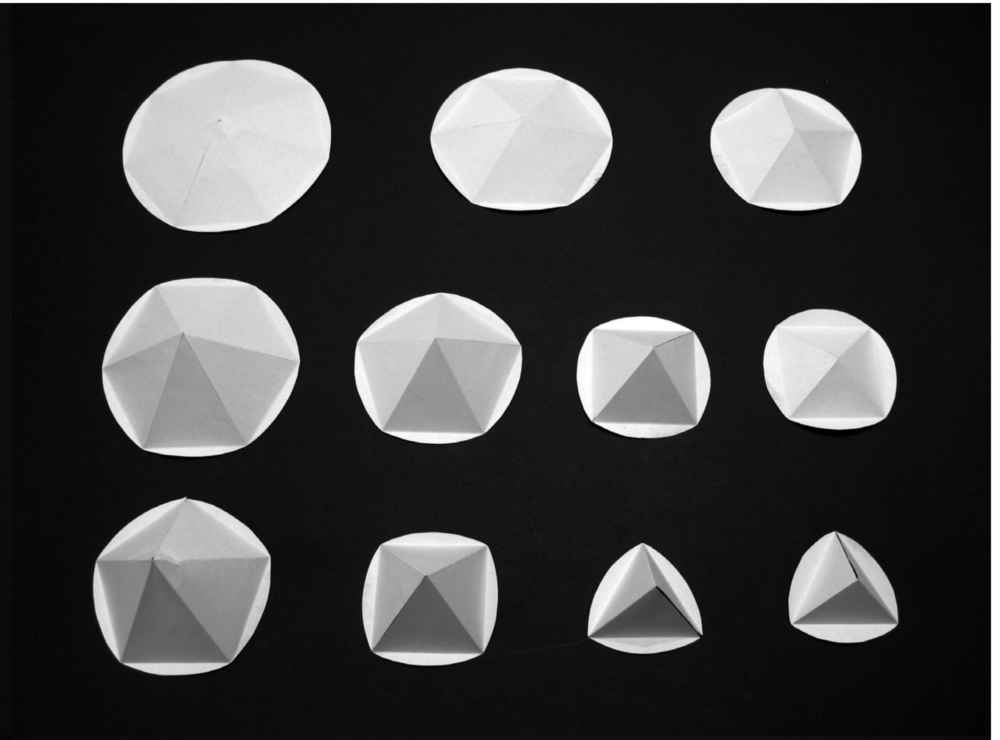
This experiment was an investigation of removing material from a circle, and how this might lead to component variations that still allow for connection to form larger arrays. In each of these experiments the pitch of the cone was explored while the outer edge lengths remained constant.

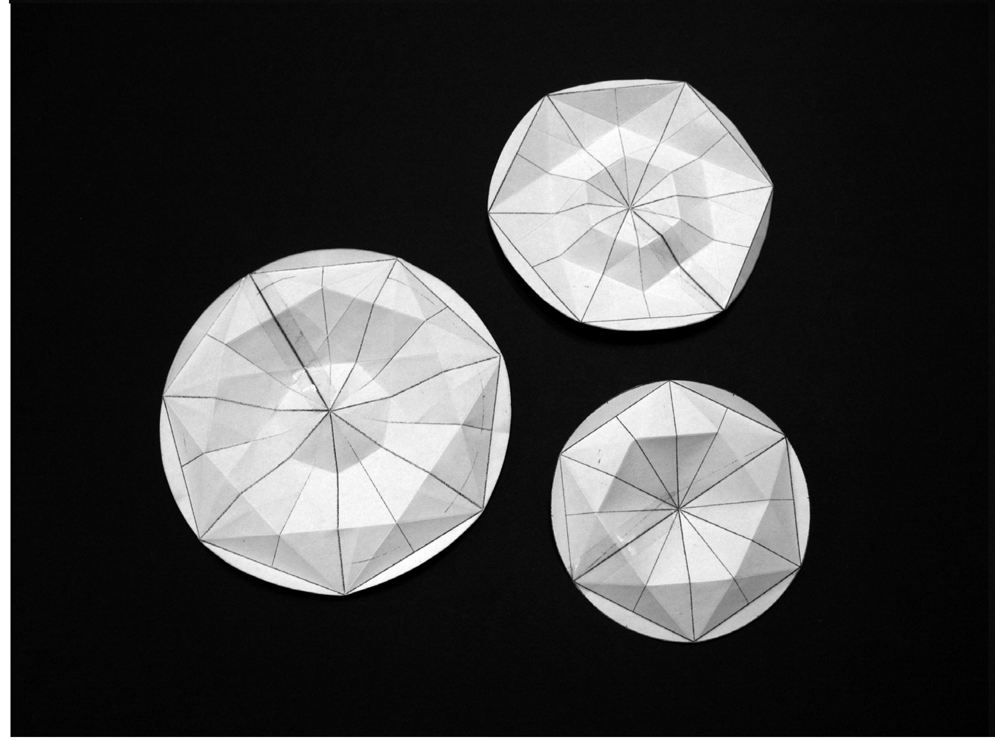
This is the first set of models that introduces a series 7, 6, 5, 4, and 3 sided shapes. This was identified as a natural by-product during the process of conical subdivision. Conical subdivision is a term used to describe the process of removing divisions of segments from a surface in order to achieve several different sided cones with identical edge lengths.

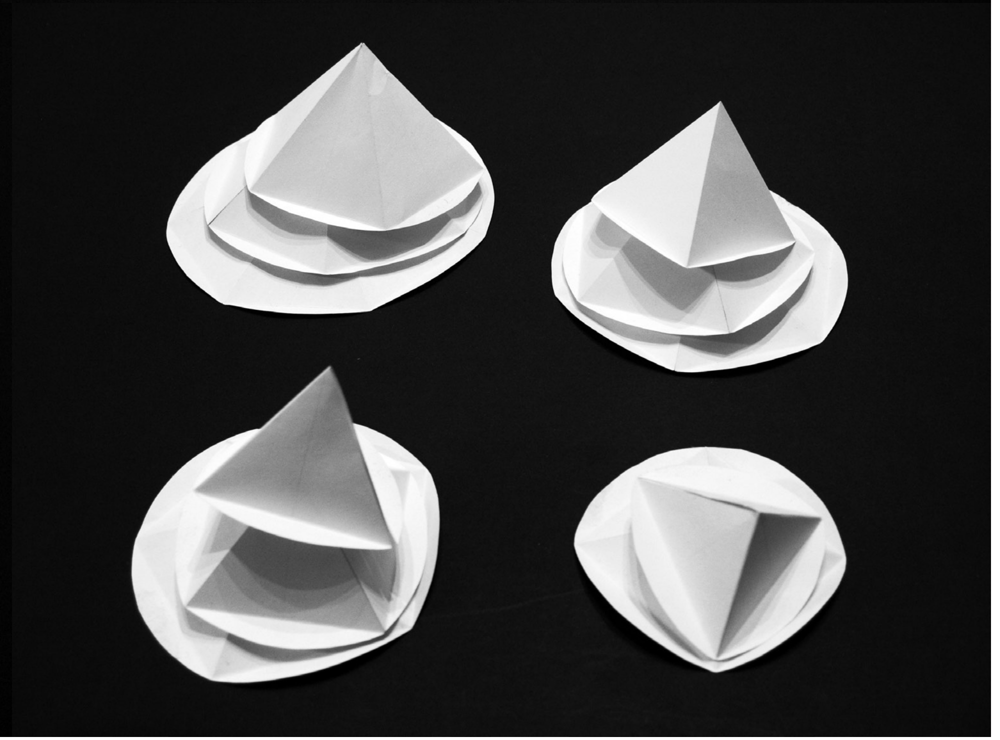
In the example on the far right, four sets of circles, each with a different circumference, was subdivided to create a larger array of unique components. In this case the four circles were cut and folded to create eleven different sized cones. For example, a seven sided pattern can be transformed into a six sided cone by removing one segment. It will become a five side cone if two segments are removed, and four sided if three are removed. The larger the circumference of the pattern and the fewer the number of segments will result in a steeper cone. This process is an effective means of achieving a wider variety of unique components from only a few standardized shapes.











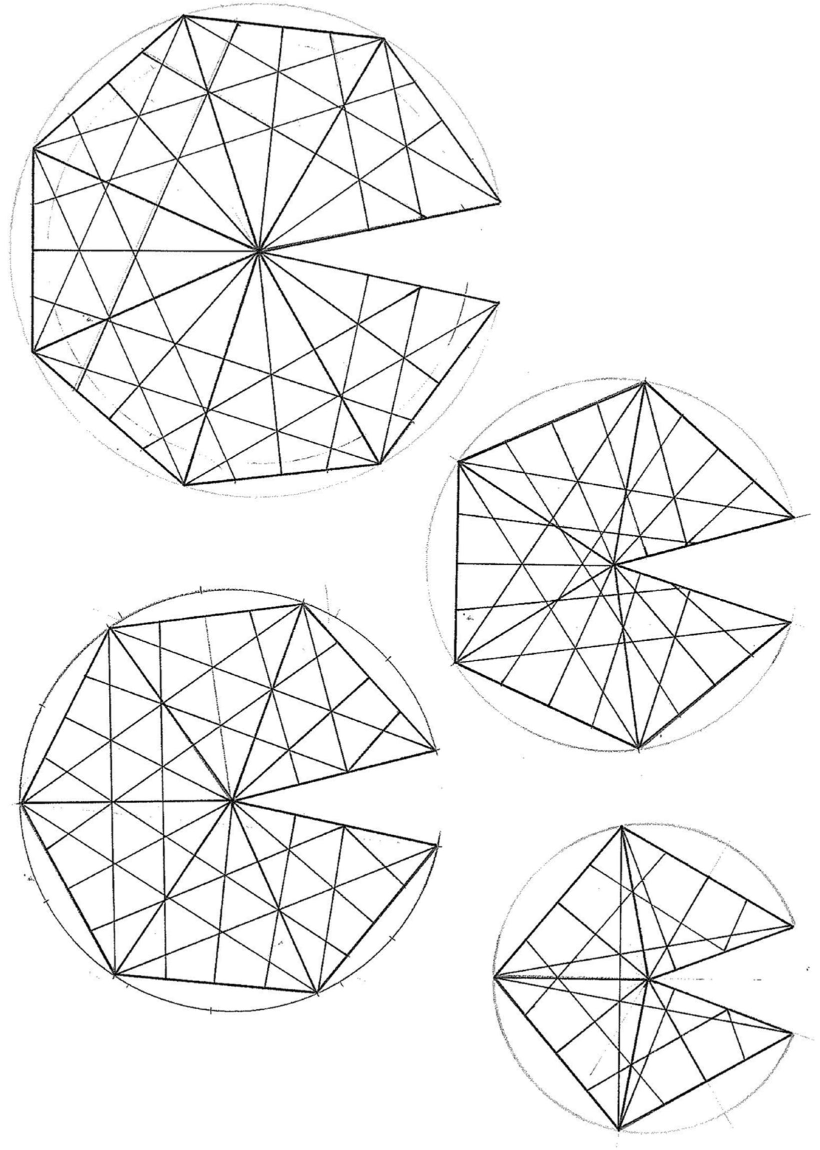
Shape Connections

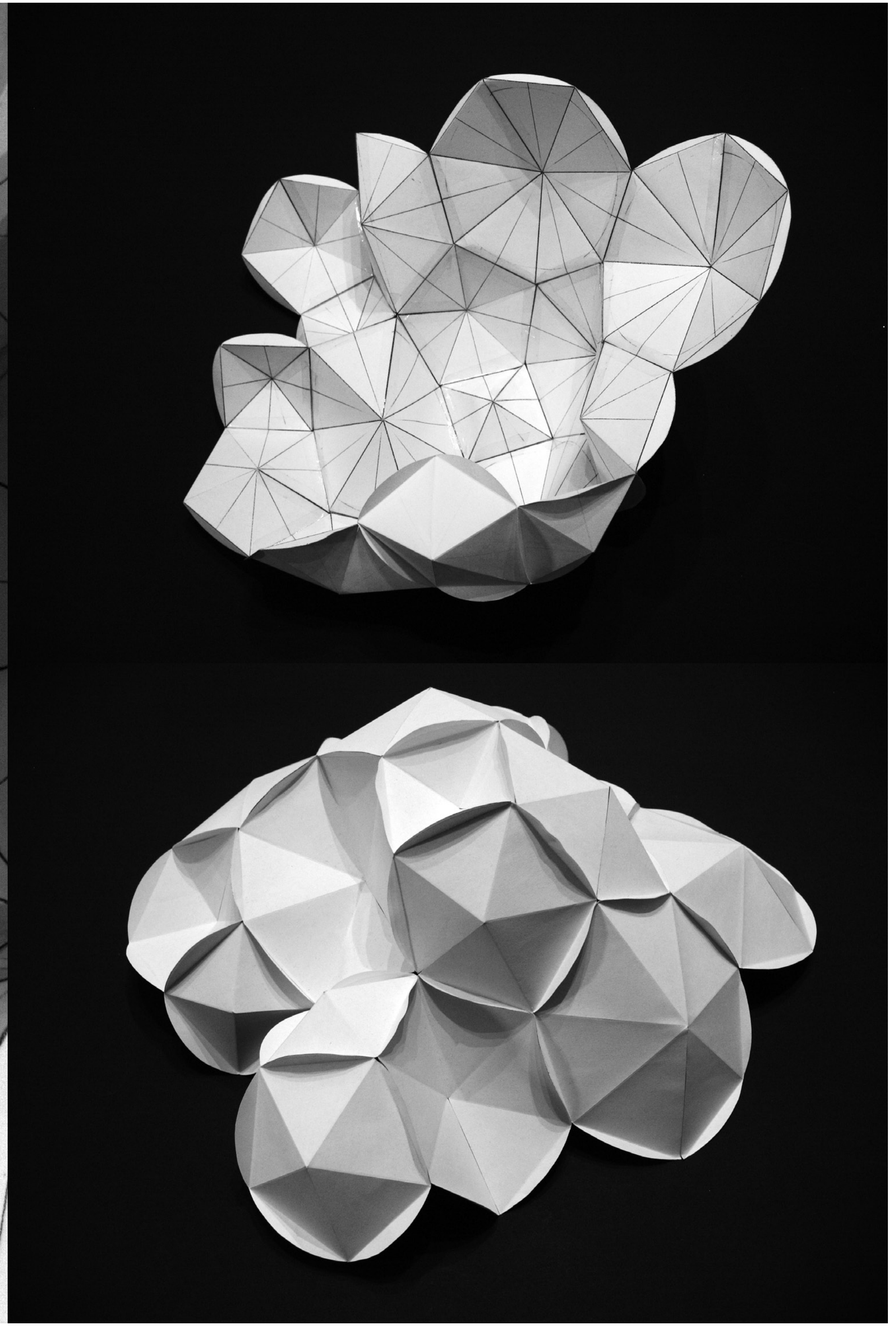
Folding Experiment 11.

In this experiment surface undulations were explored by connecting together a series of 4, 5, 6, and 7 sided shapes. The manner in which these components are arranged will determine the overall form of the surface. In this case components were connected to form an enclosed space. The greater the diversity of mountain and valley folds the more distorted the surface typology will become.

An ideal set of components was identified by developing a proportional pattern that could be applied to each of the 4, 5, 6 and 7 sided shapes. This was done to ensure each of the components had the same cone height in proportion its size. First, a standard edge length was determined in order for each of the components to fit together. The circumference of each circle was worked out by adding half the length of one segment edge to each circle. For example a seven sided shape requires a circle that is divided into fifteen segments. A six sided shape requires a circle divided into thirteen segments. The fifteenth and thirteenth segments were then removed to create the cone.

Through trial and error, this was an ideal method to derive a proportionally fitting angle separation for the height of the cone. It provides a suitable pop from concave to convex folds and is both mathematically and aesthetically pleasing.





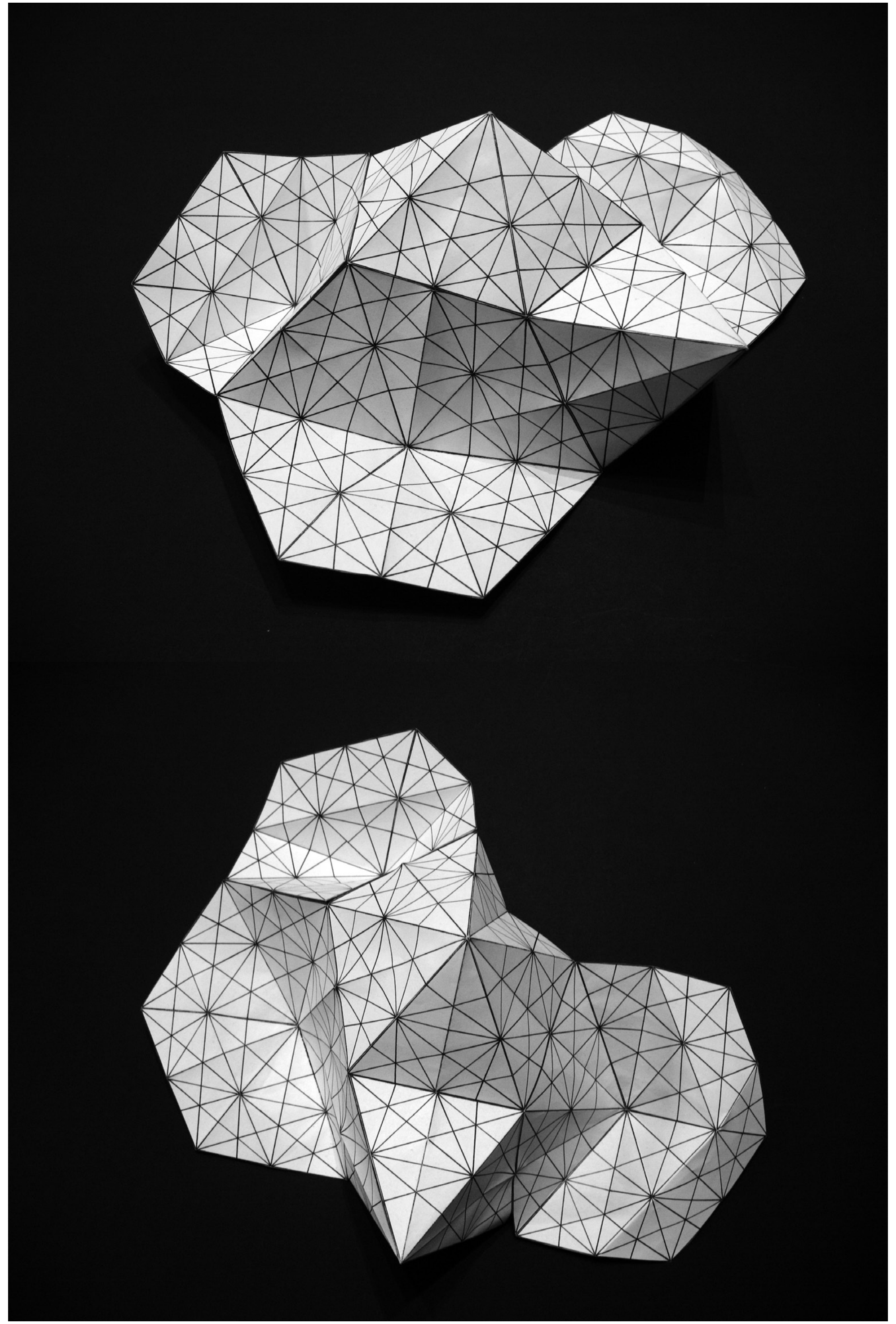
Surface Mesh

Folding Experiment 12.

This experiment explored the readability of a surface by drawing a mesh onto each of the segment's faces. The same method of surface subdivision was applied from the previous experiment onto each of the connected components. Five components were connected together, two 6's, two 5's and one 4. Each segment is identical and varying numbers of them were connected together to create the different sided components. This experiment shows the subdivision of a surface and the potential for manipulating the scale of each individual triangle.

The added mesh makes it easier to visualize the overall typography of the surface. However it also makes it more difficult to see the edges between each of the components. This creates an effect of a homogeneous surface. The mesh could be used as a method to indicate additional structural supports for rigidity, such as poles or rib lines. It could also be used to further inscribe fold lines into the surface for added flexibility.

This was an important step in the project development as it anticipates the digital element of the methodology. The mesh could be an appealing form of surface detailing when applied digitally. However the method of triangulating each segment physically may not be the same digitally. This means it would be used as a representational tool to indicate mesh subdivision, rather than a purely functional use of using 3D modelling software.

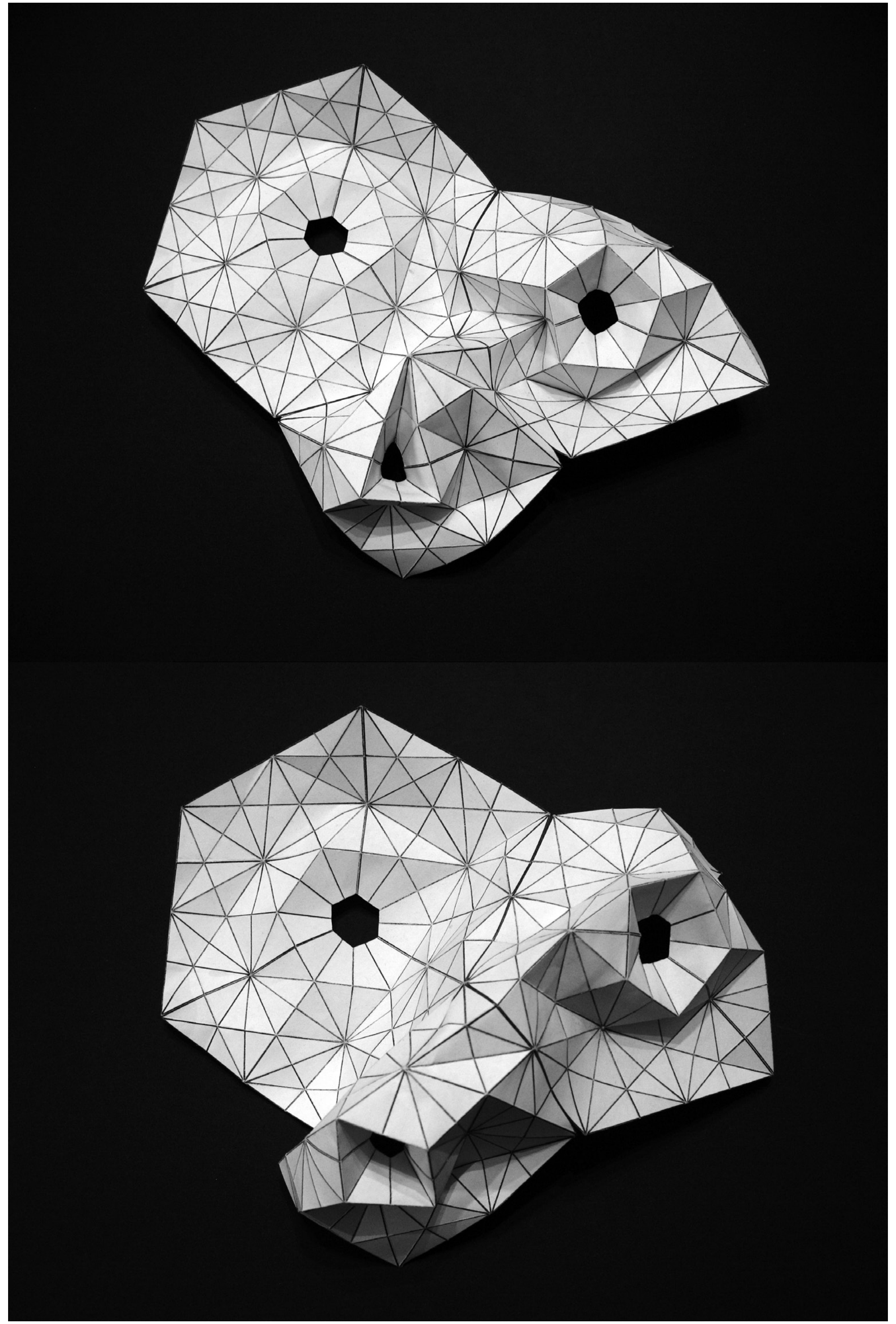


Mesh Undulations

Folding Experiment 13.

In this experiment a range of different forms were explored by manipulating the surface with a series of mountain and valley folds. This experiment illustrates that a fold line between two different components can be shaped in a way that confuses the surface topology between each component. While similar to the previous experiment in that a surface mesh was inscribed onto the surface, this experiment introduced the mesh as the means in which to create highly organic forms that have unique qualities when compared with blank surfaces.

The density of the mesh and the holes at the centre of each component provide enough surface flexibility to sculpt the surface through a series of surface undulations. With a contoured surface, folds under the most stress will have the sharpest angles. Some of these will also be structural folds that give the design rigidity. It is an option to not include non structural lines so that at no point will some of the facets bend during the folding process. This would also indicate a high sense of resolution, because there would be no fold lines that were not explicitly needed for the structural stability of the form. Despite the limitations, there is still enough flexibility across all of the components to provide a wide range of opportunities to create unique asymmetrical surfaces and organic forms.



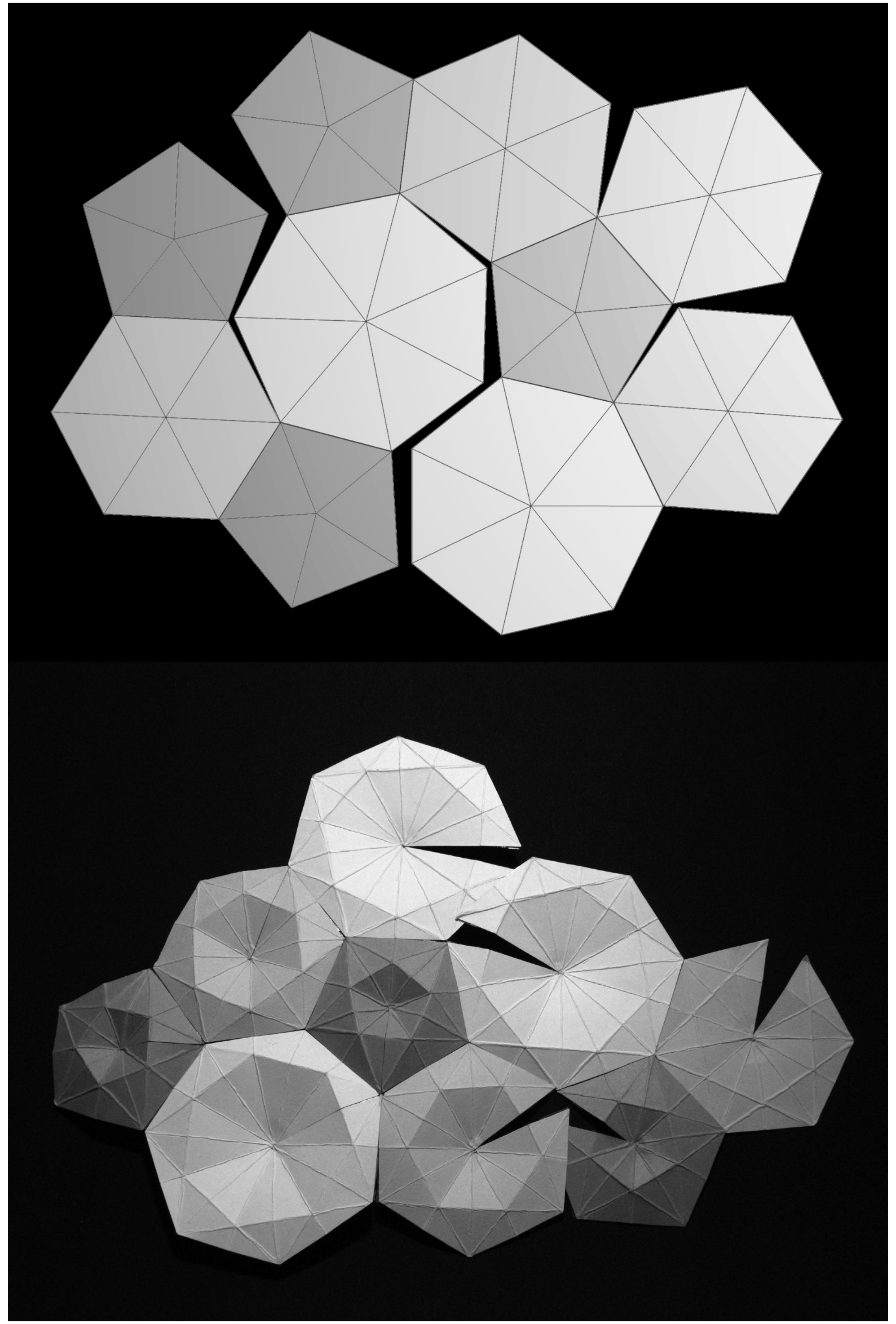
The ‘Flex Equilibrium’

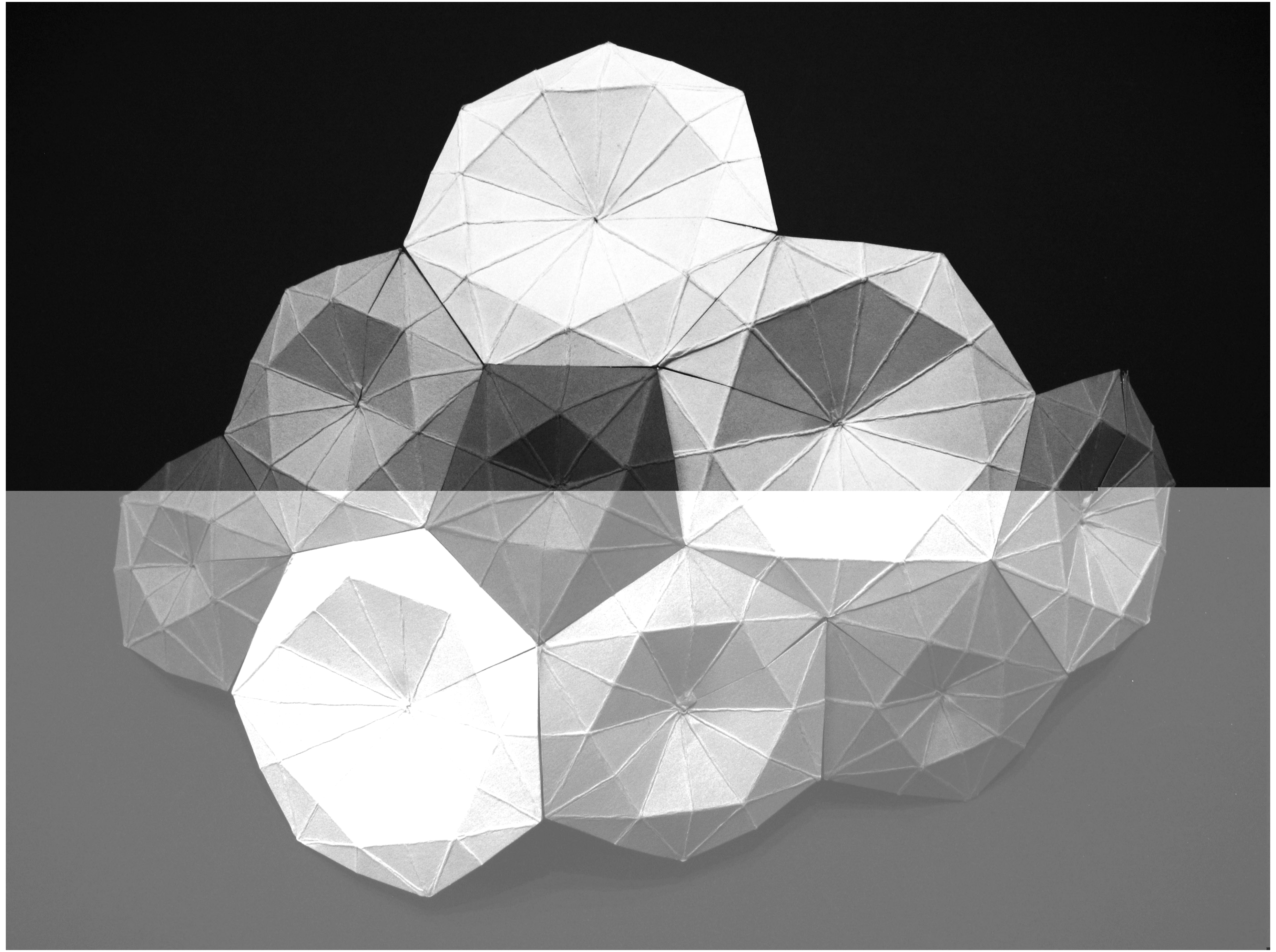
Folding Experiment 14.

In this experiment a series of 5, 6 and 7 sided shapes were connected together to form a flat surface pattern. When laying out the shapes, an obvious disconnect can be seen between each of the parts. The more shapes that are added to the surface, the greater the deviation in angle separation becomes. Therefore they were organized to fit together with as little angle separation as possible.

This experiment demonstrates that each of the shapes is flexing against each other in order to fit together. They are a series of forced connections that would completely resist connection if there were no flexibility within each of the part’s mid-folds. This allows the patterned surface to lay flat despite its natural curvature. This means that there is enough flexibility within the folds to evenly distribute the forces throughout the entire surface material. Every fold moves in relation to every other part and thus finds balance within itself. With this notion, the ‘Flex Equilibrium’ is a discovery of a inherent stability in structure yet flexibility in surface. The structure is created through its own surface tension.

An interesting aspect of this experiment is that the model cannot be easily described through mathematics because it is a by-product of surface materiality. Its attributes can only exist in the physical, and as such are subject to its own unique set of formal and structural properties. This will make it difficult to translate the surface curvature into 3D modelling software.





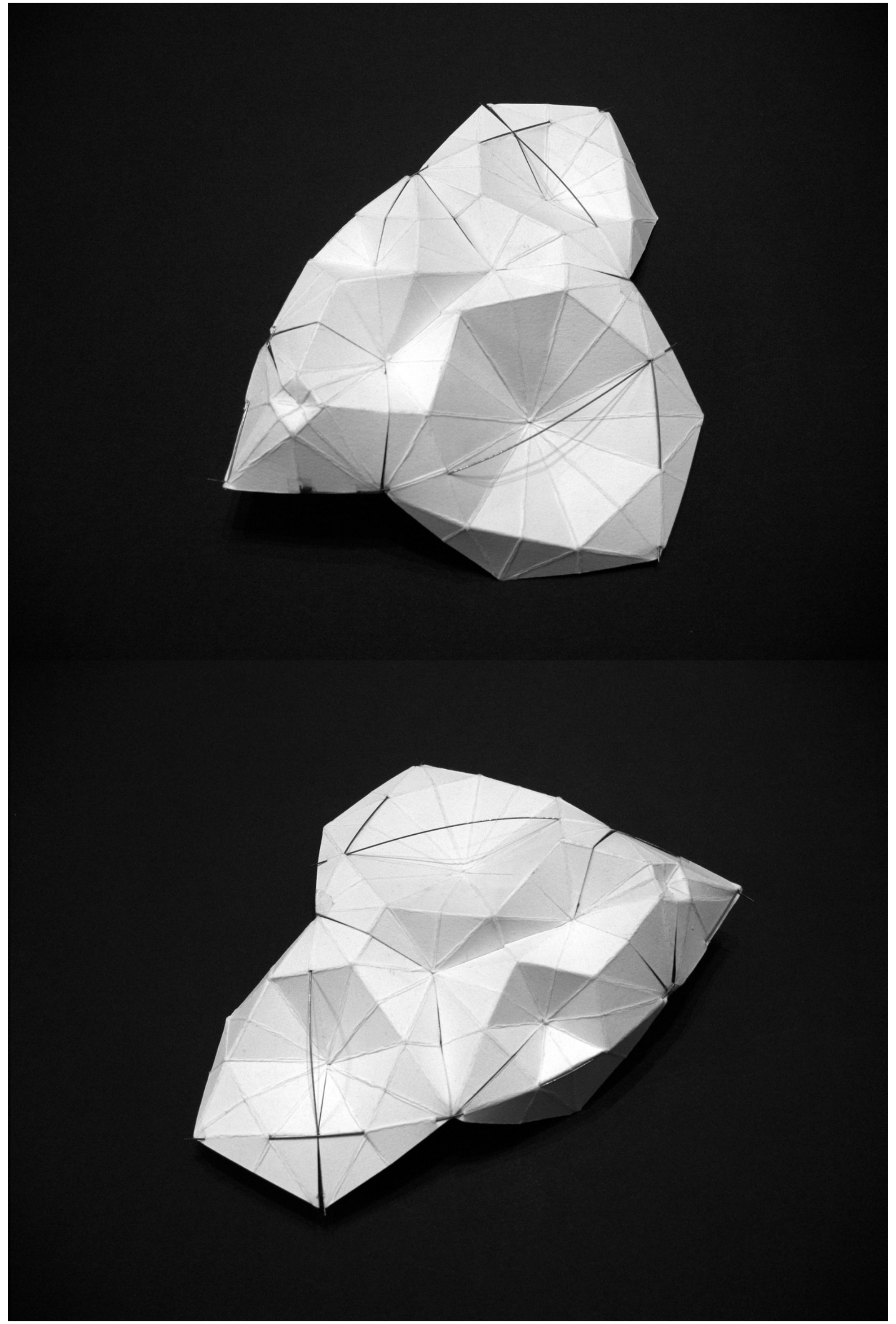
Wire Support Structure

Folding Experiment 15.

The intention with this experiment was to minimize flexibility within the model by locking each of the individual shapes together with wire. Without the wire, most of the flexibility in this model is apparent along the edge connections between the 4, 5, 6 and 7 sided shapes. The thin wire supports have been threaded through the folds of the paper and are arched into an adjacent component. Depending on the folds that are selected for each of the wire inserts, a range of surface curvatures can be achieved.

In combination with the mid-folds within each component, the wire added a great deal of rigidity to the surface material. The combination of both folds and wire is most compatible when each of the inscribed lines shares a common opposite. This was done to minimize the amount of bending the wire was placed under when the model was at rest. The greater the curvature of each wire the more tension is placed on the surface material and the greater the likelihood the components will be forced apart.

Through trial and error, a balance was found where the weight of the paper and the thickness of the wire were complimentary. This added overall strength to the model while providing enough flexibility to experiment with different configurations of surface curvature. The use of thin flexible rods is an excellent method in which to provide structural support to folding surfaces, and could be applied at a variety of scales.

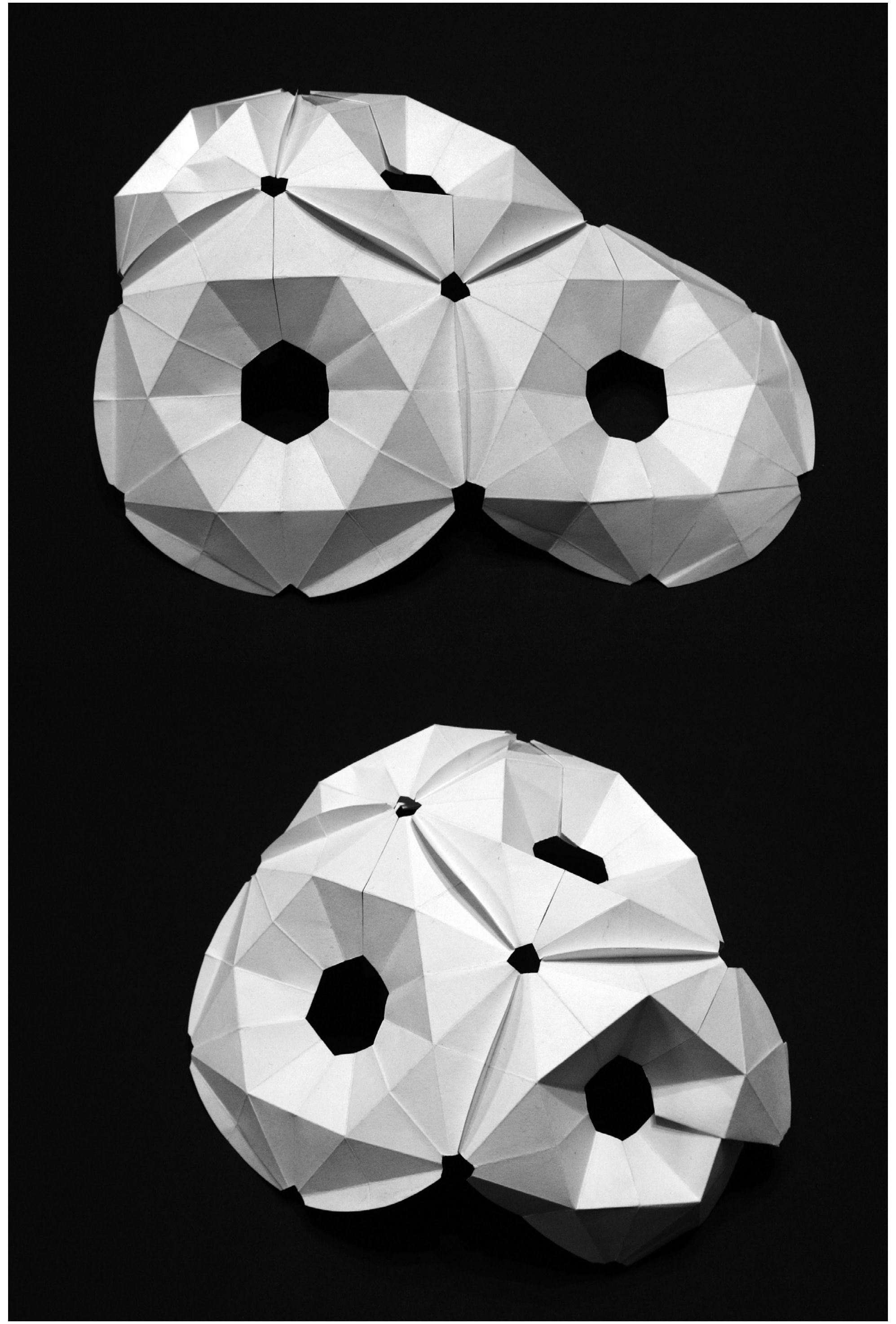


Surface Subtractions

Folding Experiment 16.

In this experiment, a six sided component was folded to explore surface curvatures with varying conical size divisions. Each of the four hexagonal modules was first laid flat and then connected together. Holes were cut out of the centre of each part to allow for greater ease of folding. Each part is identical and is a transformable module with four available configurations. The variations are created when segments of the module are folded over themselves to create smaller shapes. A six sided component can become a new five sided component; further folds will reduce the number of sides to four and three sided shapes. Each segment that is removed from the sides of the component generates greater curvature within the overall form of the surface. The more segments which are hidden away, the more pronounced the curvature of the model will be. Four 6 sided shapes will create a flat surface. Three 6 sided shapes and one 5 sided shape creates a slight curvature. Two 6 sided shapes, one 5 sided shape and one 4 sided shape creates pronounced curvature as illustrated in the bottom image.

This was an interesting experiment in contrast to the previous 5, 6 and 7 sided experiments that focused on components of set sizes. The folding away of material from a standardised component would allow for the versatile use of pattern geometry while retaining elements of expandability and collapsibility. However, it is not relevant for further exploration because its geometry is defined specifically as an output and does not allow for manipulations in the digital phase of this research.

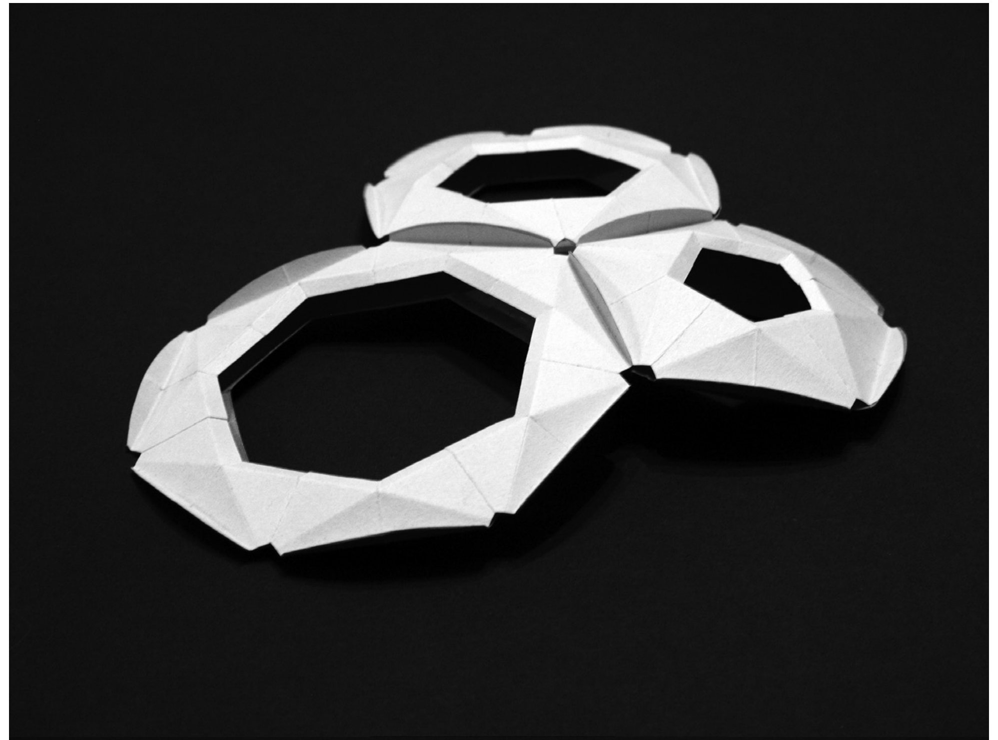


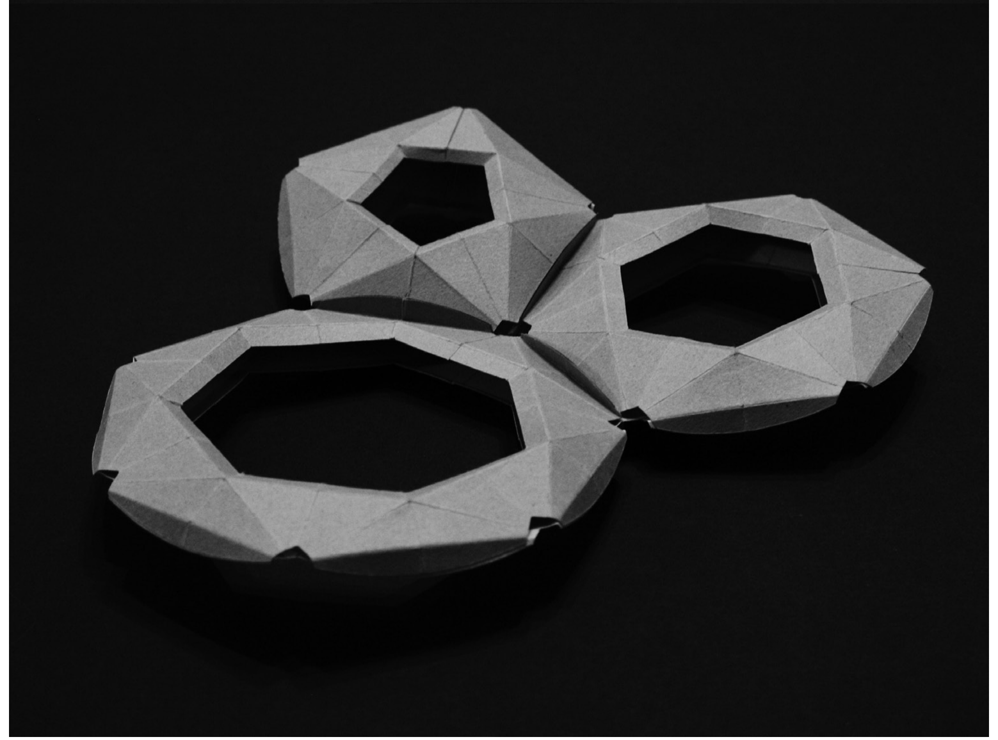
Interior Volumes

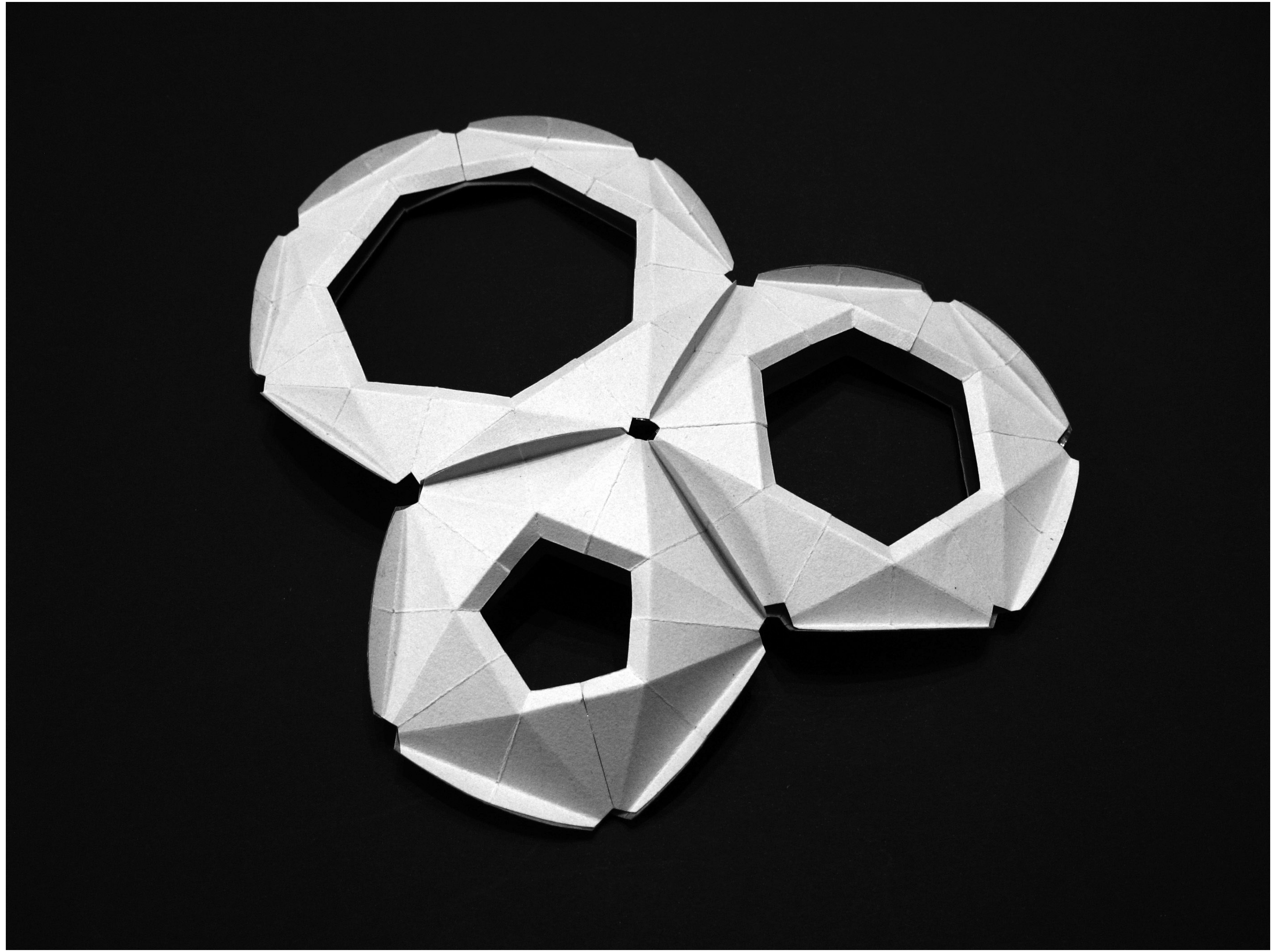
Folding Experiment 17.

This experiment investigated the qualities of an interior volume with two sets of 5, 6 and 7 sided components. The top and bottom surfaces are mirrors of each other and have been attached on the outer edges. The addition of this bottom surface adds an interior space within each of the components and increases the total thickness of the design. This extra thickness reinforces each component individually and significantly reduces the overall flexibility of the design. The slight curvature of the model corresponds with the angle separation between each of the components. The topside and bottom side have been constructed with different shaded paper to illustrate the separation of each component's surface. This is illustrated with the convex model in the top image and the concave model in the bottom image.

Each component has been joined with the tabs that are remaining from the circle. The effect of this has transformed the appearance of the design from what would be an angular surface into a softer more organic form. The interior volume within each set of components is only seen because holes have been cut out of its centres. Visually, the effect of the twin walls compounded with the larger holes in each component generates a 3D form that frames its interior volume with a sense of both space and structure. This experiment is a successful example of how physical folding can be used to create organic symmetries that are both structural and flexible.







Living Hinges

Polypropylene Material for Large Scale Design.

This section describes the process of identifying a material that would be suitable for constructing 1:1 scale structures. Throughout this investigation, paper has been the principle material worked with to explore the physical properties of folding. At a smaller scale paper is an ideal material to experiment with as it is widely available in different grades of thickness, is easy to cut and can be glued or taped together. It is traditionally the most prominent material of choice for every folding exercise. However, for the purpose of prototyping habitable spaces at a 1:1 scales, a material is needed that will be proportionally stronger and lighter than paper.

In choosing an appropriate material, several criteria were considered to meet the objectives for folding at larger scales. First, lightness to strength ratio: the material must be light enough that it is self supportable and would not collapse under its own weight. Second, material fatigue: the folding hinges must not create stress on the material when used and tear, rip or break down over time. Third, ease of folding: the material must not require more force than a person can easily exert to fold.

After extensive research into the physical properties of sheet materials that may be used at larger scales, the plastic polypropylene (PP) was identified as suitable material for such prototyping. It is available in a wide variety of material thickness, is recyclable and may even be made translucent. For outdoor uses the PP can be made UV resistance which would greatly increases its lifespan.

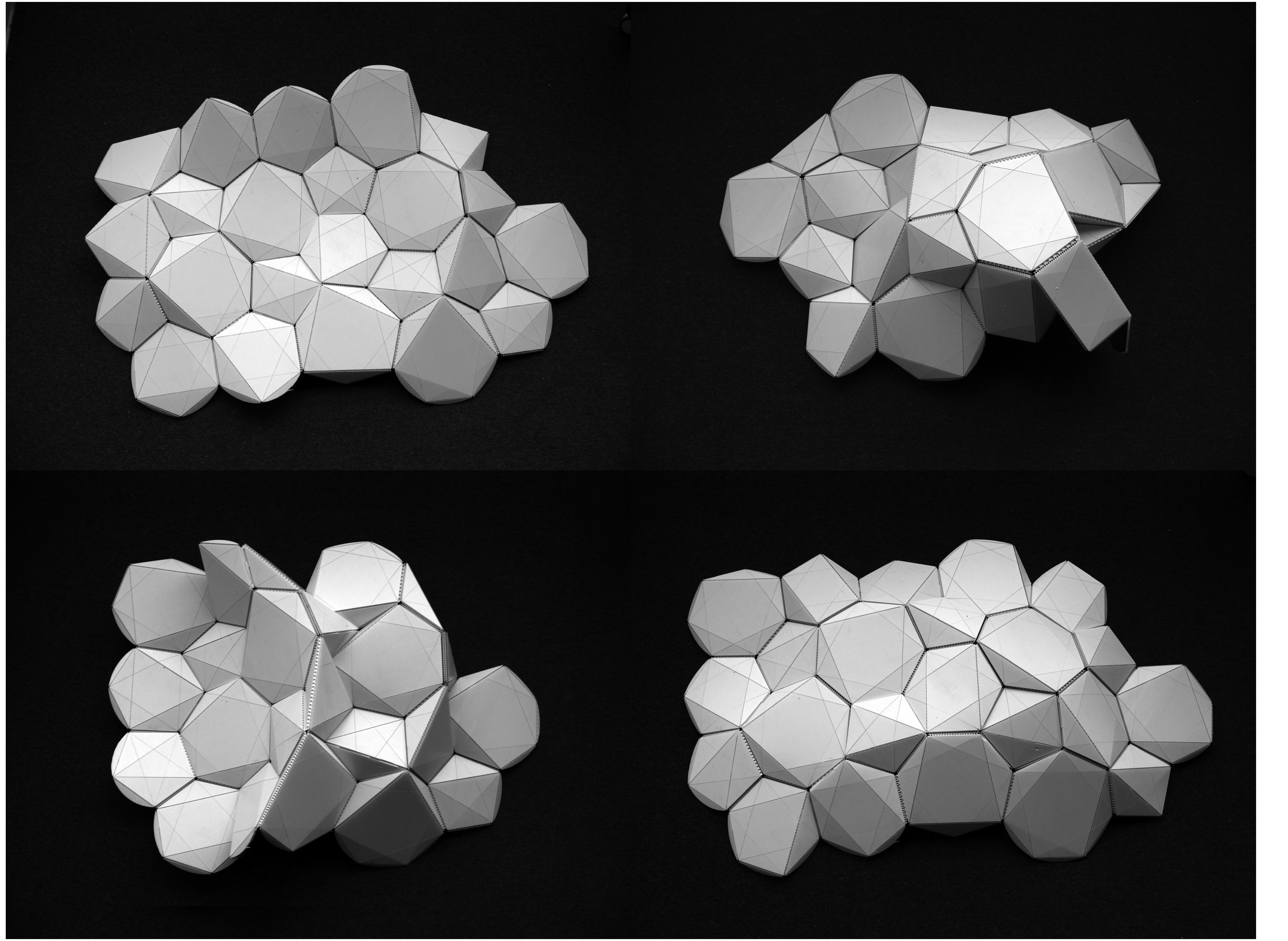
Polypropylene exhibits the physical property of being able to fold without tearing or breaking. This unique physical characteristic is called the living hinge. The use of living hinges are often applied in designs requiring a folding mechanism. Many examples of living hinges have been appropriated throughout the manufacturing industries, and are used prominently in disposable packing. The most widely known example of this is the flexible fastenings on a vastly differing range of plastic boxes, e.g. the lid of a Tic-tac container. The benefit of folding a polypropylene hinge means it will result in little to no material fatigue. The act of folding the hinge actually makes it stronger. This makes it a durable yet flexible solution for folding sheet materials at larger scales.

One method of folding with polypropylene is to engrave fold lines onto the surface of the material. The groove creates a path of least resistance and the material will naturally fold along this line. This could be done by hand with craft knives, or with fabrication machines such as vinyl and laser cutters. In this project the emphasis was placed on the use of a 3 axis CNC router to cut the material. This machine's maximum bed size is 1.2m x 2.4m, which is a standard material size throughout industry, and suppliers of polypropylene cut sheets to this size.

For ease of engraving patterns with a CNC machine the most versatile material to use is a twin walled fluted board. This is a corrugated plastic sheet often referred to as corflute, coroplast, fluted PP board or twin-wall corrugated sheet. It is an extruded polypropylene board that for its weight and thickness is very strong. The fluted core keeps the board flat and its interior structure can be fabricated at different densities. It is often seen as a low-cost solution for real-estate signs.

The benefit of using this surface is that one of the walls can be cut open so that when the material is folded it will cleanly follow along the fold line. This can easily be done with the CNC router as the drill bit will have a larger clearance when cutting through the material. If a single wall sheet were used, each engraving would have to be exactly the same depth. Inconsistencies in the depth of the groove would result in imperfect folds. This is not an issue with a twin walled board as only one surface is altered and therefore there is little risk of puncturing the adjacent surface.

To test the use of corflute a series of 5, 6 and 7 sided patterns were cut with a laser cutter (illustrated on the right). The corflute used was 5mm thick and is considerably strong. The tabs to connect each shape were made from the edges of each circle. These were doubled sided taped together and then fastened tightly with cable ties. This experiment also tested the structural durability of the surface. This was tested by forcibly attempting to rip the surface connections apart. The hinges were considerably stronger than initially expected. It was decided that this method would work very well for the design and construction of larger prototypes for fabrication with a CNC router.



Summary of Findings

In the experiments described in this Chapter, a series of folded and folding designs were explored covering a broad range of concepts and strategies that could be applied in the next stage of this project, Digital Manipulations.

From a fairly simple starting point, a flat sheet of material, various folding techniques were introduced, and further refined. The hexagonal shape was explored in the experiments as an ideal shape to tessellate forms. If elements of symmetry were incorporated within the design, there would be a great deal more flexibility and in a few cases a completely collapsible structure was achievable.

After this first set of experiments, the refinement process began. It was found that one flat pattern may generate a variety of paper folds which become a series of objects that share a number of intrinsic properties which are similar but not identical. The later experiments in this stage took 5, 6 and 7 sided shapes as a repeatable array of components that would fit together to create both flat sheets as well curved surfaces.

Along with the practicality of the repeatable pattern there was a deeper more meaningful relationship with the organic. A series of components that look very similar and yet appear different is perhaps a play on the way in which nature will mutate in response to its surroundings.

This combination of 5, 6 and 7 sided shapes was discovered to tile together but not in a perfect tesselation. Each of the 5, 6 and 7 sided shapes could be interpreted as the same geometry: the 5 and 7 sided shapes are simply mutations of a 6 sided shape, and by products of the curvature of the surface, whereas a 6 sided tessellation is most appropriately displayed as a flat surface.

This was an iterative process as some ideas and forms were discarded in order to design a modular form which could be 3D modelled in the next stage of this research.

From the strategies for investigation raised in the introduction of this Chapter, the following concepts were identified as key elements for success.

Creation of structures that are flexible and have strength and integrity

During the investigation stage of paper folding, it was found that the notion of flexibility and inflexibility played a major role in deciding the surface geometry and materiality of the folding design. A general theme developed early in the investigation experimented with geometries that retained elements of symmetry to achieve flexibility and in some instances allowed the design to fold flat. For example, it was found that some fold hinges could be thicker or thinner in order to allow the surfaces to fold over themselves.

While this produced flexibility, the notion of increasing the structural integrity of a design was considered to be a greater priority. Emphasis was placed on the asymmetry of surface to achieve inflexibility. As a result of this, the formal aspects of using symmetrical components were developed with the intention of later subtly altering the form in 3D modelling software to achieve stability when needed.

Increasing structural integrity was done by manipulating the degree of an angle to affect the overall geometry of the surface, which in turn affected the ability of the surface to be folded. This type of flexibility and movement is not easily simulated in 3D computer modelling because the virtual representations of these physical movements must be explained through mathematical formulas. Unfortunately, few 3D modelling programs are able to fully define the infinite flexibilities and inconsistencies of the physical world, and even fewer are able to do so while retaining the same mesh geometries for digital fabrication. As a result, the notion of flexible folding geometries was passed over with the intention of embracing the opposite principles to achieve rigidity and structural integrity within 3D modelling software.

Workability, economy and ease of assembly

As a design technique, the economy of folding and unfolding offered an effective means of working with low cost sheet materials such as paper and plastic. In this stage, CNC production and materials for fabrication were explored within the constraint of working with the maximum standardised sheet sizes, in this case a sheet of 1.2 X 2.4 meters. At the larger scale the use of corflute, a fluted polypropylene sheet material, was introduced as an appropriate material in which to construct surfaces and spaces to envelop a person. Fabricating at this scale suggested the need to develop methods in which to look at the opportunities of a un/folding strategy in relation to digital fabrication.

One of the most important premises behind this strategy was the need to develop methods in which to create a modular form language consisting of repeatable components that could be expanded into larger arrays. This is a type of form language and its resulting assembly language was imperative for the workability of connecting surfaces together. Emphasis was placed on the capability of dividing the surface of the material into self contained components or modules. These in themselves could be self contained parts of a component that are pre-assembled before a final assembly of all of the components. It also provided versatility for a variety of pattern configurations.

Ease of transition between a physical and virtual form

For the purposes of this research, the ease of transition between the physical and the virtual and vice versa was the most essential and defining element of the design process. A physical form and surface geometry was needed that could be used as an example of a form that could be made with 3D modelling software. A working array of physical components needed to be found which could be used for further experimentation in the next stage of this project.

The 5, 6 and 7 sided components developed in the latter stages of the experiments were considered to be the most valuable for ongoing development. This is because they met the key conditions of flexibility, structural integrity, economy, ease of assembly and were also firmly grounded in symmetry and organics. Most importantly however, they were the most suitable for mediating between the virtual and the physical because they could be modelled in 3D software.

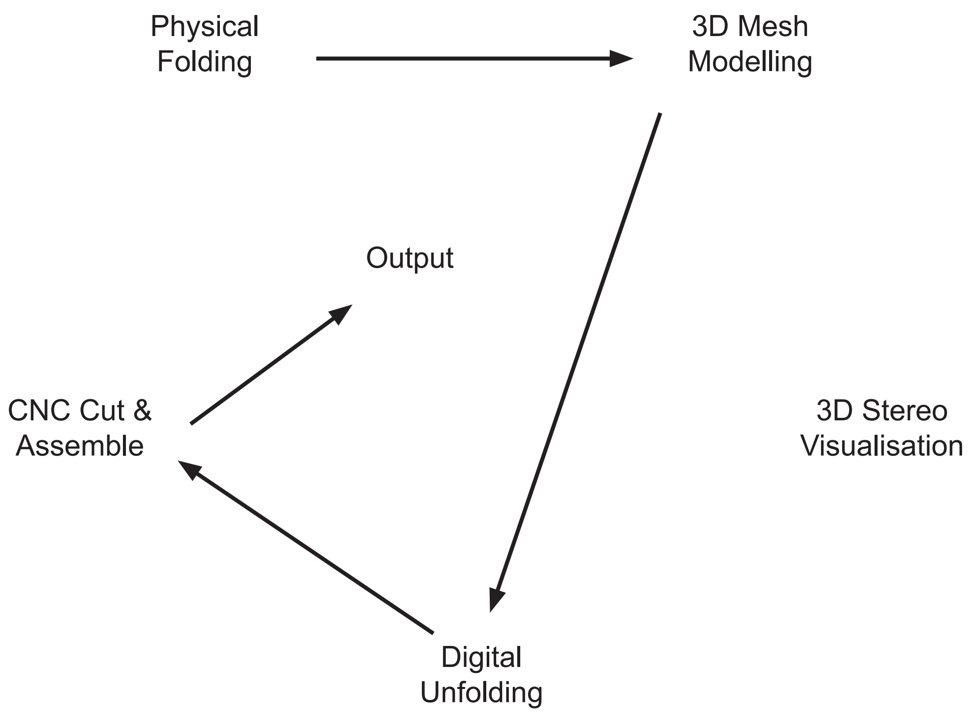
The findings of this experiment stage was not necessarily about using the 5, 6 and 7 sided components, but about framing the research within the scope of a methodology for meditating between the virtual and physical. The principles discovered in the course of the experimentation could be extended to other physical mediums that may involve folding.

Digital Manipulations

In this second stage of the project, the concepts developed in the previous stage were extended with a series of digital and physical modelling experiments. Through these experiments, a number of digital strategies were investigated that would aid in the transition to 3D immersive environments.

These experiments investigated the virtual and physical making strategies that would define the manner in which form was generated and manipulated in 3D. As indicated in the diagram on the right, the physical folded forms were first 3D modelled as surfaces that could be manipulated digitally, using the software, Blender. The design of the virtual forms were then unfolded into patterns for fabricating physically. These patterns were developed with the unfolding software programme Pepakura and could be fabricated through either the use of desktop printers or CNC machines. The flat cut shapes could then be folded and assembled into a 3D form.

The focus was to cross between each of these design mediums to explicitly create opportunities to investigate the interrelationship between virtual modelling and physical making. This was the intermediate phase between the small scale concepts in 'Physical Folding' and the large scale visualisations in 'Immersive Environments'. Once a suitable process of form generation and manipulation was developed, these digital materials could be exported into 3D stereoscopic environments as a method of further interacting with 3D spaces.



Introduction

3D computer aided design (CAD) is widely used throughout many of the creative industries, whether it be product design, architecture, the movies, or advertising. For the skilled designer, using 3D modelling software is an essential tool through which to rapidly turn thoughts of 3D form into a virtual reality.

Three-dimensional design refers to the creation of objects that are constructed on three planes (X, Y and Z). It follows then that with the use of computer aided manufacturing (CAM) a designer can use these coordinates to drive the cutting paths of CNC machines. This process is called digital fabrication and it is the means through which a digital design can translate to a physical reality.

In this research CAD/CAM and CNC machines are not used to design the fabrication of 3D physical folded forms, but rather 2D unfolded patterns, which are later manually folded into a 3D form and assembled. This method provided the opportunity to work with large sheets of material that would fit onto a 1.2m x 2.4m CNC router, keep costs low, and fabricate parts at high speeds.

One of the central elements of this research is the notion of translation, i.e., it is not only the translation between physical and digital mediums but also the translation of a flat surface into a 3D form and back again into a flat surface. This involved utilising the folded forms developed in the Physical Folding stage and exploring these further with Blender and Pepakura. The digital manipulations consisted of both modifying the surface geometries of folded forms, as well as defining the manner in which a folded form would unfold and could be nested on a flat 2D sheet. These two computer programmes are described on the following pages.

The main aim was to move beyond the limitations of the physical and explore possibilities within the digital medium. The methods in which we make digitally will inform the manner in which we can make physically. Thus, we need a better understanding of the digital materials that will transition to physicality while retaining the opportunities that the virtual medium has to create and influence form.

The experiments investigated in this stage of the research project were therefore evaluated according to the ease of transition from physical to virtual and the complexities of the interfaces required to model and manipulate the object. Analysis of the results of each experiment would reveal several configurations that were more appropriate for continued development in the 'Immersive Environments' stage of this project.

The strategies used for investigation in this experimental stage are set out on the right. This stage explored the manner in which modular components could be used to create large surface arrays that have their own inherent structure and can be used as large scale digital materials. The capability of the digital materials to envelope inhabitable space is the focus of the next stage of the research. The strategies for investigation assisted in guiding the design development process to this end.

Strategies for Investigation

- Investigate computer software to model a folded object in 3D, unfold it, and then print it for reassembly.
- Investigate the relationship between 3D folded forms, their unfolded surface and their resulting cut patterns.
- Investigate the digital manipulation of surfaces that provide a range of options for designing with digital sheet materials.
- Investigate the opportunity to incorporate structure through folds, and the triangulation of faces of a surface.
- Investigate twin-walled designs to create structural integrity and space within the structure itself.
- Investigate surface thickness as a constraint of mediating between virtual surfaces and physical structures.
- Investigate the marking of seams for the separation of parts and pattern nesting.
- Investigate the physical process of cutting with CNC machines and assembling with fasteners.
- Investigate and create content that is suitable for visualisation within 3D stereoscopic environments.

Blender 2.56a Beta

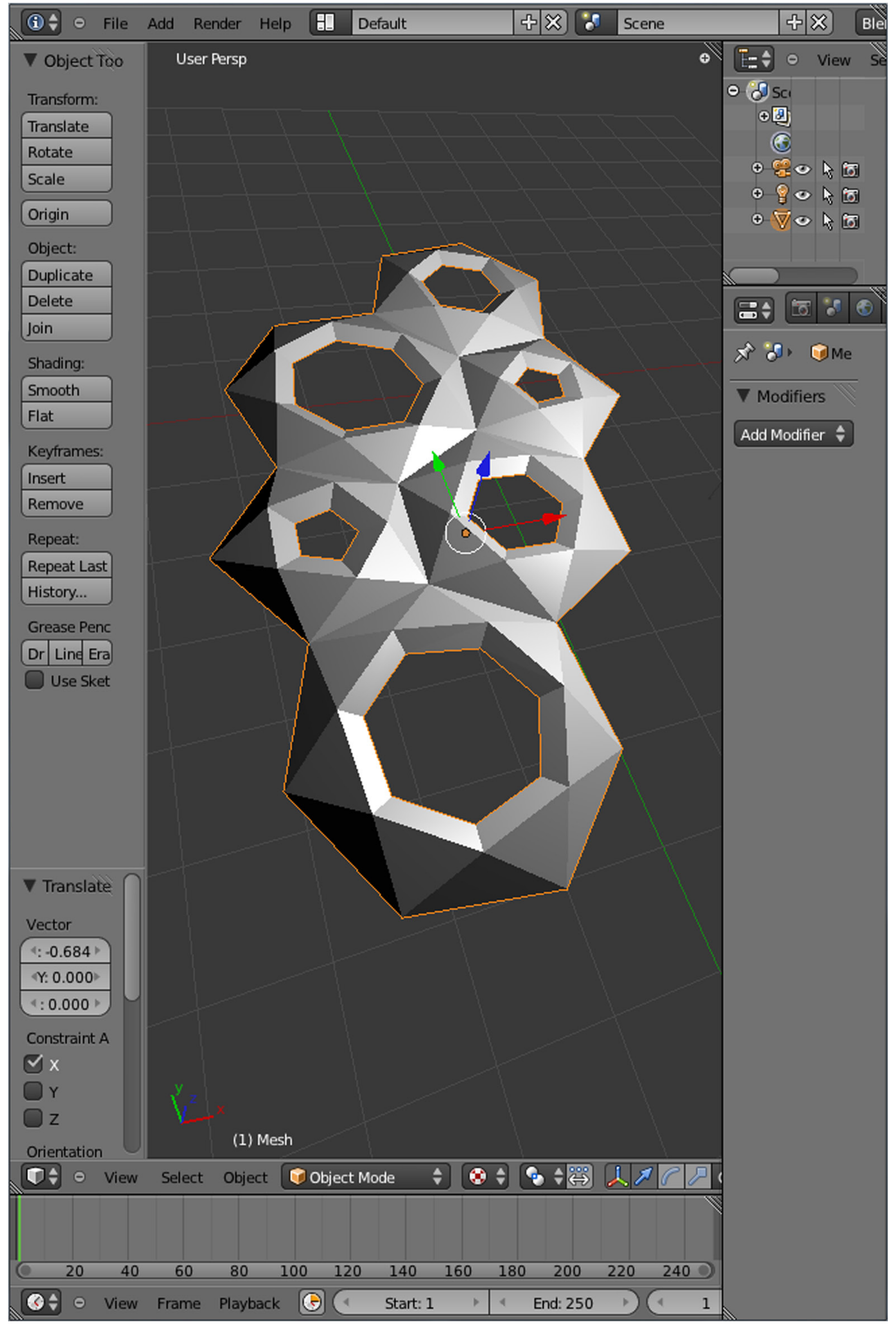
A Free open source 3D content creation suite.

In this research Blender was used as a medium in which to make 3D models, manipulate them digitally and then export them for unfolding and viewing in stereoscopic environments.

Blender is a free, open source software used by a wide community of students, professionals and contributing developers. Its functionality is very similar to software such as 3D Studio Max and Maya. Its features include 3D modelling, character rigging, UV unwrapping, shading, rendering, animations, and real-time 3D/game creation. Blender is typically used as a subsurface modelling tool with limited parameter control. In this research, Blender is preferred over parametric software such as Solidworks because it enables a wide variety of mesh based surface modifiers. This means it is advantageous for working with low polygon count mesh.

Blender provides a wide range of modelling tools to digitally manipulate surface geometries. Some of the main functions explored in this research include surface modifiers such as soft selection push/pull, bevel, cast, warp, twist, bend, and mesh subdivision. Through these surface modifiers it is possible to manipulate the edges, vertices, and faces of a mesh's surface, which can then be duplicated, scaled or reoriented. Many of the images in this stage and the next were rendered in Blender.

With the use of Blender in this research, the versatility of 3D modelling tools was investigated to create both simple and complex models that could be exported for unfolding in Pepakura.



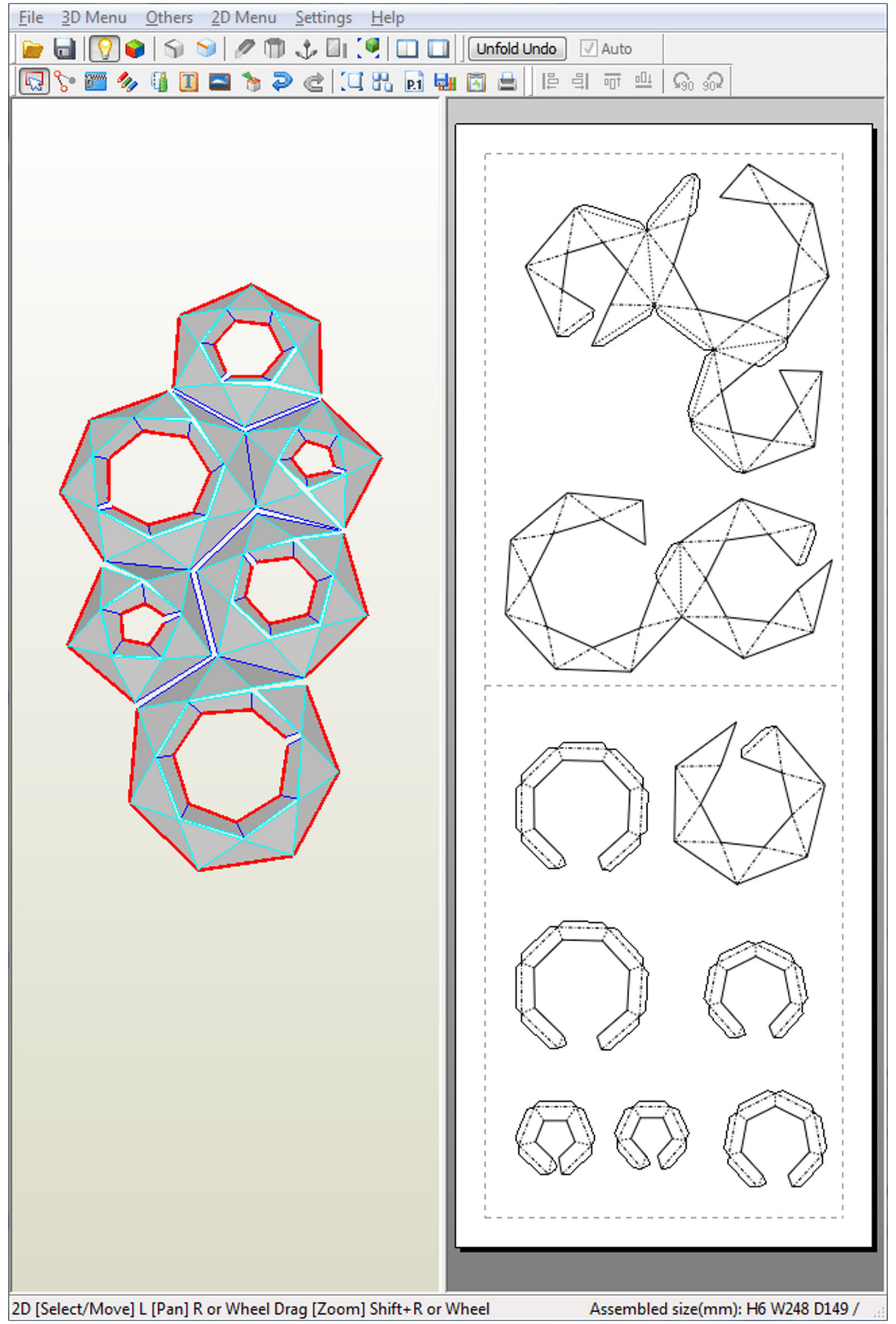
Pepakura Designer 3.0.7a

Making papercraft models from 3D data.

Pepakura Designer is a low cost software that unfolds 3D models into a flat pattern for printing, cutting and reassembly. Its users range from school children to professionals, and it is predominantly used for projects that take only a few minutes to make, for example a small paper toy. The benefit of using Pepakura over other unfolding software is that the program has been specifically designed to allow for a great deal of control over the manner in which a form may be unfolded and its resulting patterns can be laid out onto a flat sheet. The sheet sizes are fully customisable and the tabs for reconstruction are a freely adjustable.

Pepakura provides an automatic unfolding algorithm that takes a flat form and unfolds it in the manner in which it considers is the most appropriate. However, at this point the algorithm lacks human intuition, and therefore it was necessary to make use of the component pattern configurations as a way of working around the inefficiencies of unfolding complicated geometries. This was in order to make the patterns simpler and more easily understood for reconstruction.

Most importantly, for the purpose of this research, Pepakura is able to output file formats that are readable by other software as vector formats. In this way patterns are not only able to be exported as an image which could be printed on paper and cut out with scissors. Patterns are able to exported in file formats that CNC machines identify as cut paths.

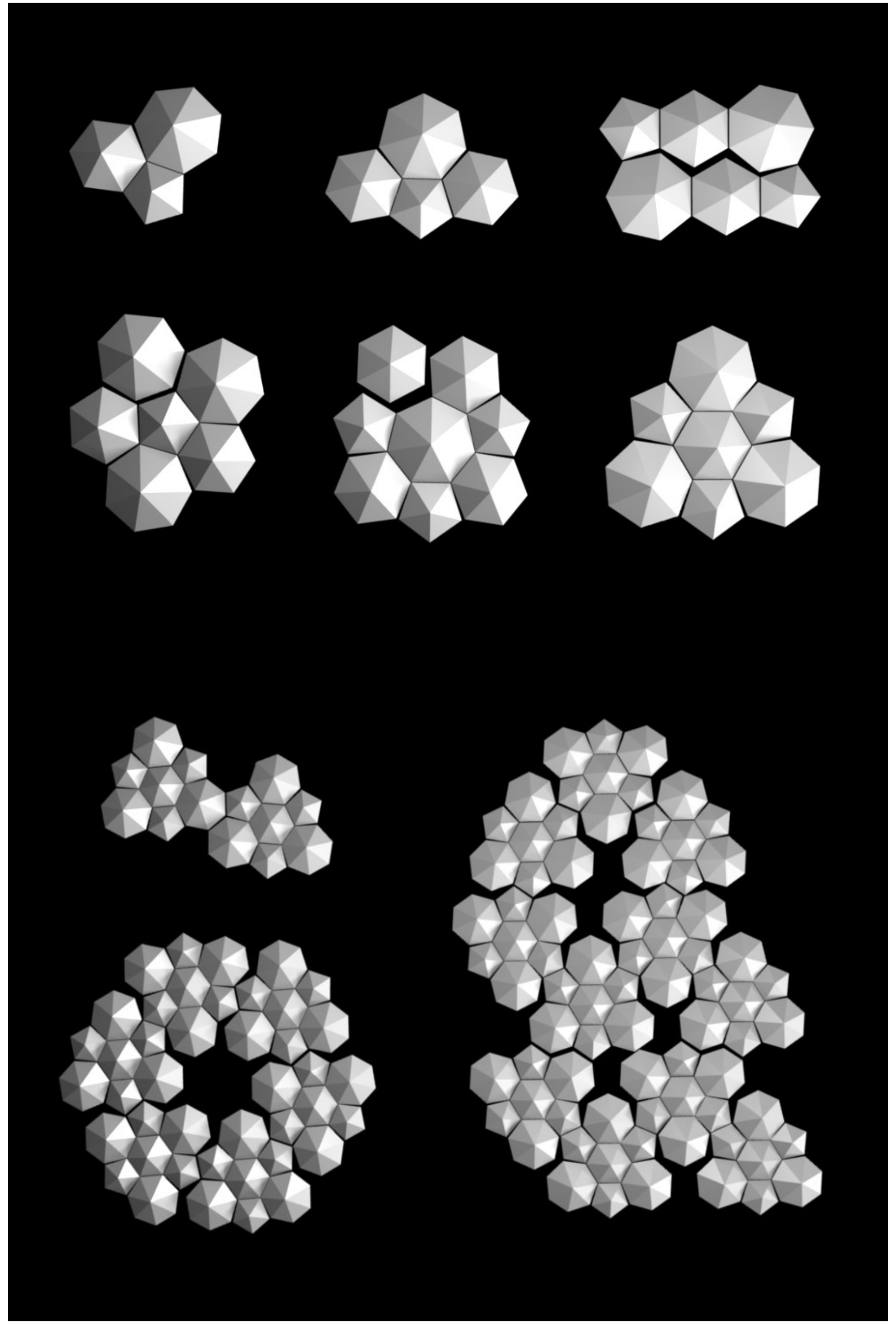


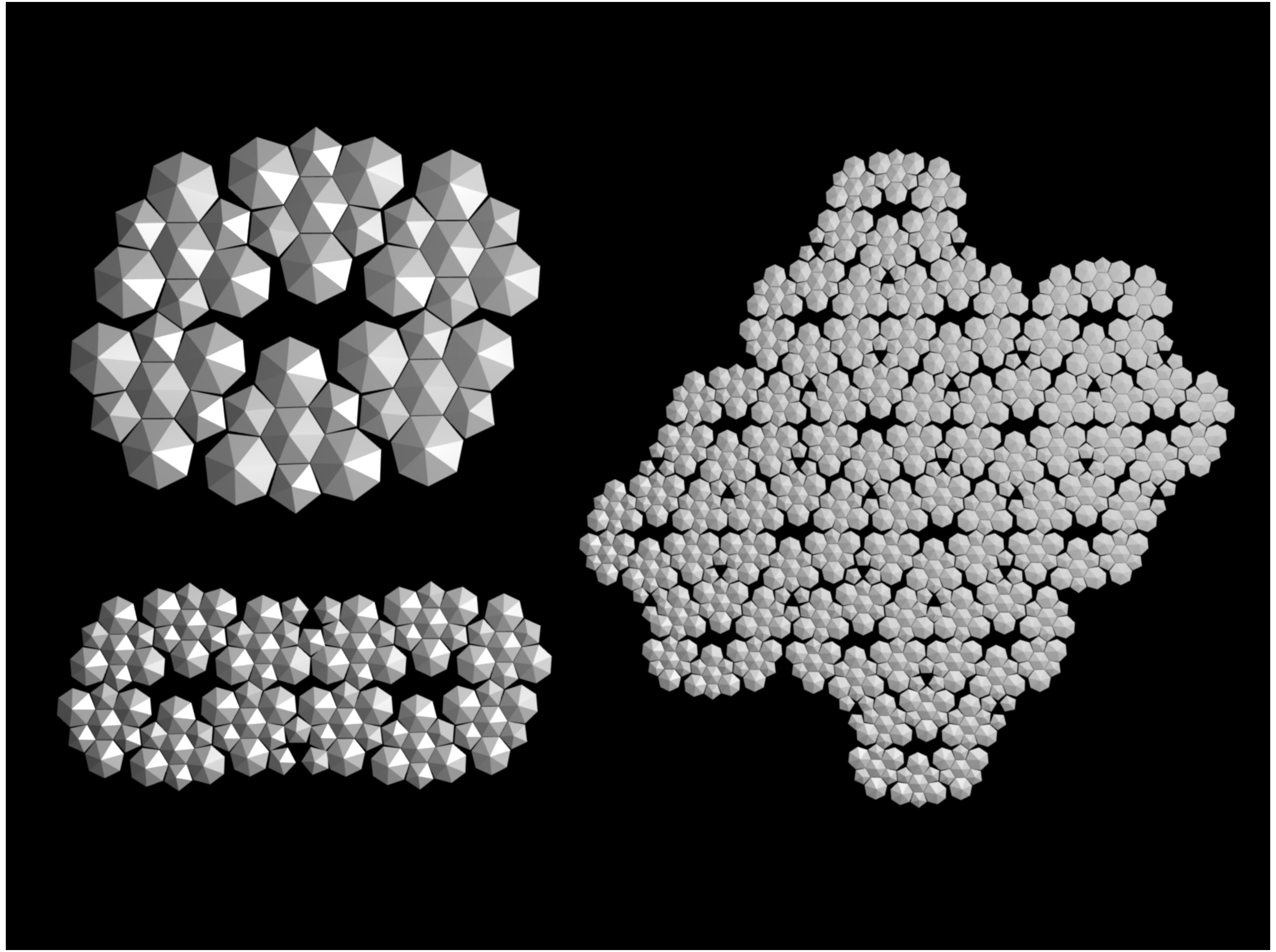
Recursive Patterns

Digital Experiment 1.

In this experiment, a recursive pattern was composed from a configuration of 5, 6 and 7 sided components. This experiment began by aligning each of the 5, 6 and 7 sided shapes so that they would fit together on their closest edges. The aim of this experiment was to identify different combinations of components that could be used to create larger sheet configurations. The set of components in the top left image indicates that there are a variety of initial configurations available, and one was chosen to be expanded upon in the following iterations. The larger the surface becomes, the more the visual quality of the surface begins to take on the appearance of a cellular like structure, and achieve an organic beauty where its likeness is more akin to a fractal or tessellation.

The result of this experiment is an understanding of the relationships each set of components has when they are connected to sets of their identical counterparts. It was important to define where on a surface we may diverge from a recursive pattern in order to introduce new sets of components. This will create a visual hierarchy within the surface's composition, and provide the opportunity to introduce new design elements.





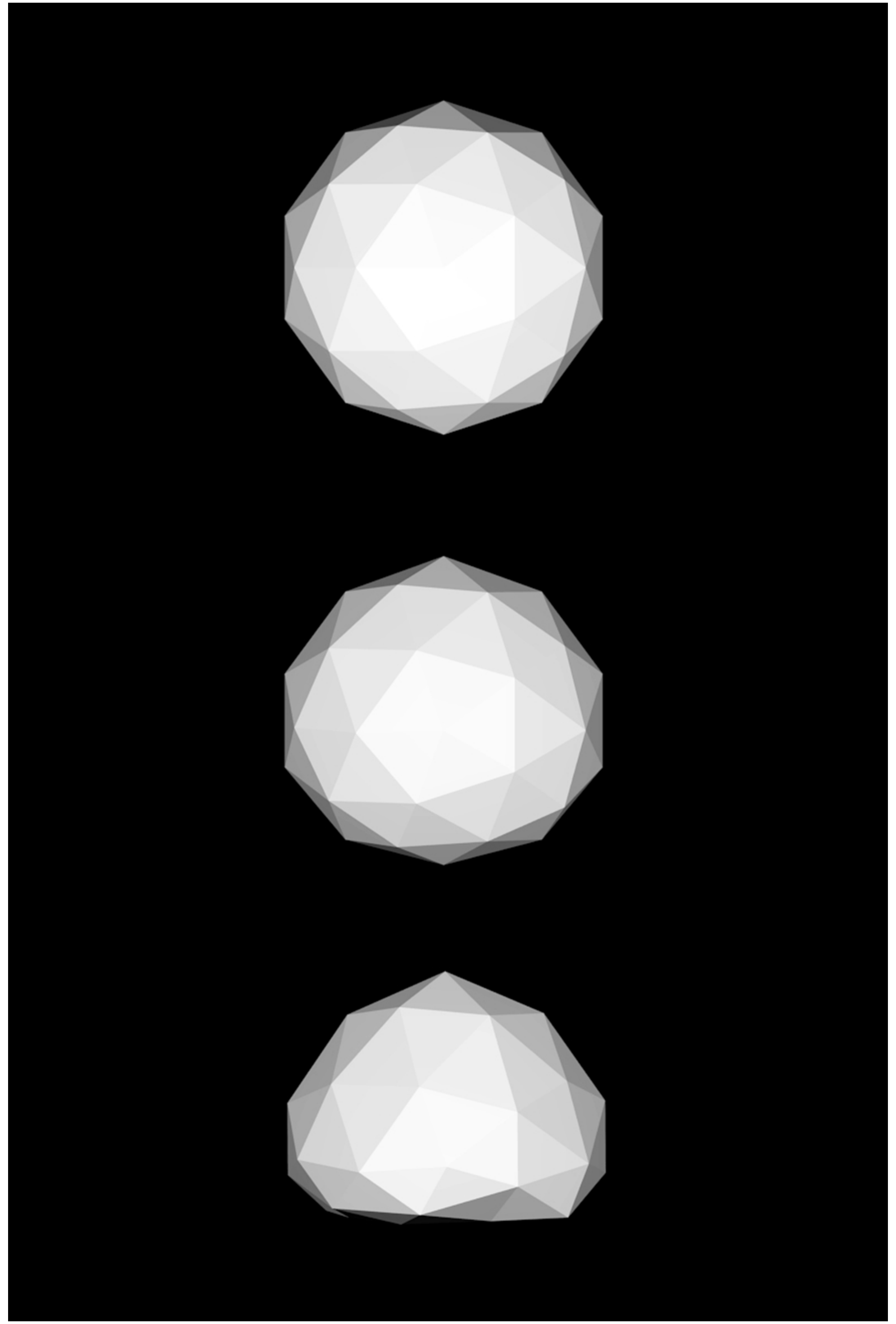
Form Manipulation

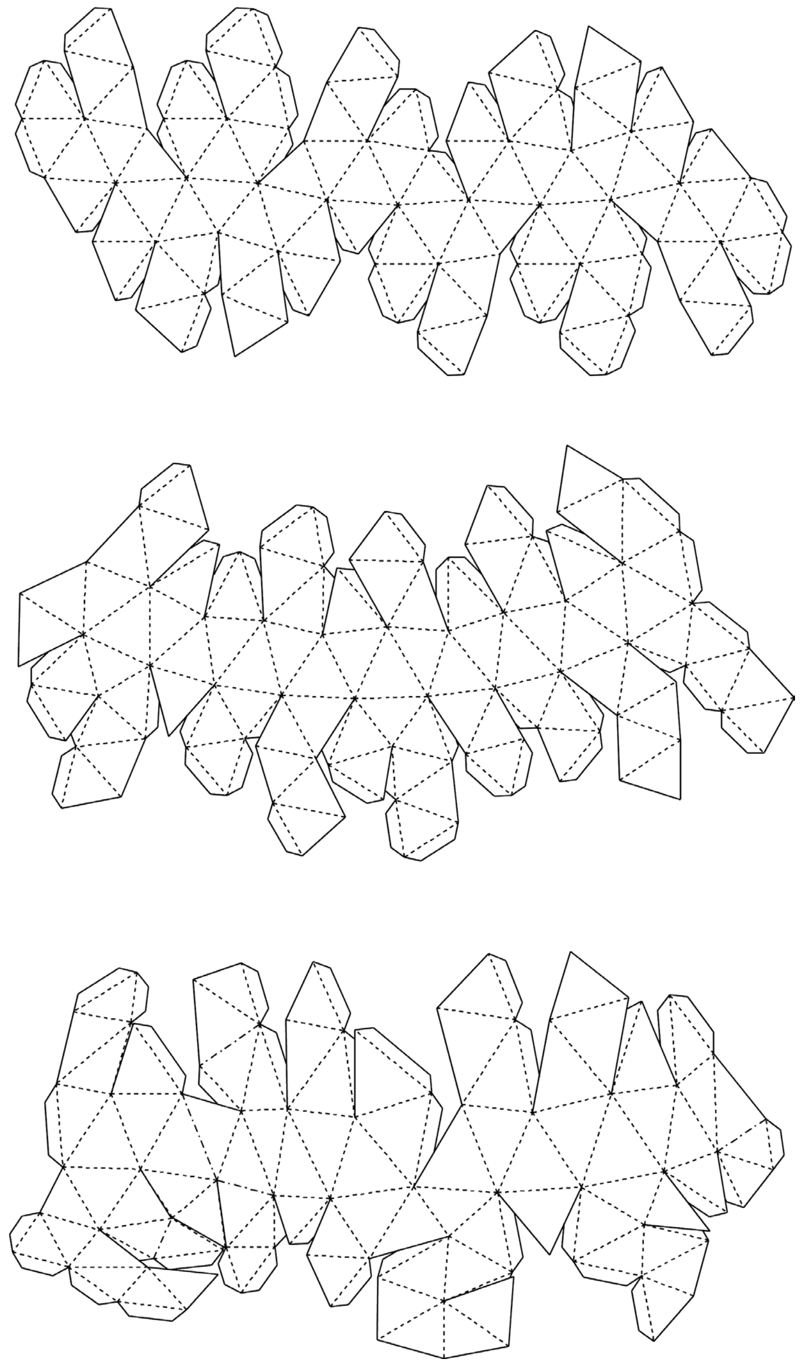
Digital Experiment 2.

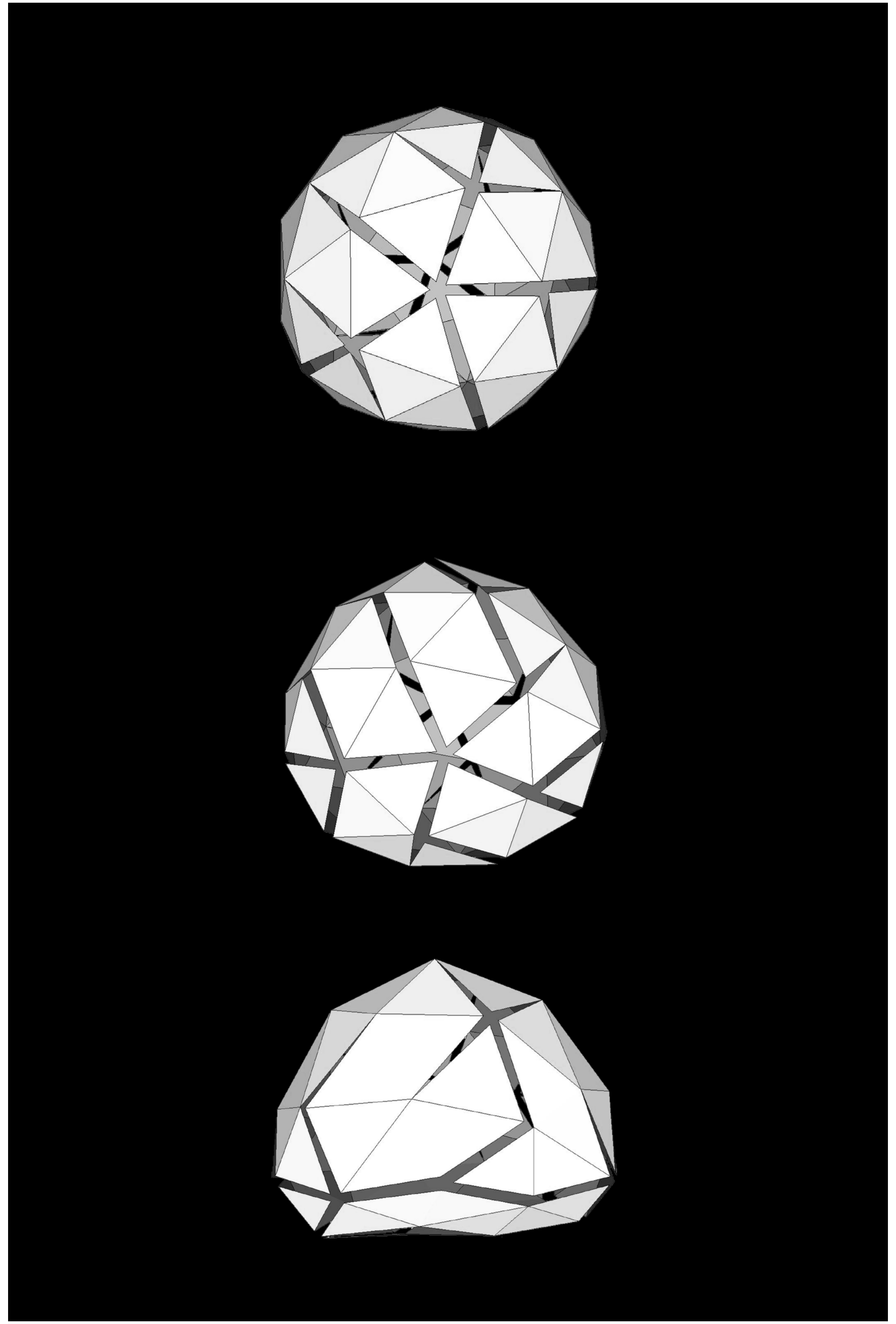
In this experiment a three dimensional object, the sphere, was manipulated in Blender. A sphere is a primitive within Blender and is a basic object that is typically added for a variety of subsequent modelling operations. A sphere was chosen for this experiment because it can be subdivided into a series of 5 and 6 sided shapes, similar to the geodesic domes developed by Buckminster Fuller. The aim of this experiment was to explore how subtle manipulation of a 3D form may impact on its unfolded pattern.

The sphere underwent two transformations illustrated with the set of spheres in the left image. The sphere was squashed against a flat plane with two iterations. The top is unaltered, the middle image is subtly altered and the bottom has been altered again. The unfolded pattern was outputted as an automatic process from Pepakura and no seams were marked prior to this unfolding.

This experiment indicates that the more a form is altered from a typically symmetrical object to an asymmetrical object, the more distorted its unfolded pattern will become. An interesting observation is that when unfolded, the middle iteration still retains similar seams as the unaltered sphere. For the purposes of this research however, the automatic unfolding within Pepakura will not be suitable for unfolding 3D forms because as a surface becomes more distorted, there needs to be greater emphasis placed on the manner in which these forms are unfolded and which seams are most suitable for separation.







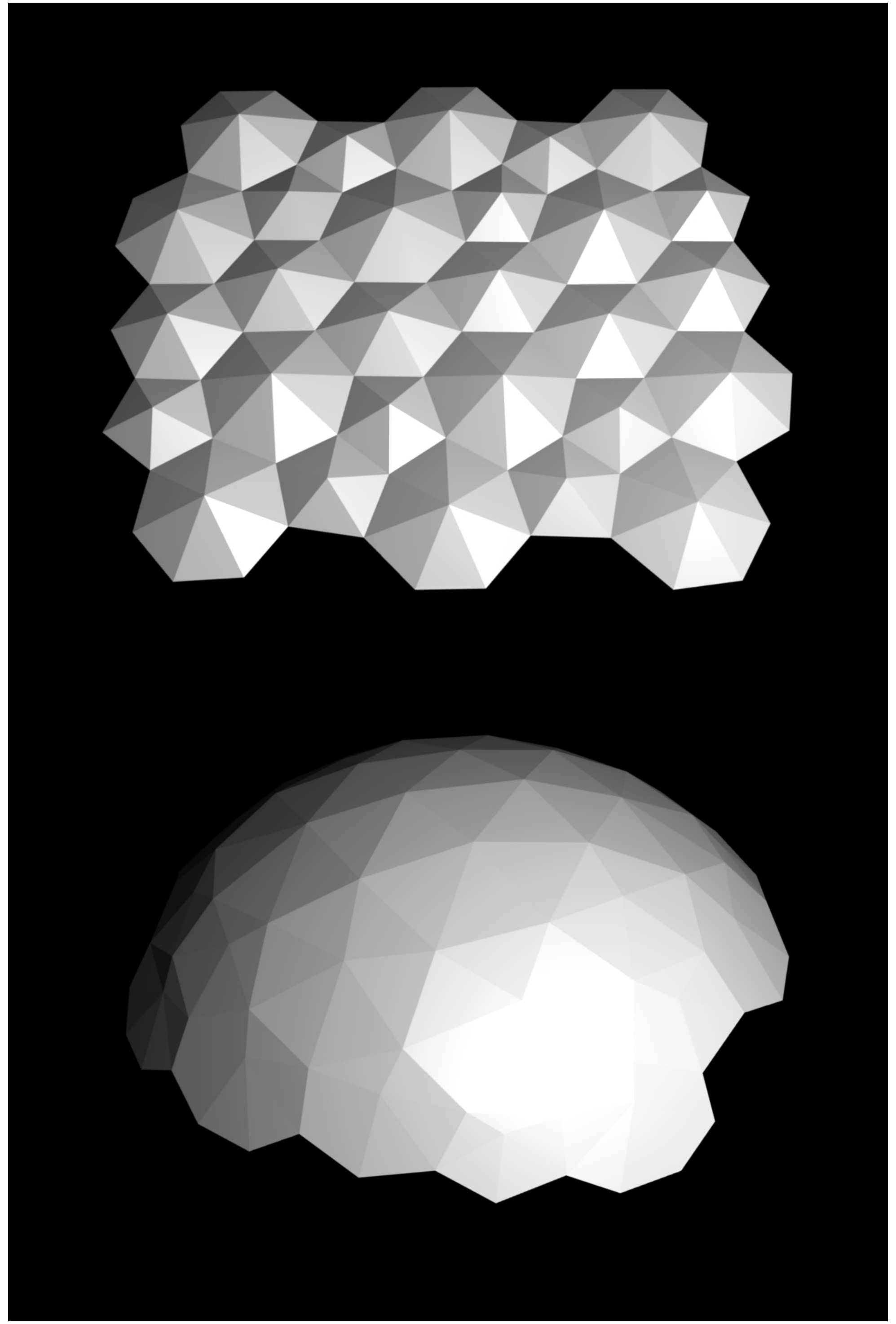
Pattern Unfolding

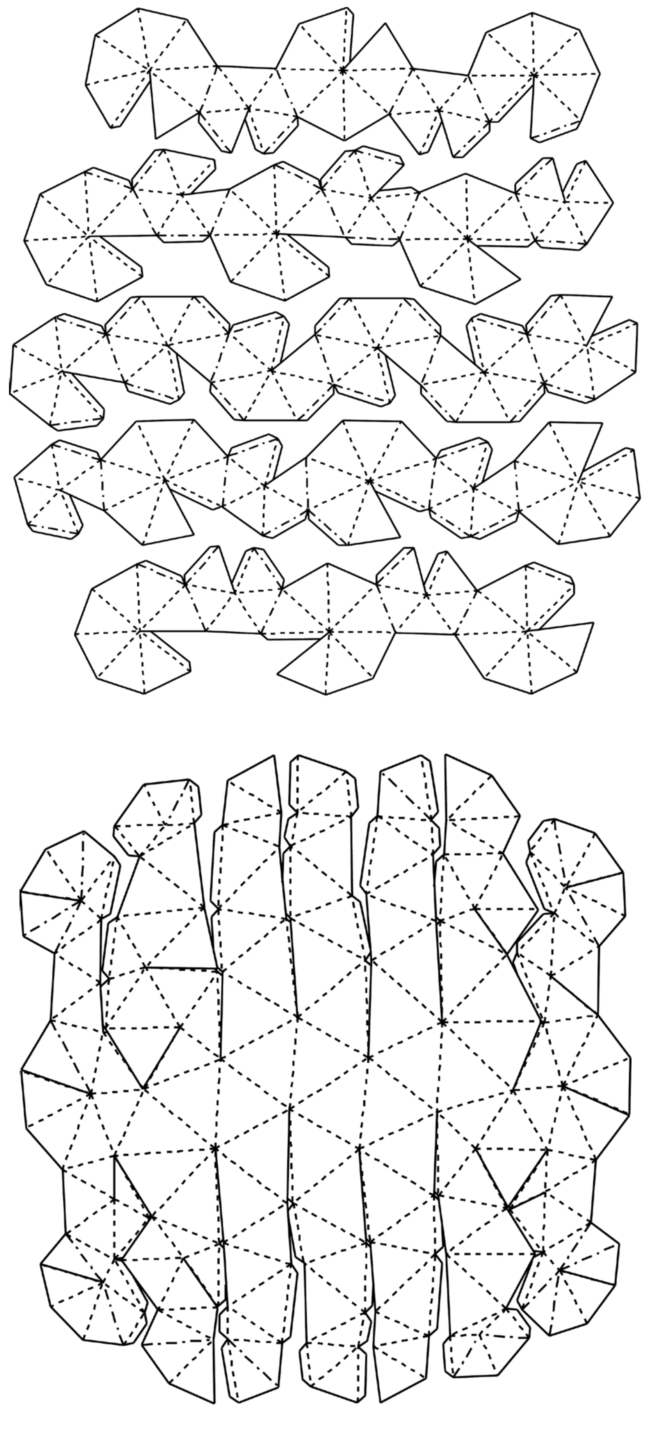
Digital Experiment 3.

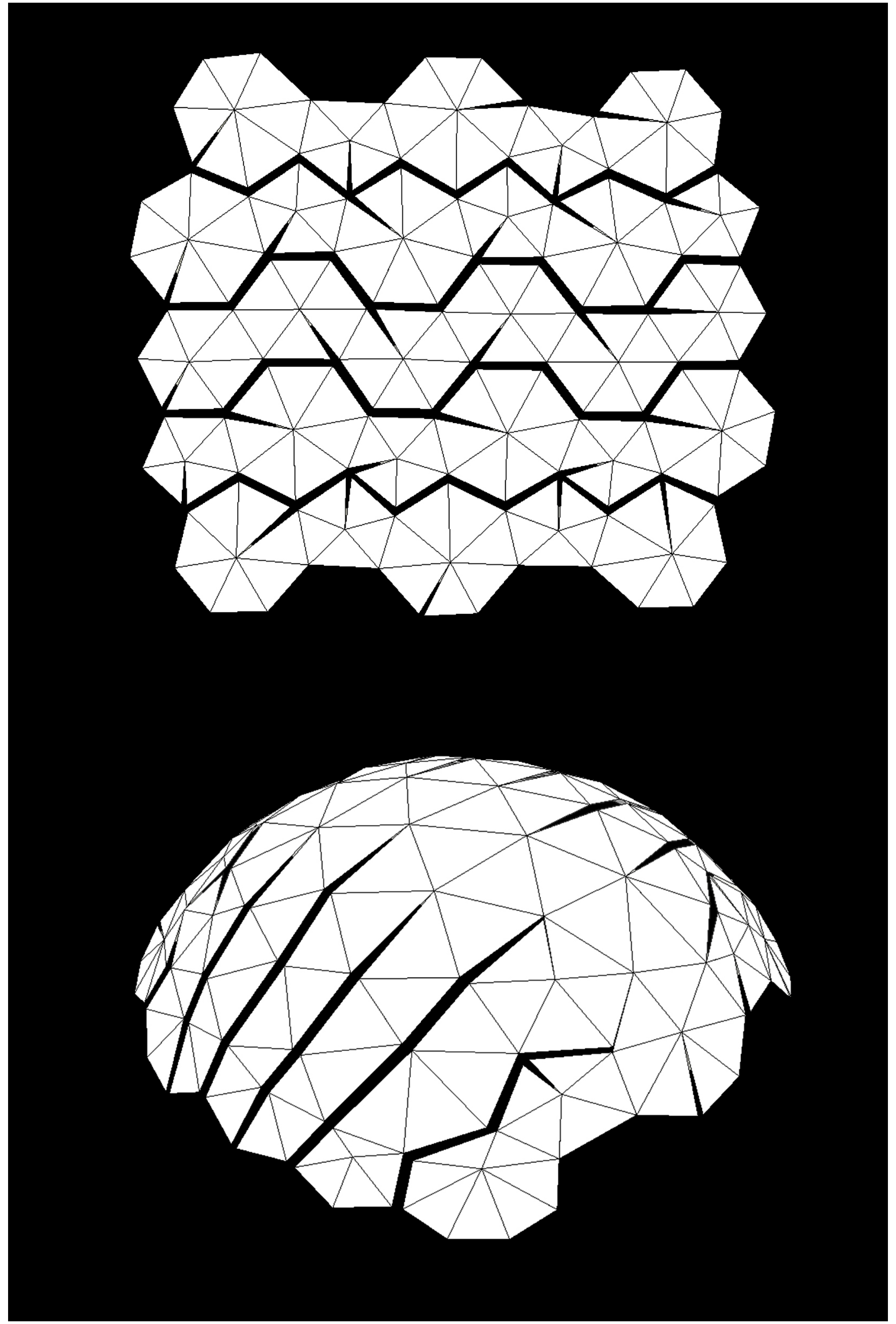
In this experiment pattern unfolding was explored as a method in which to achieve surface separations that are easily recognisable for reconnection. This was addressed as a visual assembly process that may reduce the time in which it takes to understand which edges are connected, and where.

Two models were investigated. The first was a set of 5, 6 and 7 sided components that were aligned and edges merged within Blender. This is a flat pattern, aside from each conical component, and has had no manipulations done to its surface. The second model was a development of the first pattern, and has been cast into the shape of a sphere. The casting tool is a modifier within Blender. This was done in order for the surface to appear smooth and the conical form of each component no longer recognisable.

The automatic unfolding of these models in Pepakura did not result in surfaces that mimicked their 3D counterparts, so the edges were marked for separation. While the difference between each model's edge separations are noticeable, they are easy to understand because a sense of order and symmetry have been applied. The manner in which surfaces are separated must result in reassembly configurations that are easy to interpret, and thus easier to rebuild. Ease, within the context of this research, relates to the time it takes to determine which unfolded parts go where, and is something the designer determines during the design development process.





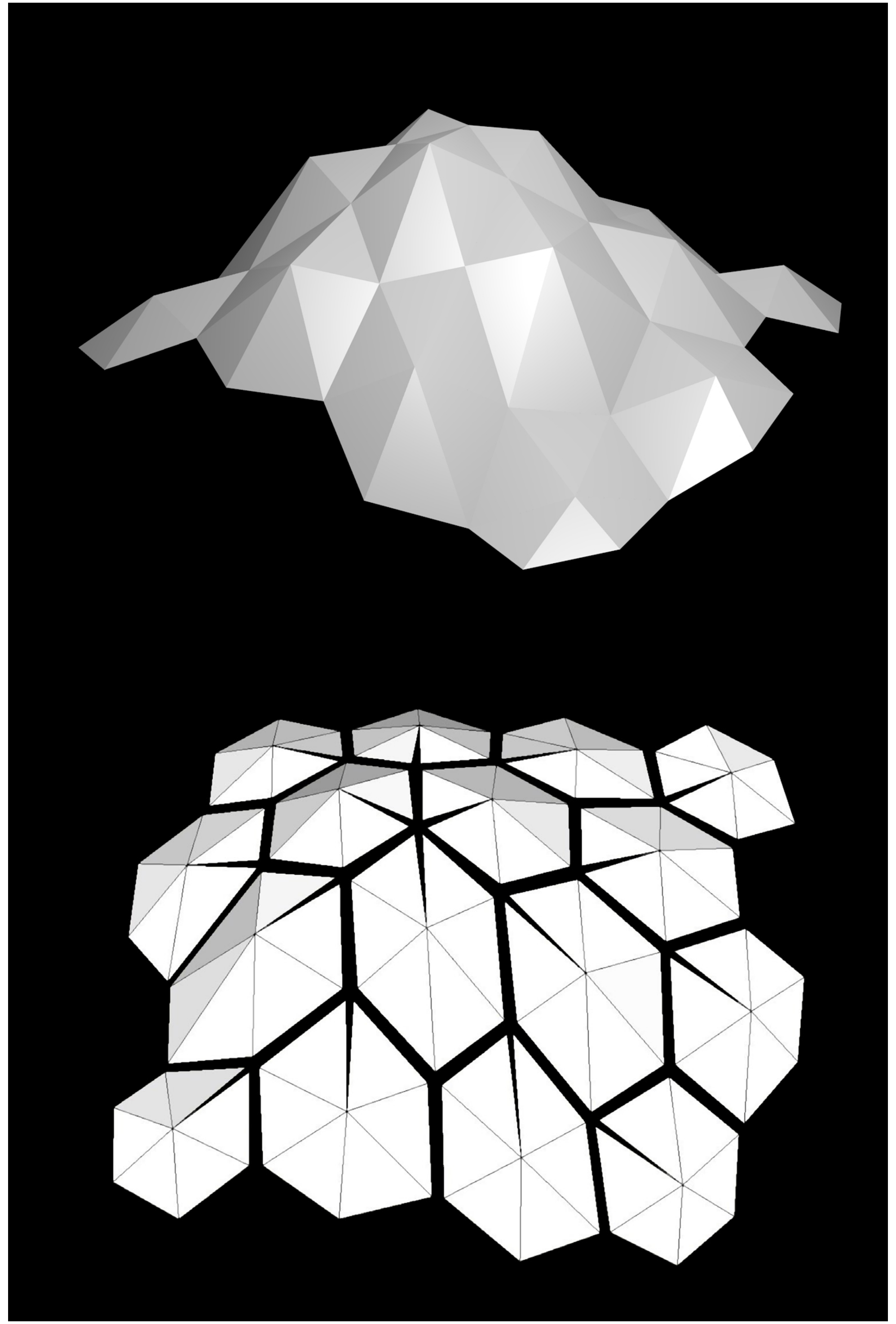


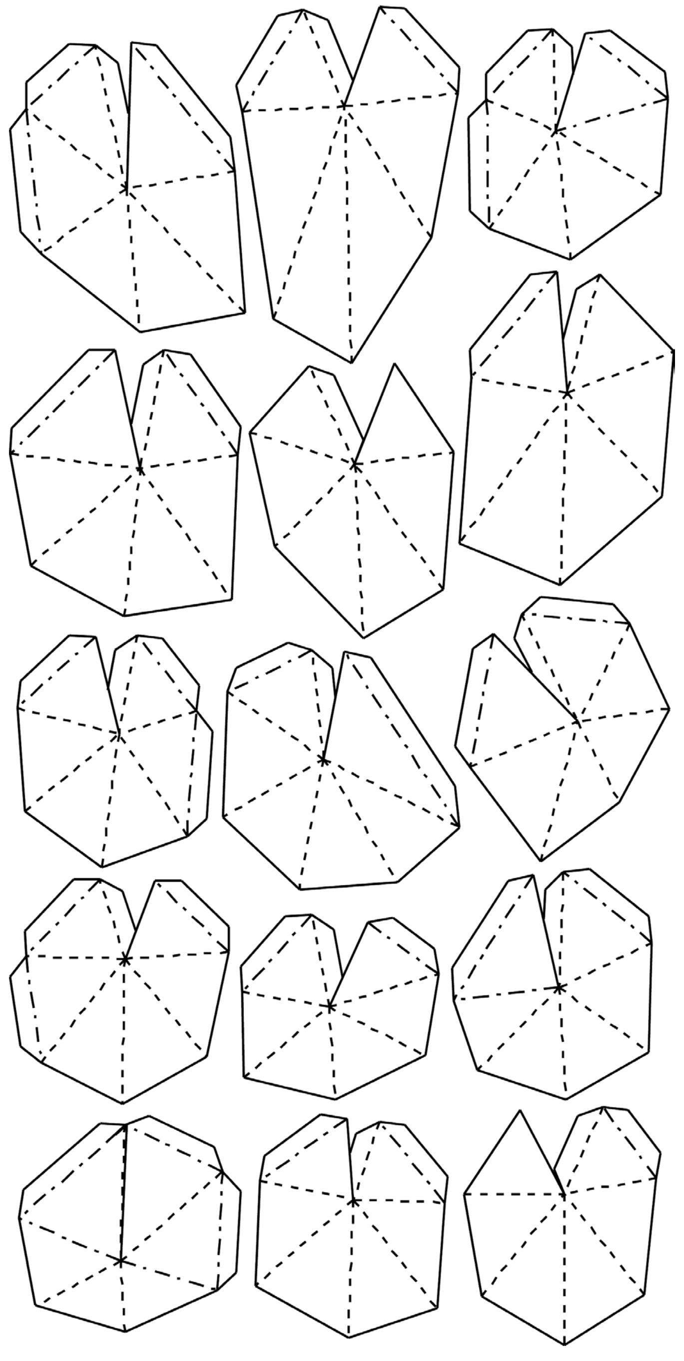
Inverting Folds

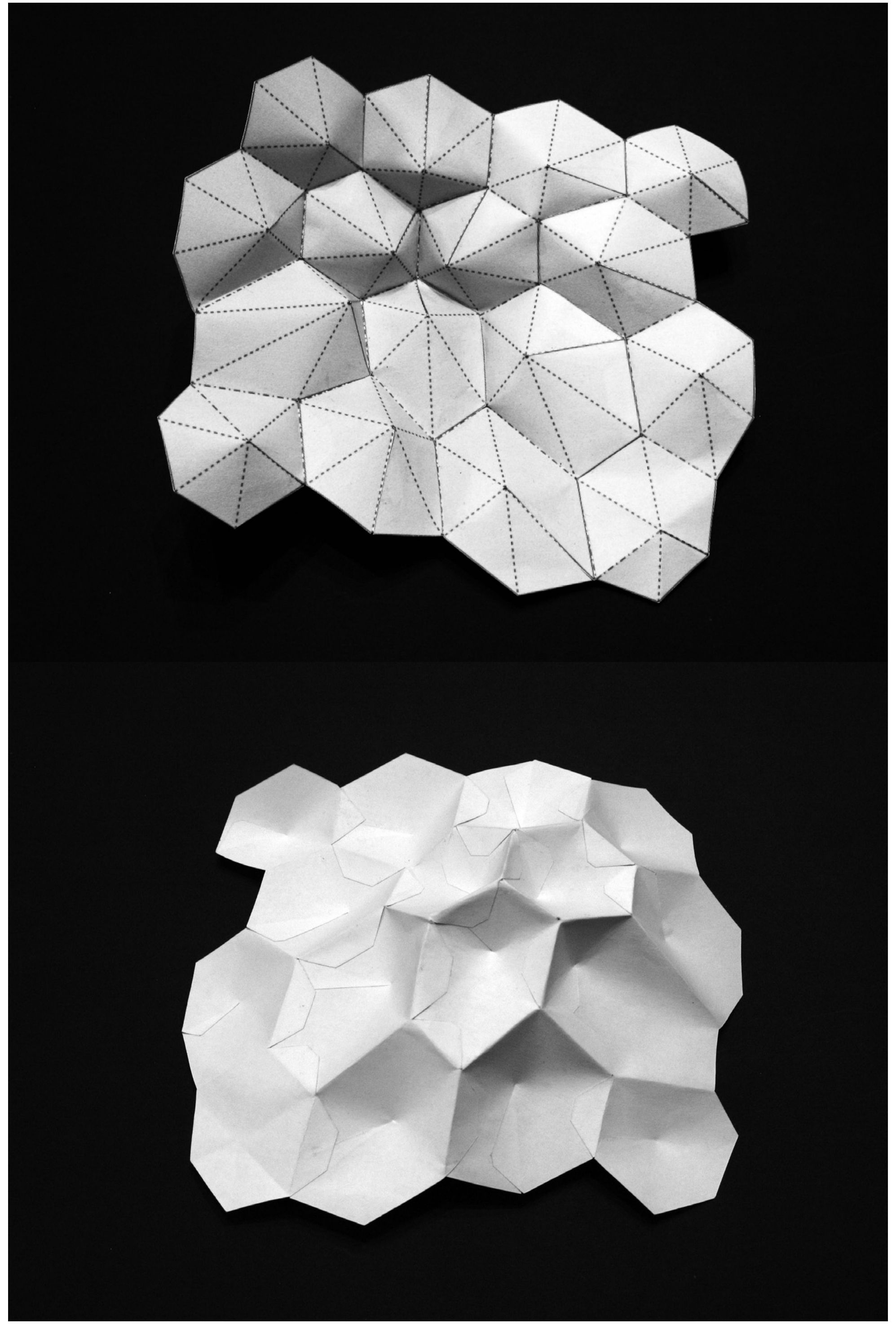
Digital Experiment 4.

This experiment investigated the notion of inverting a selection of folds as an investigation of surfaces that could deviate from their digital counterpart. Firstly a series of 6 sided components were arranged into a flat surface and a central point on the surface was pulled upwards. With the 'soft selection' push/pull feature turned on in Blender, it was possible to evenly manipulate the surface of the mesh with as little distortion of the pattern. The mountainous form was then manually unfolded and nested together for cutting reassembly.

Each individual component was assembled so that it was the same as in the digital model. The divergence from the digital model was applied along the edges connecting each of the components together. The output is a form which could be interpreted as a mirror of the original surface. This means that all of the edges that were connecting the components together were at more acute angles then their digital counterparts. This resulted in a paper model that is significantly more stiff than anticipated. The additional strength may have occurred because there is no additional material on each of the tabs to account for the more acute angles of the model. The finding of this experiment could be applied at later stages as there is an advantage to reducing the tolerance allowed for each of the components to fit together. This would ultimately result in forms that may be more resilient than their digital counterparts.







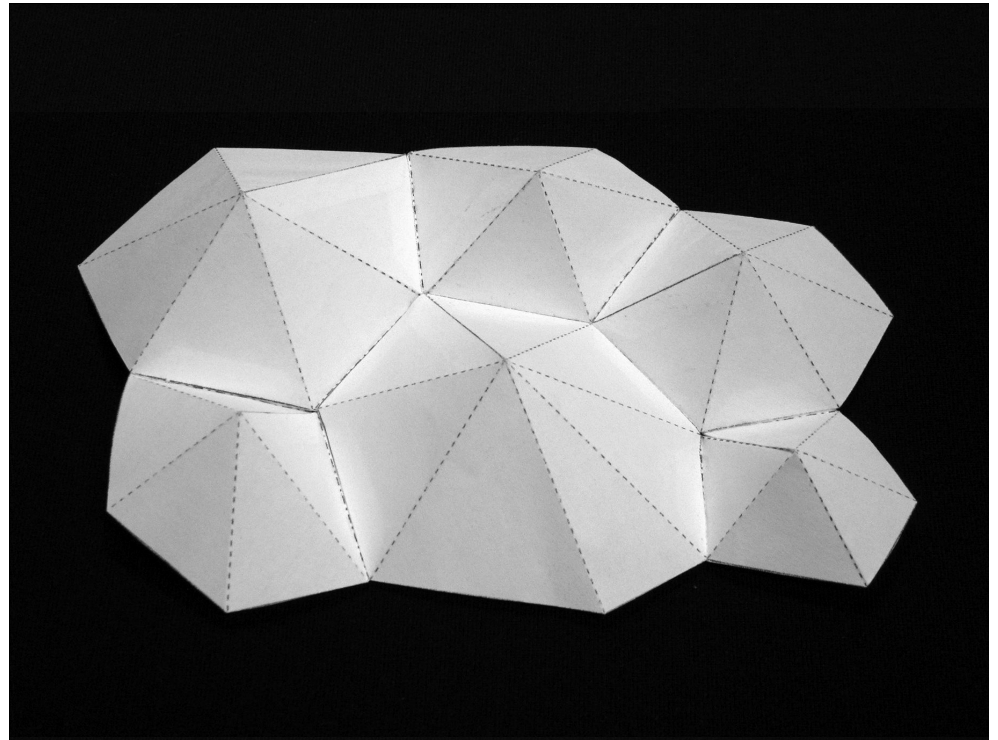
Flexibility

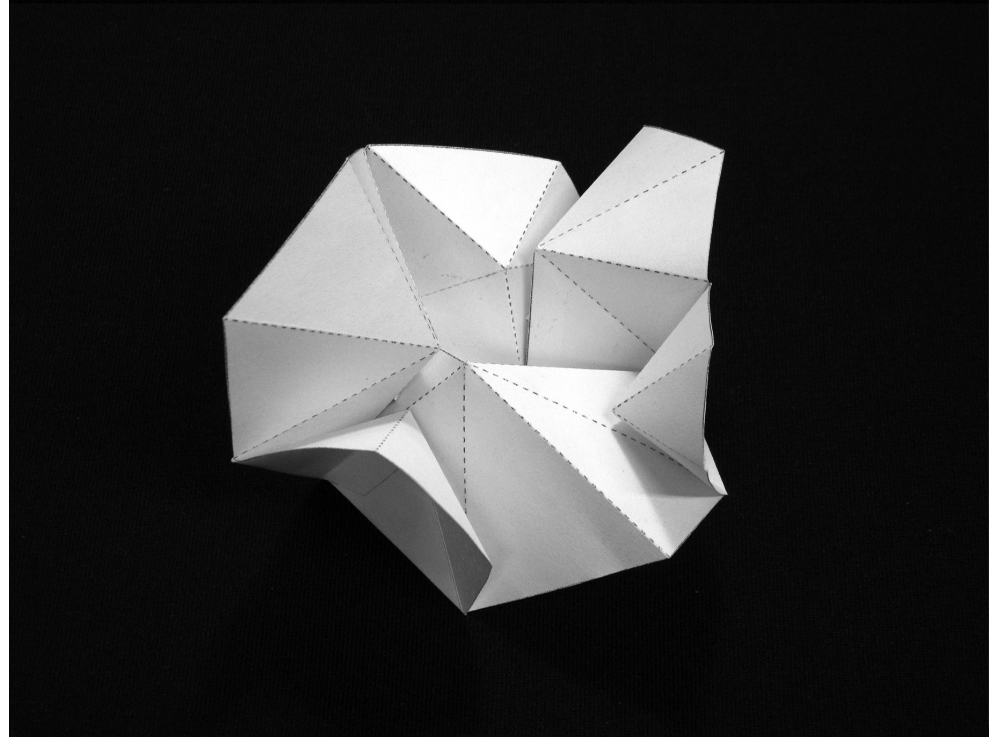
Digital Experiment 5.

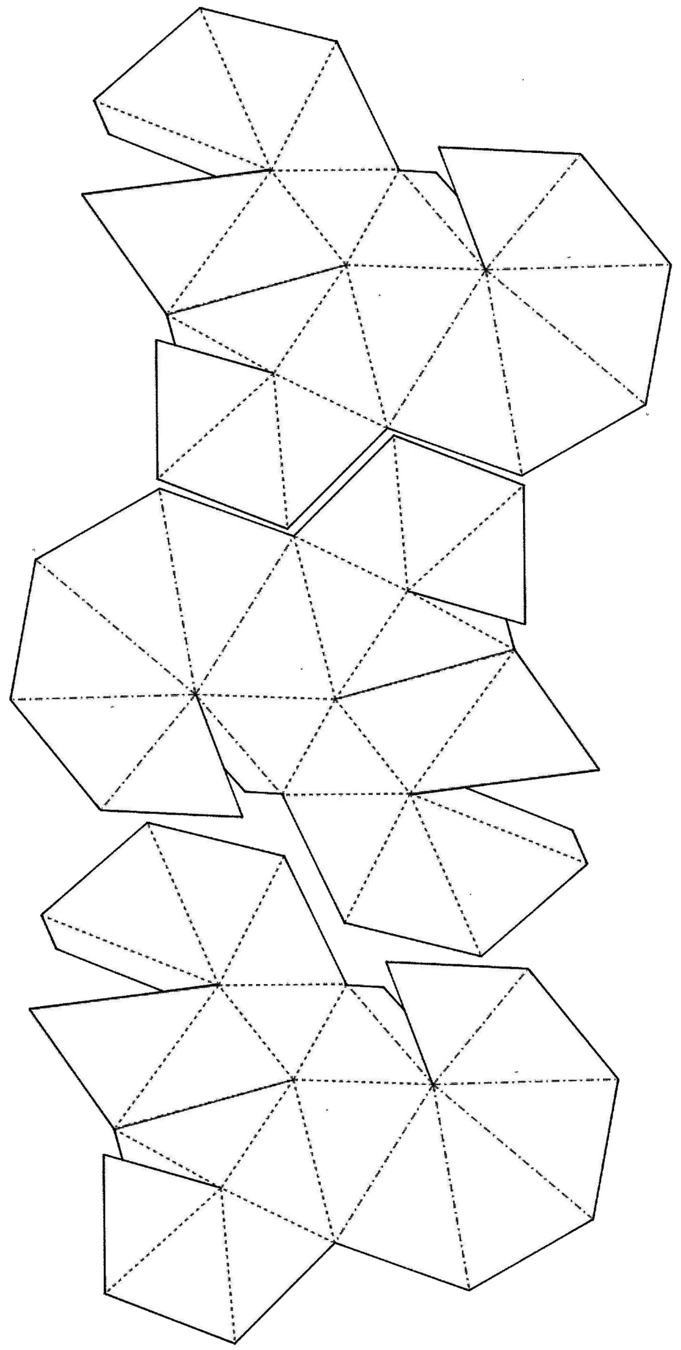
This experiment explored flexibility as natural result of the disconnect between 3D modelling software and the physical properties of folding. In the left image, a set of components were printed and assembled together without any inherent structural qualities. This meant the surface was free to fold in on itself as indicated in the bottom image.

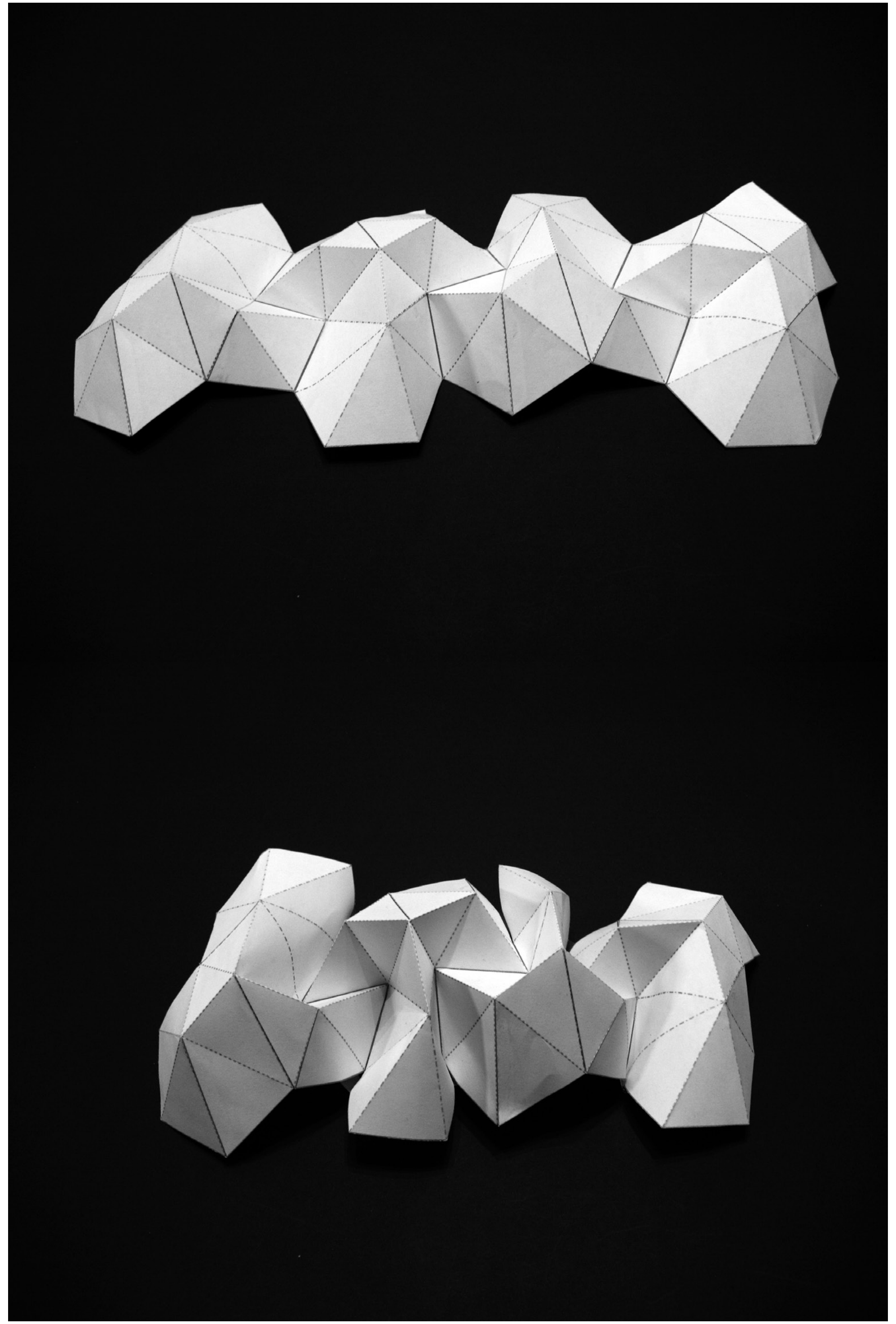
The images on the far right are a continuation of this experiment. The intention was to introduce some elements of rigidity while still focusing on flexibility. One set of 5, 6 and 7 sided components were connected together and subtly warped in the middle to introduce an asymmetry. The edges of the components are still all the same length so they will connect with two duplicates of themselves as indicated in the unfolded pattern. The output is a form that has an inherent symmetrical flexibility, in which its limits are defined by the asymmetry applied within the centre of the form.

This experiment is compelling and would be interesting to develop further. The possibility of introducing structural geometries that incorporate flexibility through folding was one of the initial goals of this research. However this relies on physical folding to be fully addressed within 3D modelling software, and at the time of this research, such software was not yet available, as Blender does not allow for real-time folding manipulations. The opportunity to delve further into this area and develop flexible yet structural geometries, forms and spaces will be very exciting once 3D modelling software incorporates visualisations of physical folding.







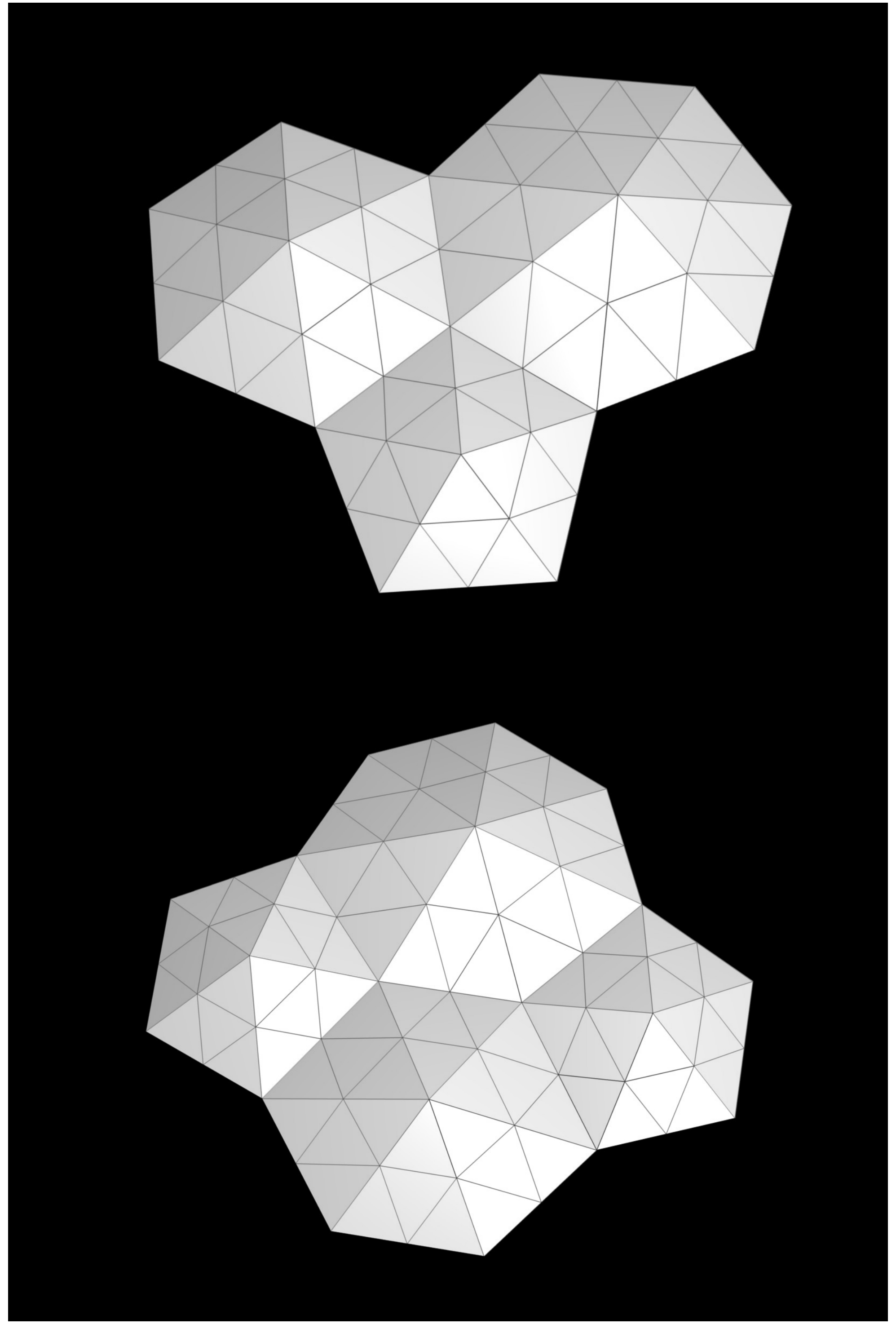


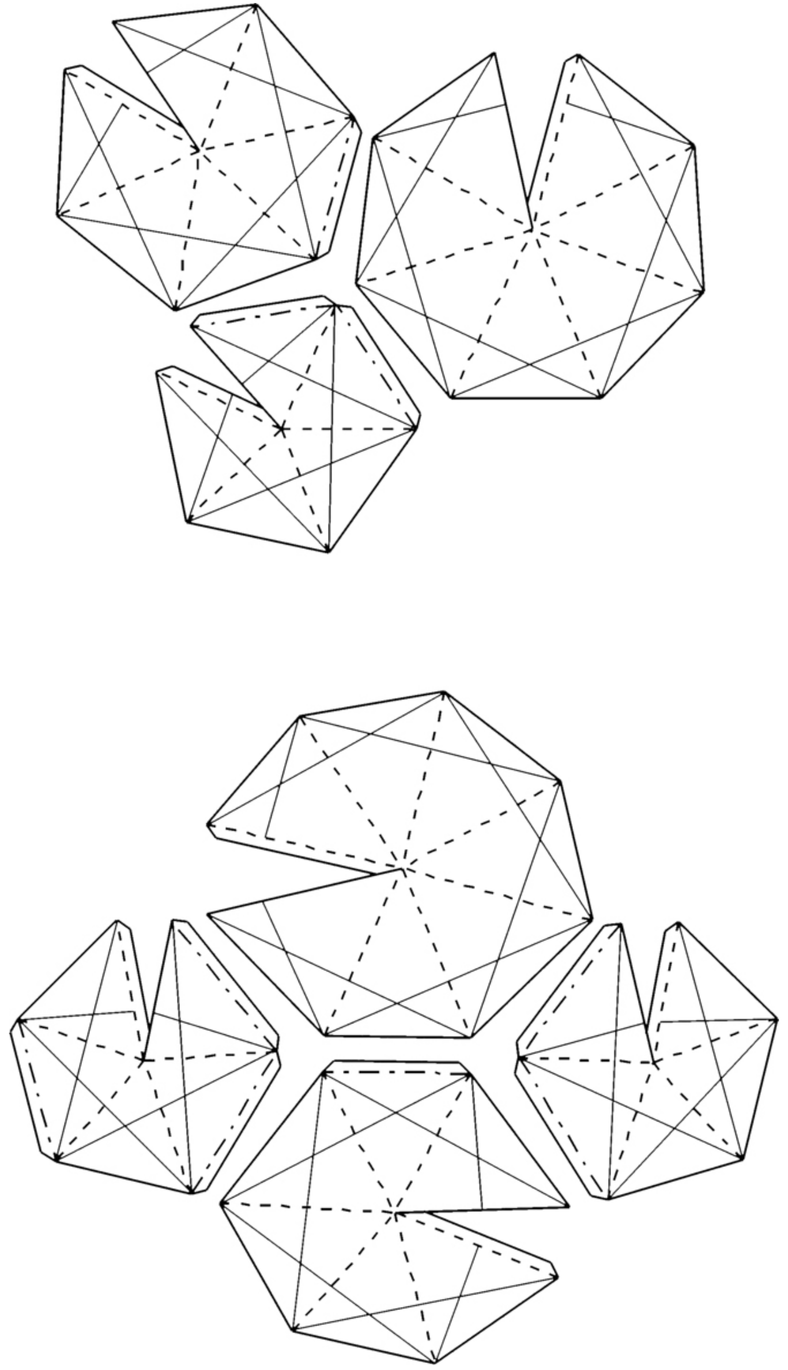
The 'After-fold'

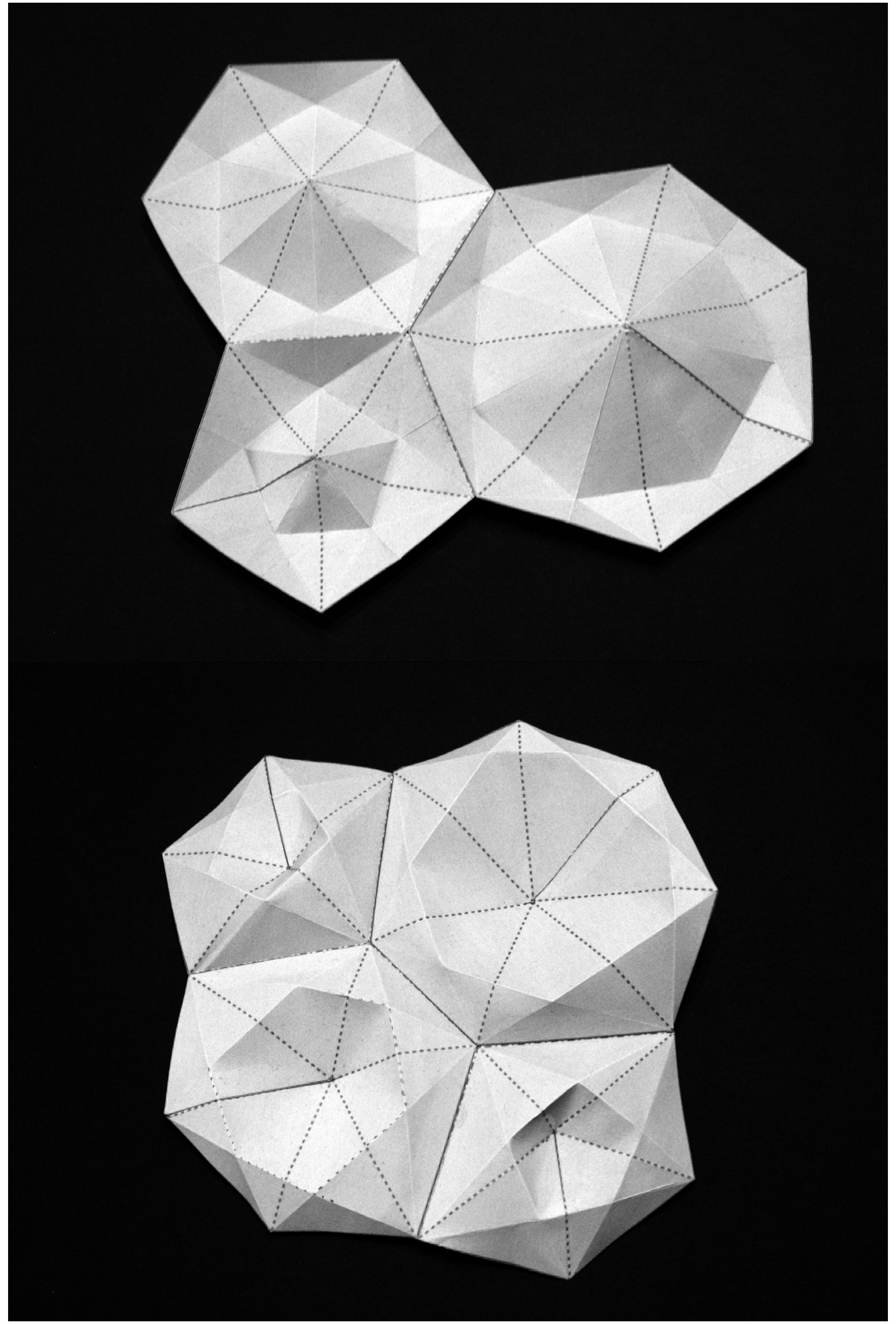
Digital Experiment 6.

This experiment illustrates one method of adding folds to a digital pattern after it has been cut and assembled. First, two sets of 5, 6 and 7 sided components were aligned and edges merged. The top set was unaltered, and the bottom set was warped. The mesh on the surface indicates the subdivision of the surface in Blender and how additional fold lines could be added. As a comparison, and similar to the methods developed within the physical folding stage, a mid-fold can be added to a component by folding a line from one point to another point on the adjacent edge. This is illustrated in the unfolded pattern on the right, and the folded model on the far right.

The benefit of adding folds to the surface after each of the components is unfolded is that surfaces can be subdivided without adding to or removing any additional material from the surface. The disadvantage is that it is difficult to describe these folds in Blender because it is a physical process that is dependent on strictly maintaining edge lengths. This is difficult to do without explicitly defining the measurements of each edge, and constantly maintaining them. The after-fold is a process that only adds unnecessary layers of complexity during the design development stages. Despite this, it is an interesting investigation of the interlinking of digital and physical folding processes.





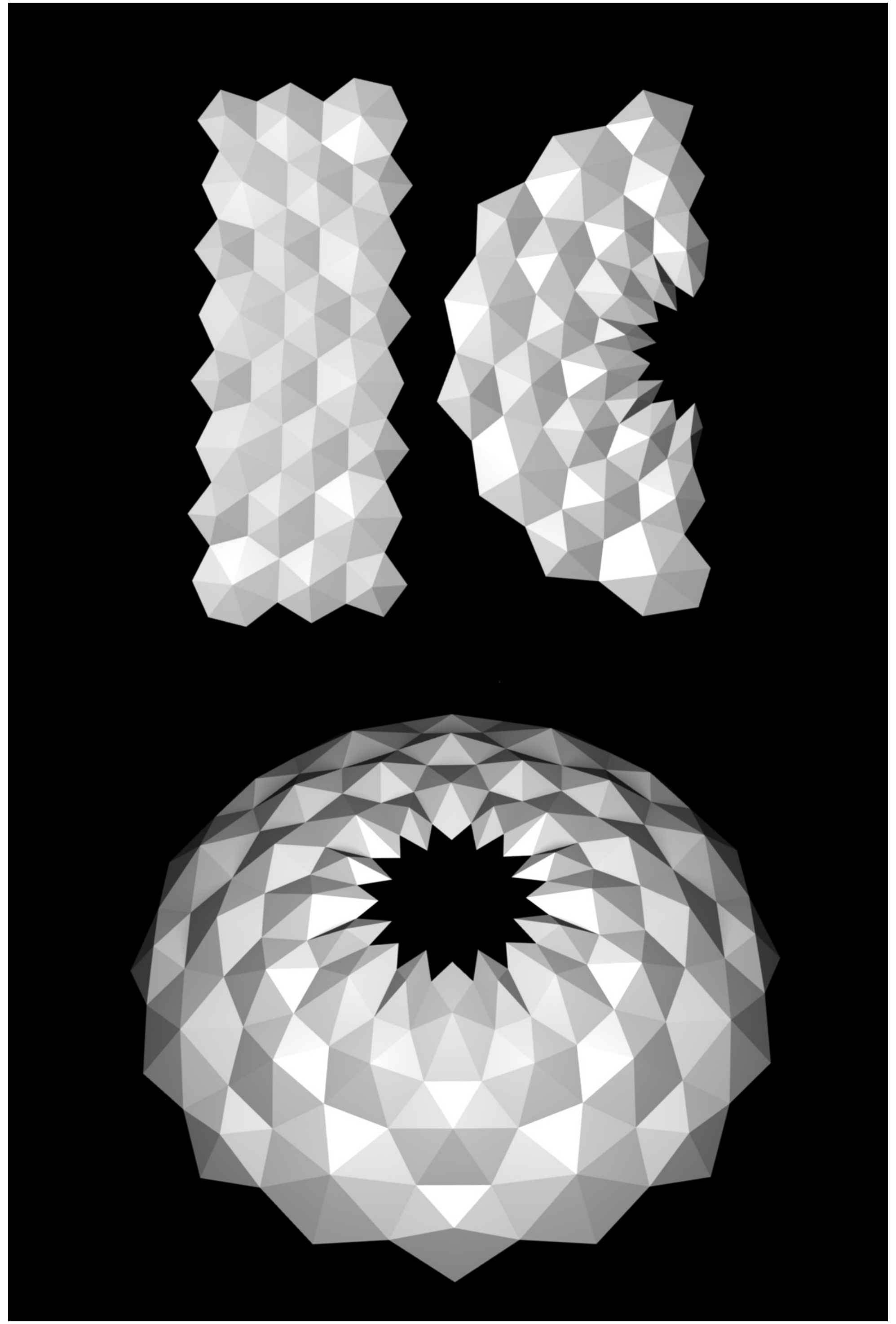


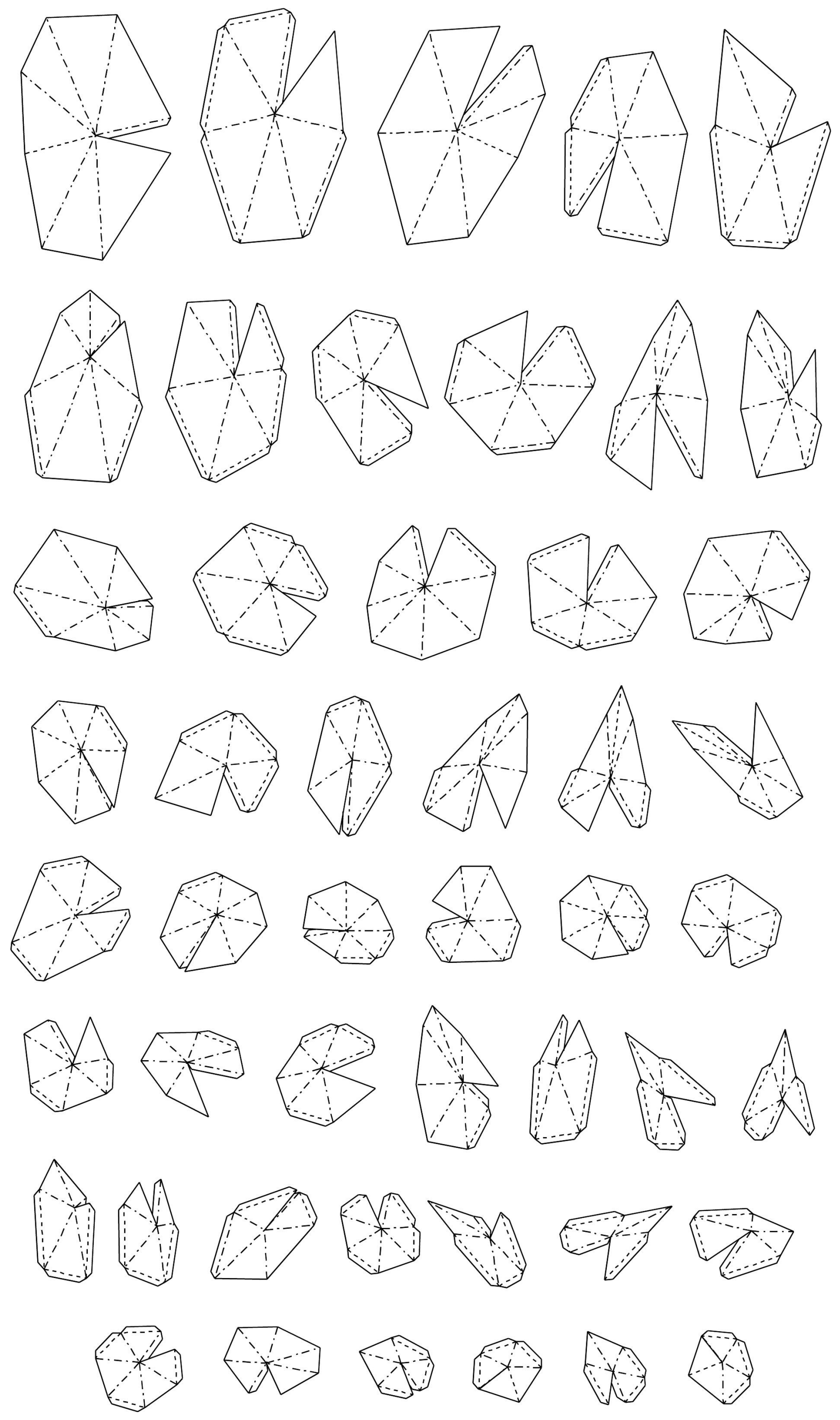
Surface Manipulations

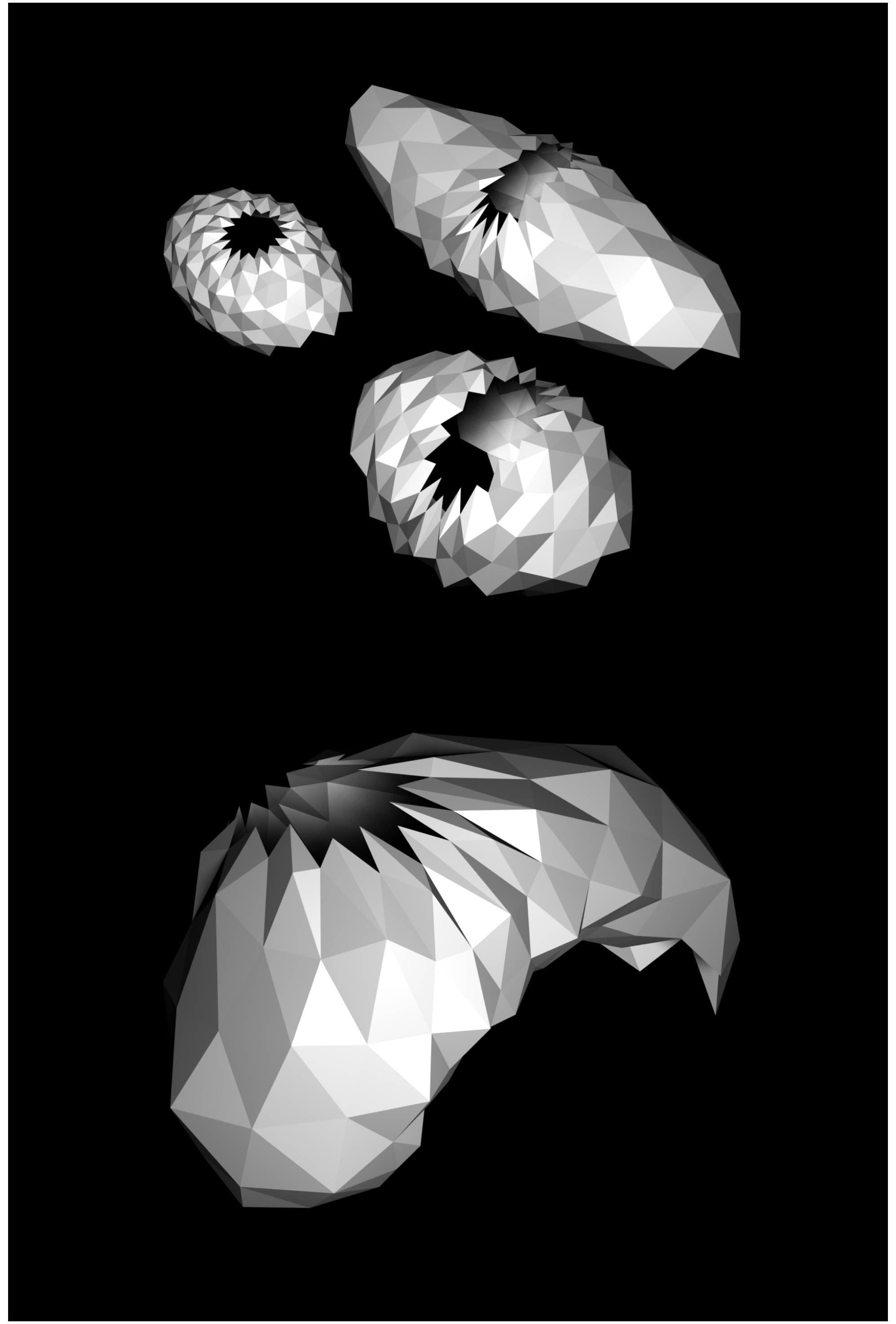
Digital Experiment 7.

In this experiment the surface manipulations were explored in Blender through a series of warps. The warp is a modelling command within Blender that allows for a mesh to be rotated around a point in space. The models on the left are a series of iterations creating a dome like surface from a single rectangular configuration of components. The effect of this is that the components in the centre become smaller and crowded together, while the components on the outside are larger and more distorted. This range of different component sizes is illustrated with the unfolding of the mesh indicated on the right.

The image on the far right is a series of further manipulations of the domed mesh. The use of the warp in combination with a Blender's soft selection is an ideal method of manipulating the surface of an object because the designer has a great deal of control over the typology of the surface. The main finding of this experiment is in the understanding of the extent to which a surface can be modified before a surface loses its readability. The result is a set of components that vary to such a degree that a great deal of time is spent assembling components for very little surface curvature. Therefore it is pointless to make a set of components that are so small that they are arduous to assemble, introduce more seams, and ultimately reduce the structural integrity of the surface. A greater balance is needed between the extents at which surface geometries are manipulated to create form in relation to the ease at which they may be unfolded into their resulting flat components.







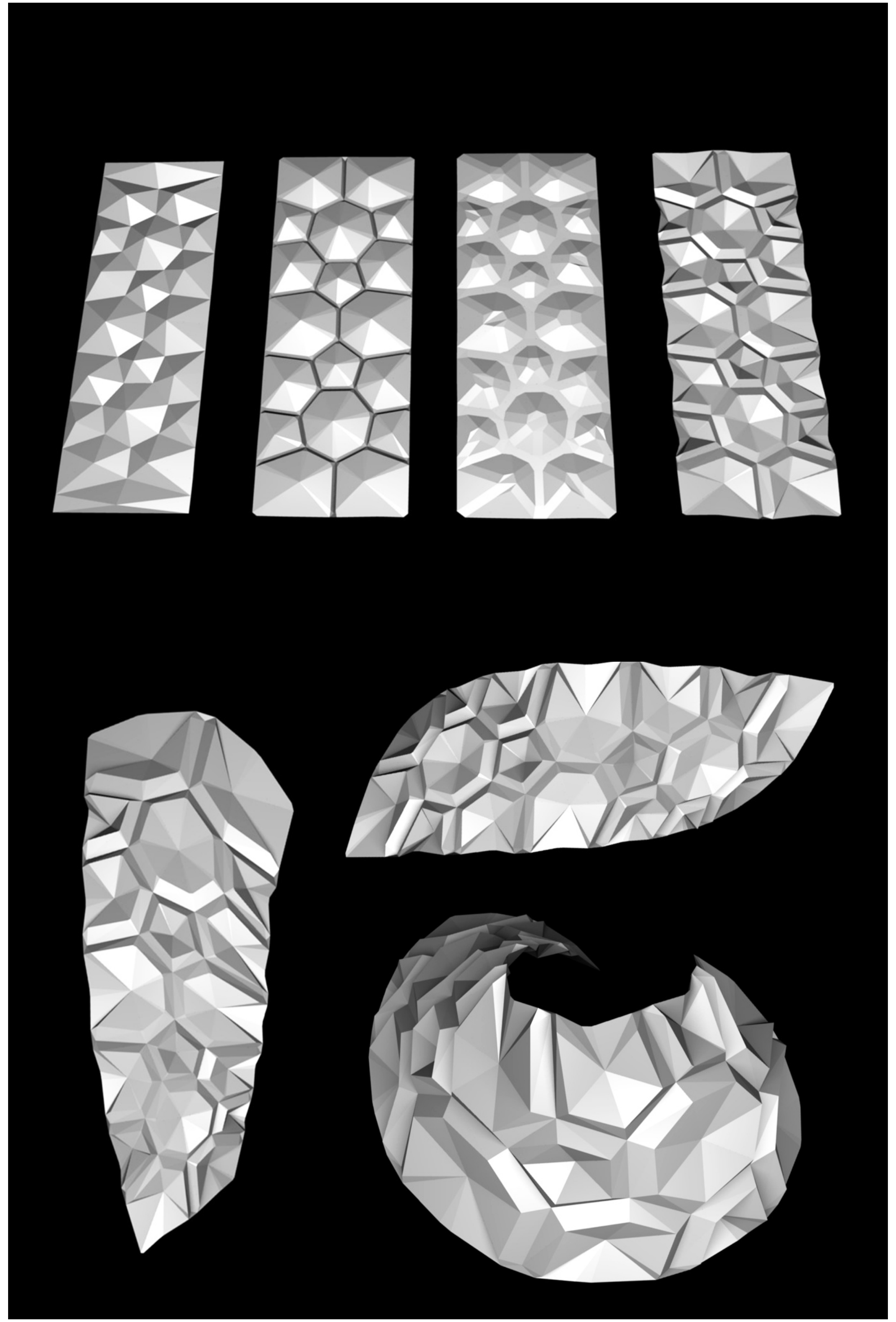
Digital Sheet Materials

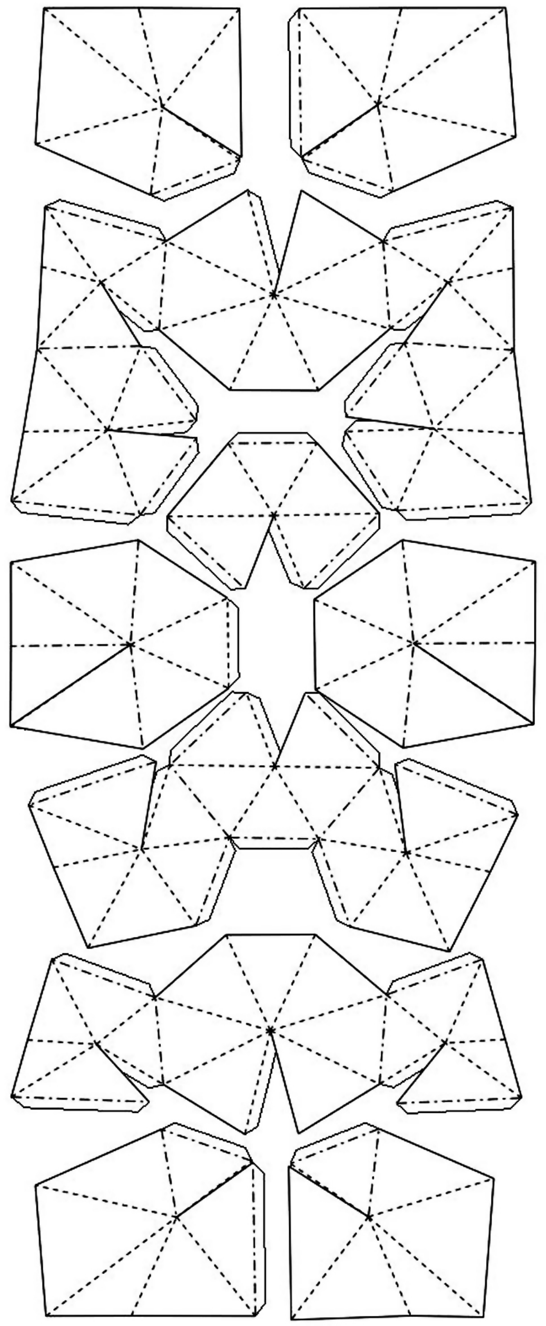
Digital Experiment 8.

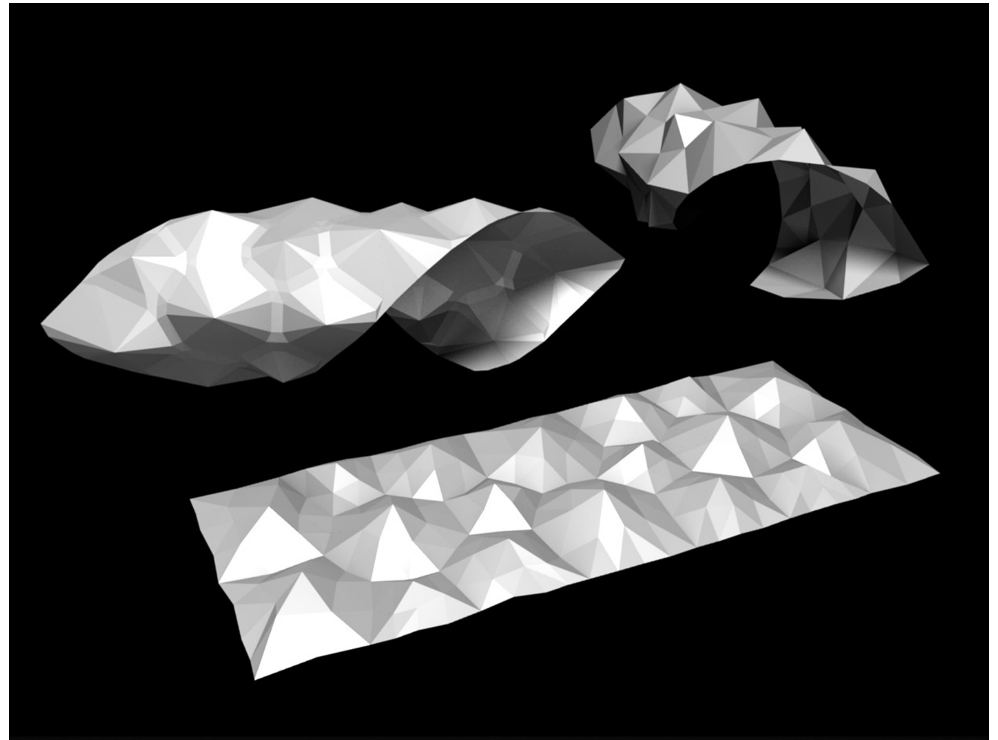
In this experiment a series of 5, 6 and 7 sided components were aligned and positioned into the shape of a rectangular sheet of digital material. A variety of modifications were applied to the surface of the sheet as an exploration of the form of each surface. The use of the warp tool in Blender was a continuation of the previous experiment, but with an emphasis on maintaining surface integrity. Additional modifiers were explored including stretches, bends, tapers and twists. The warp however is still by far the most effective way in which to make subtle modifications.

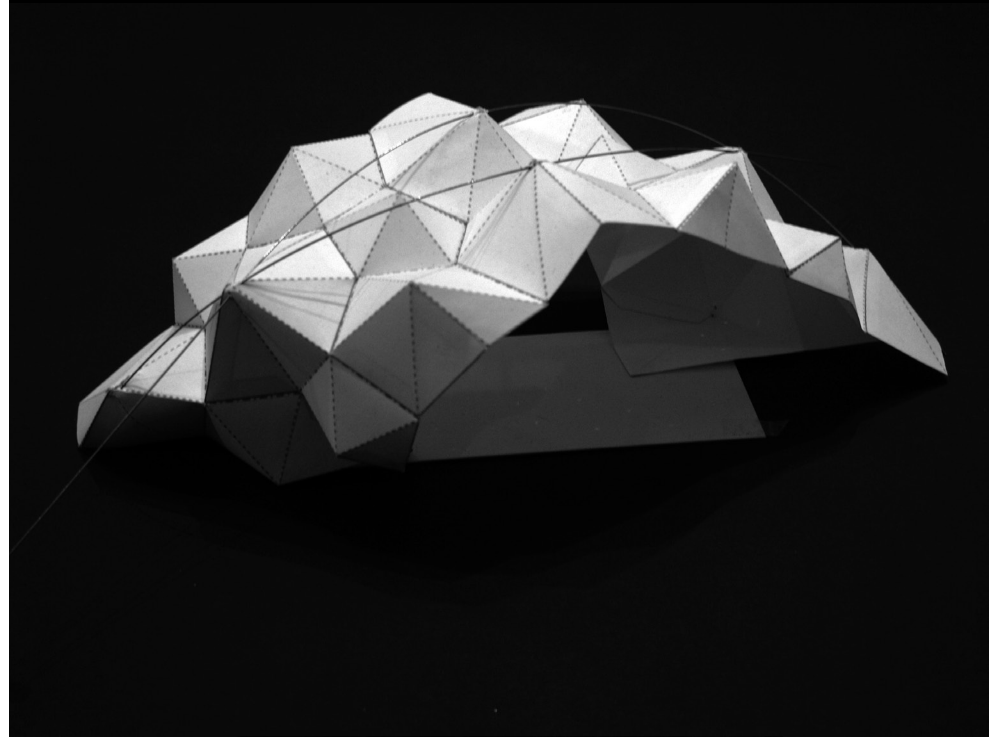
The unfolded pattern in this experiment is a simplified mesh of the helical warp on the far right, yet it appears that it has not been warped at all. The distortion of the pattern is minimal because the warp has been used in a similar way to twisting a sheet of paper. The physical reconstruction of the surface can both lay flat and twist into its digital form. This results in the surface having no inherent structure of its own. Additional supports were introduced in order to maintain structural integrity, otherwise the surface would not support itself.

This experiment illustrates that the use of digital sheet materials is an interesting area for ongoing development because the reconstructed patterns will lay flat without structure. This will aid in the assembly of larger components and open up the physical surface to a number of reinterpretations not available within the digital medium.









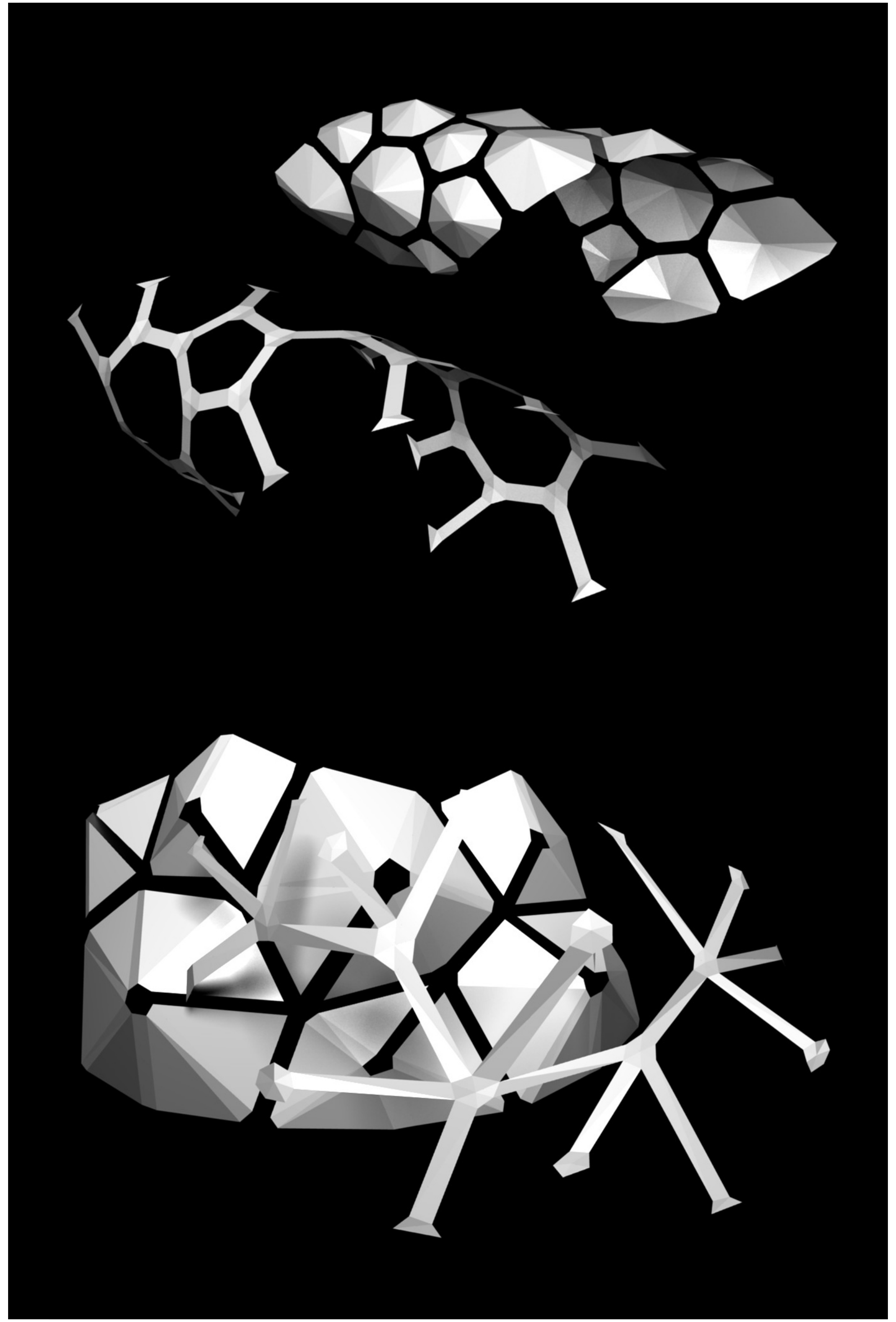
Bevelled Structure

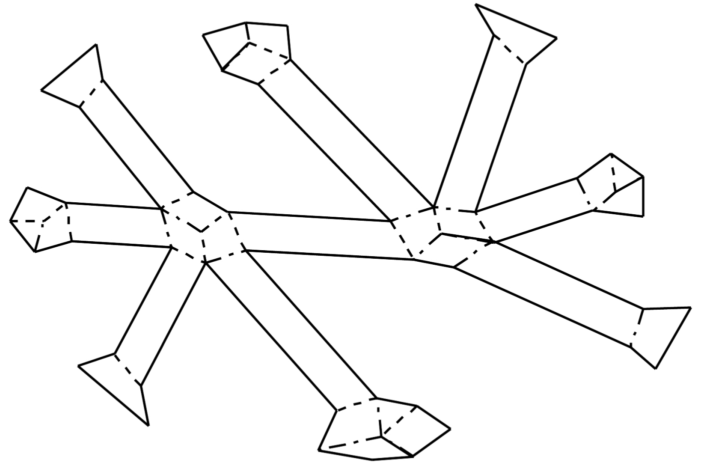
Digital Experiment 9.

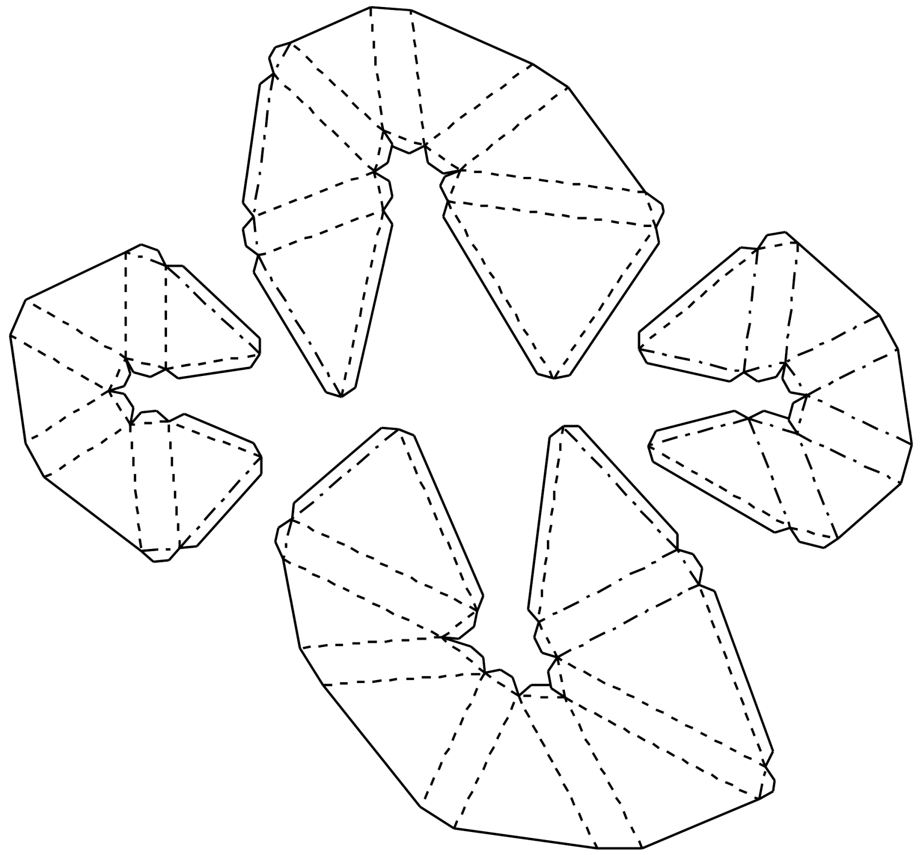
In this experiment the notion of a bevel structure was investigated as a means of adding structure to a surface. The weakest points on the surface were identified as the connection points between each of the components. Therefore there is a need to identify digital methods of developing structure around these connection points that can be translated to a physical medium.

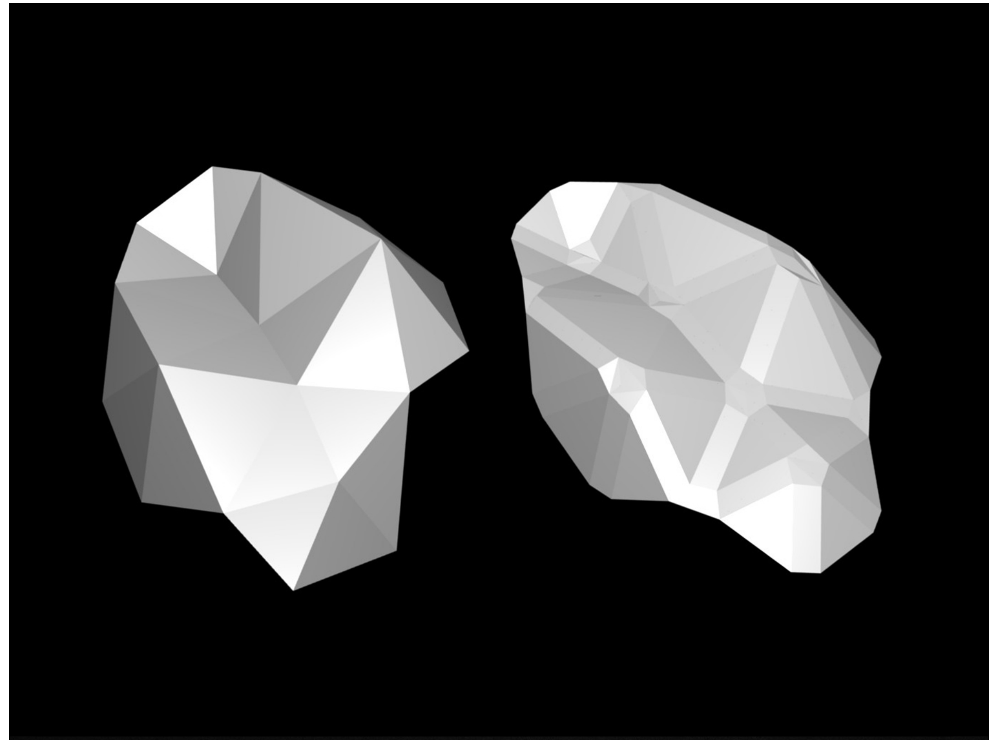
A bevel is used in Blender as a modifier to split the edge of two faces into a third face. Illustrated in the images on the left, the component surfaces were bevelled and separated to distinguish the fact that they may be made from different materials. For example, the thinner fragments could be made from a metal while the more expansive internal components could be made from plastic.

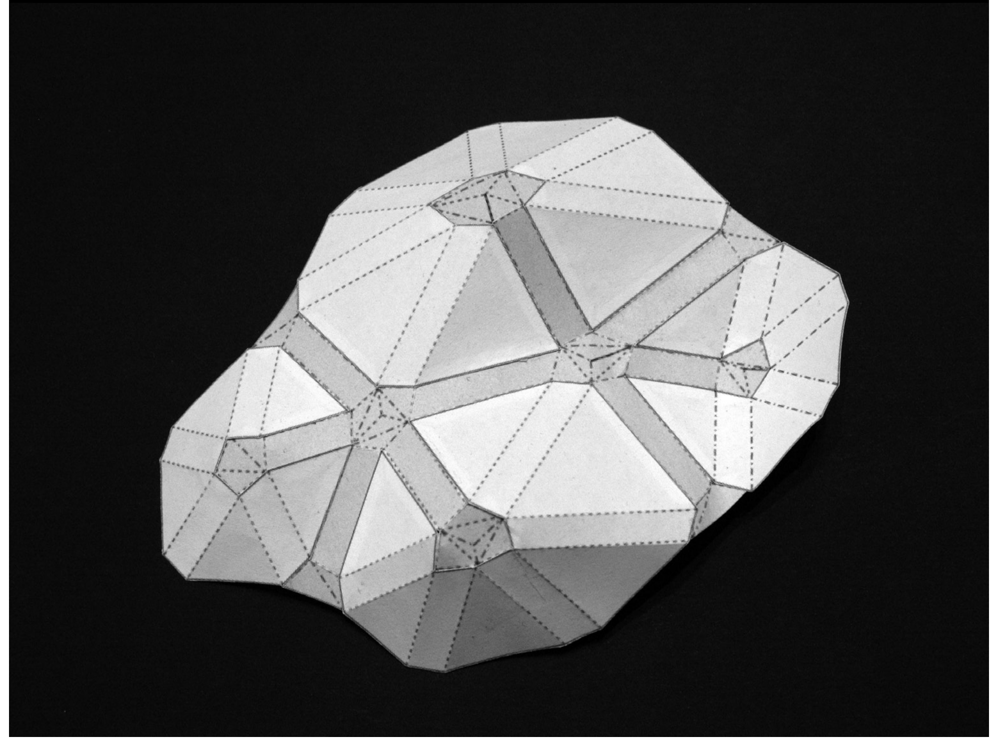
In the same way that the ribbing in a leaf provides structure, the form of two intersecting materials draw on this organic aesthetic. One of the potential disadvantages of this method however is that there are more folds on each of the plastic surface, meaning it is more flexible than a self contained component. The notion of bevelling a surface would be most beneficial when used as a technique in which to apply additional support to a surface and effectively lock the form into place. This method would be most applicable at a scale when stronger materials are necessary and there is a need to reduce the amount of material used. This would segregate the surface materials into both structure and skin.









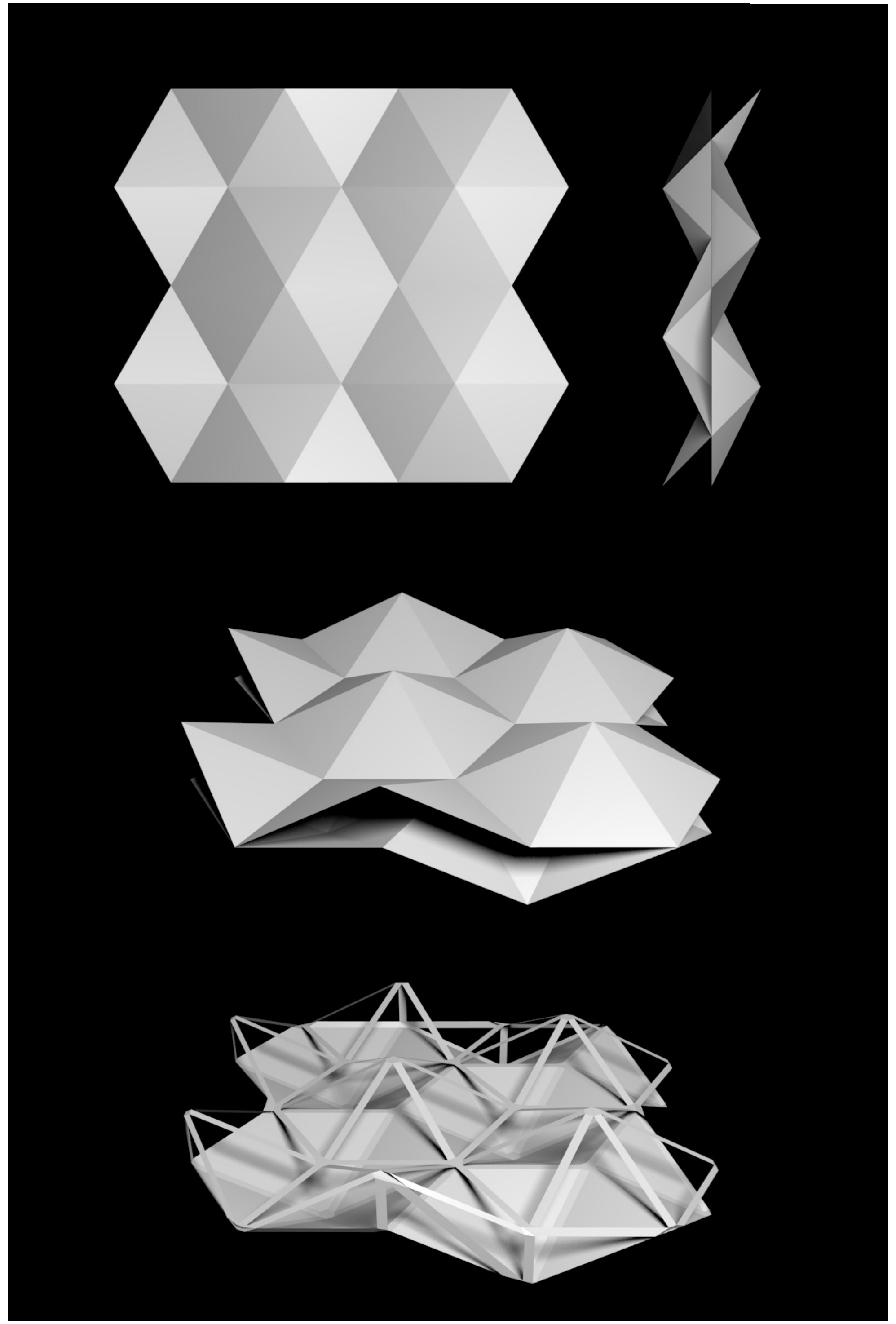


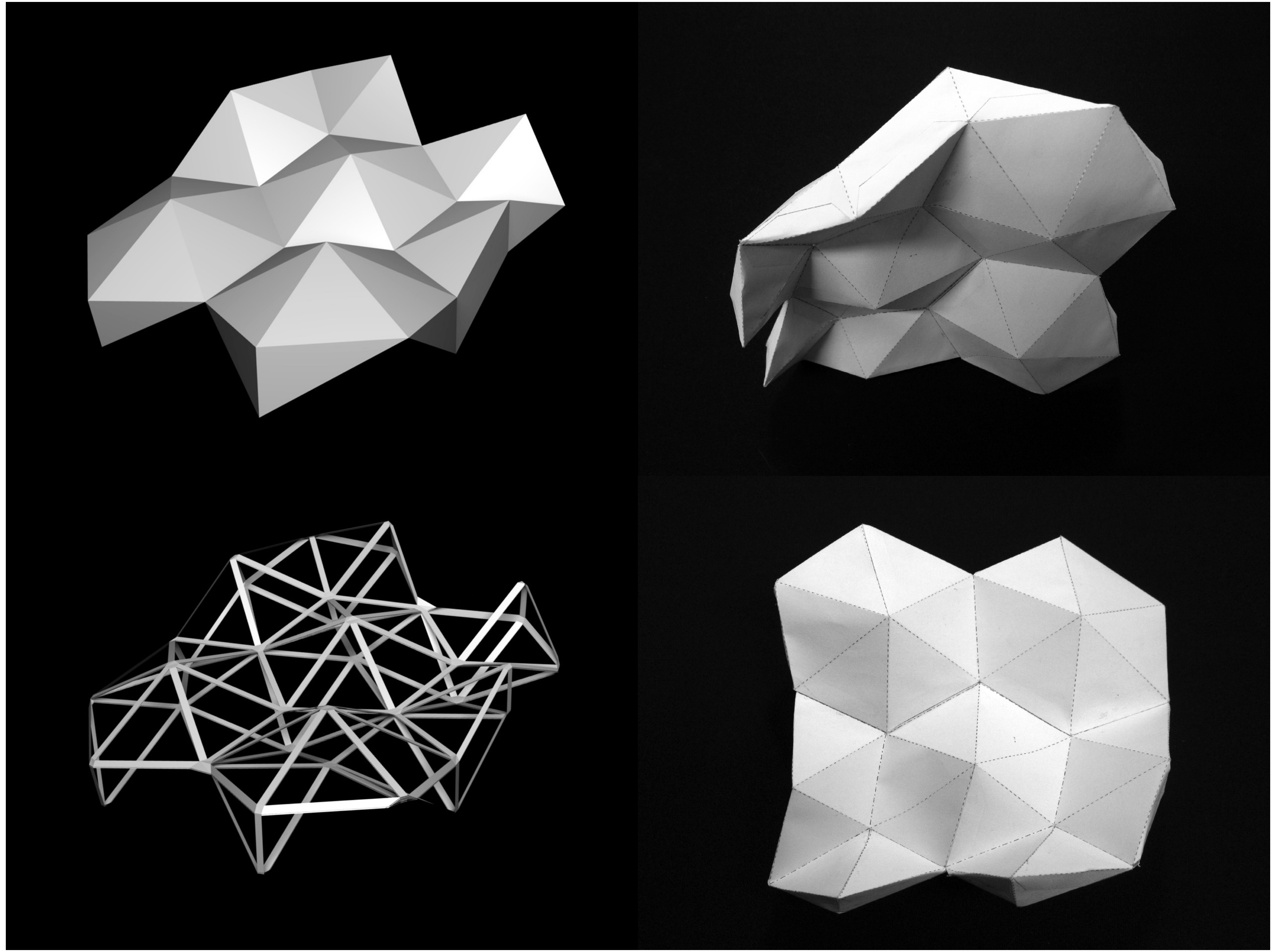
Hexagonal Truss

Digital Experiment 10.

In this experiment a hexagonal truss system was developed to introduce structure from the surface material itself. A series of hexagonal cones were connected together into a surface. Then the surface was duplicated and mirrored so that the cones point in the opposite direction. The points of each cone were then offset from each other so that only a few points on the surface touch each other. These are the structural folds of each surface. The experiment is called the 'hexagonal truss' because the faces have been bevelled and the interior surface removed to expose only the edges of the faces and therefore the main structure of the surface.

In this example the triangulation of fold edges creates the surface structure. After the initial form of the object was developed, the surfaces were warped together with a soft selection modifier in Blender resulting in each of the truss triangulations maintaining its connection points. This method of creating surface structures can be expanded to create larger self supporting structures. The twin walled surface is an interesting method in which to develop self supporting surfaces and its interior spaces open opportunities for exploring volumes within the structure itself.



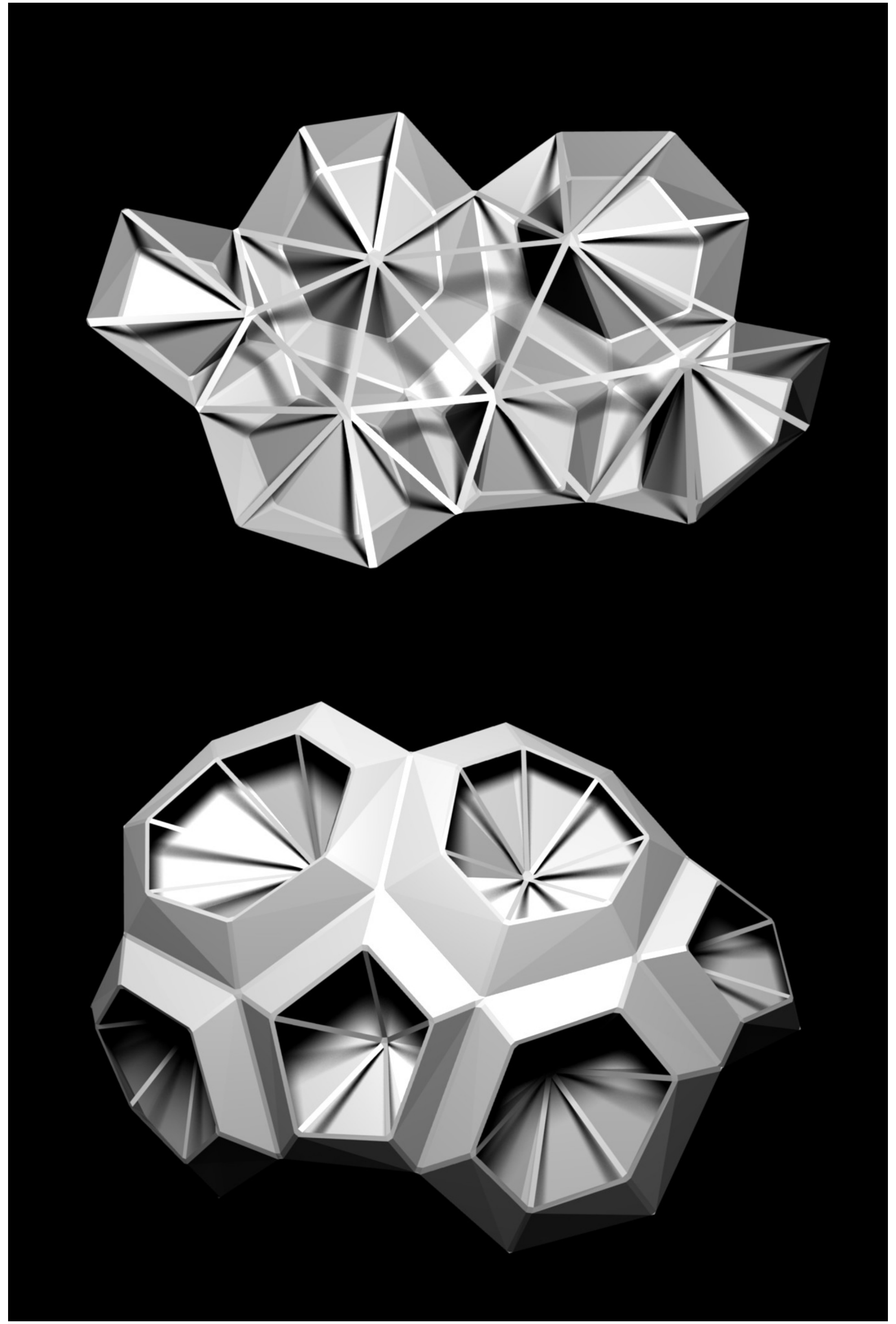


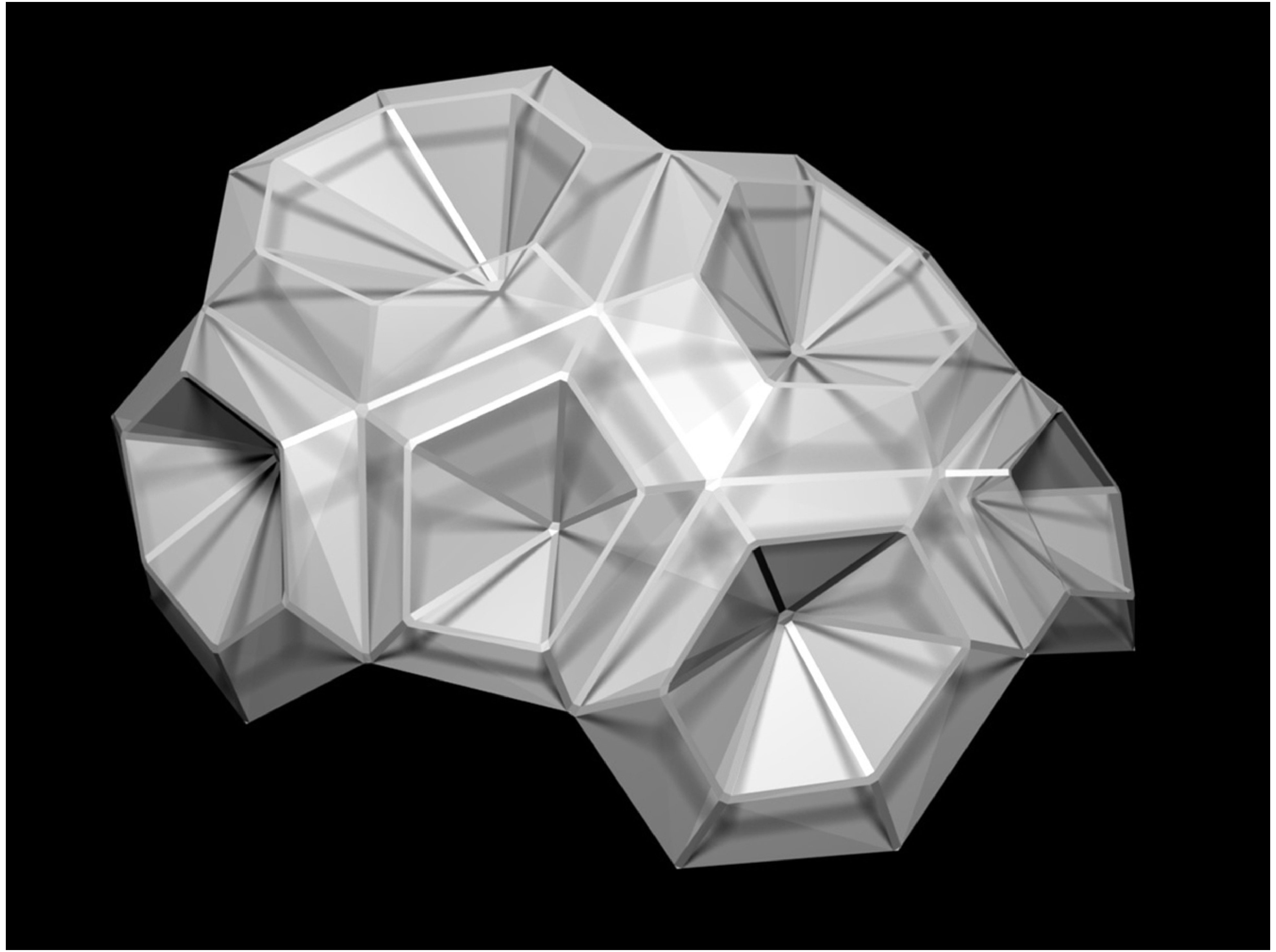
Twin-Wall Structure

Digital Experiment 11.

In this experiment the idea of using a twin-walled structure was developed to create rigidity for use with 5, 6 and 7 sided components. Each of the components was triangulated on their underside with a single face. This was in order to lock each of the components together into a fixed position. This method of triangulation means that a wide variety of surface curvatures can be explored with arrays of 5, 6 and 7 sided components before each of the points are connected. The difference between this experiment and the previous experiment is that there is a clear definition between underside and topside. This means that is is possible to distinguish each of these surfaces as different in both form and in materiality.

In the image on the far right, the top surface has been rendered to have a transparent surface. This is to aid in the visualisation of interior space that is created with each of the cones and to indicate the volume of space within the structure. The twin-walled surfaces present the opportunity to use the interior space as functional area within the structure.





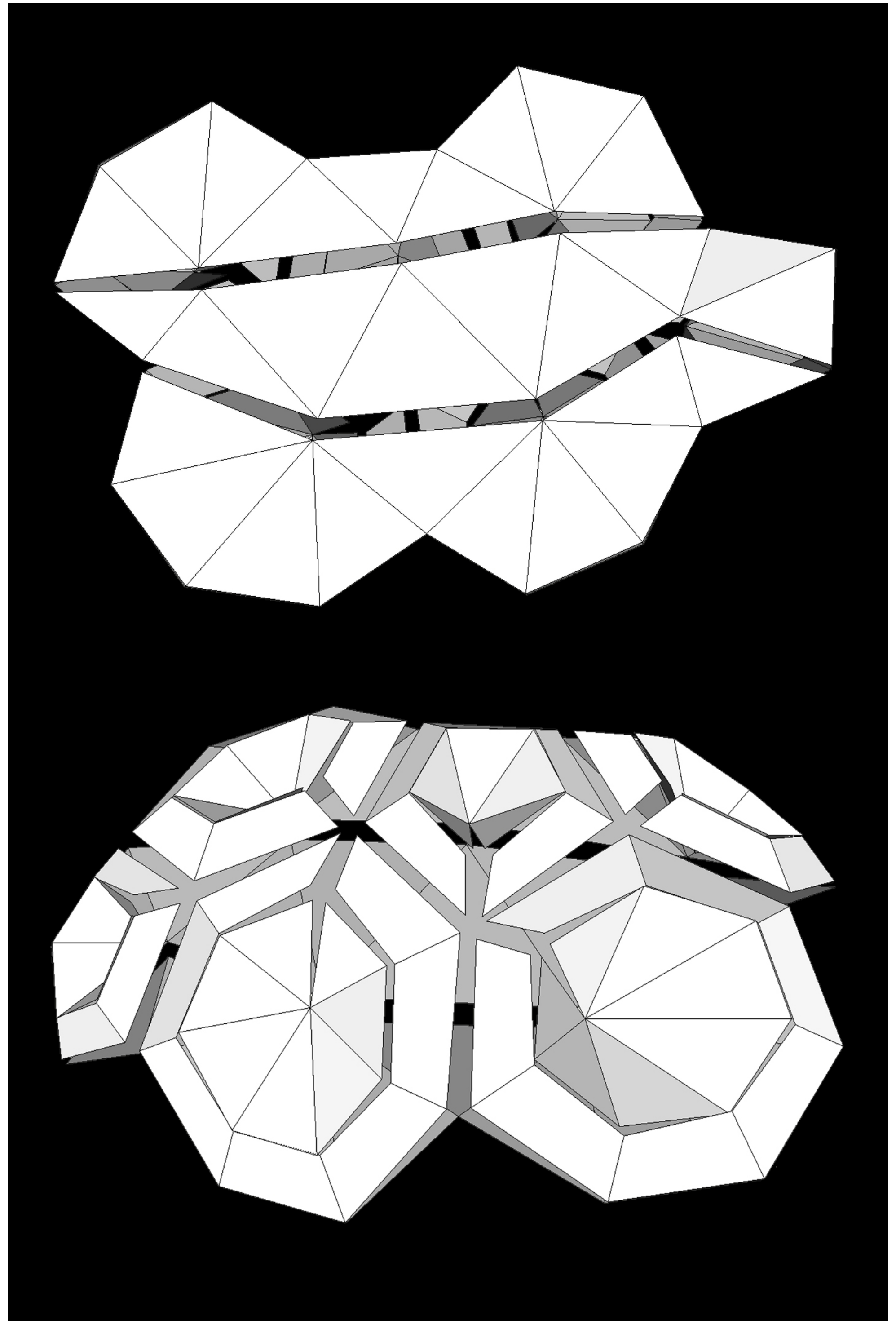
Marking Seams

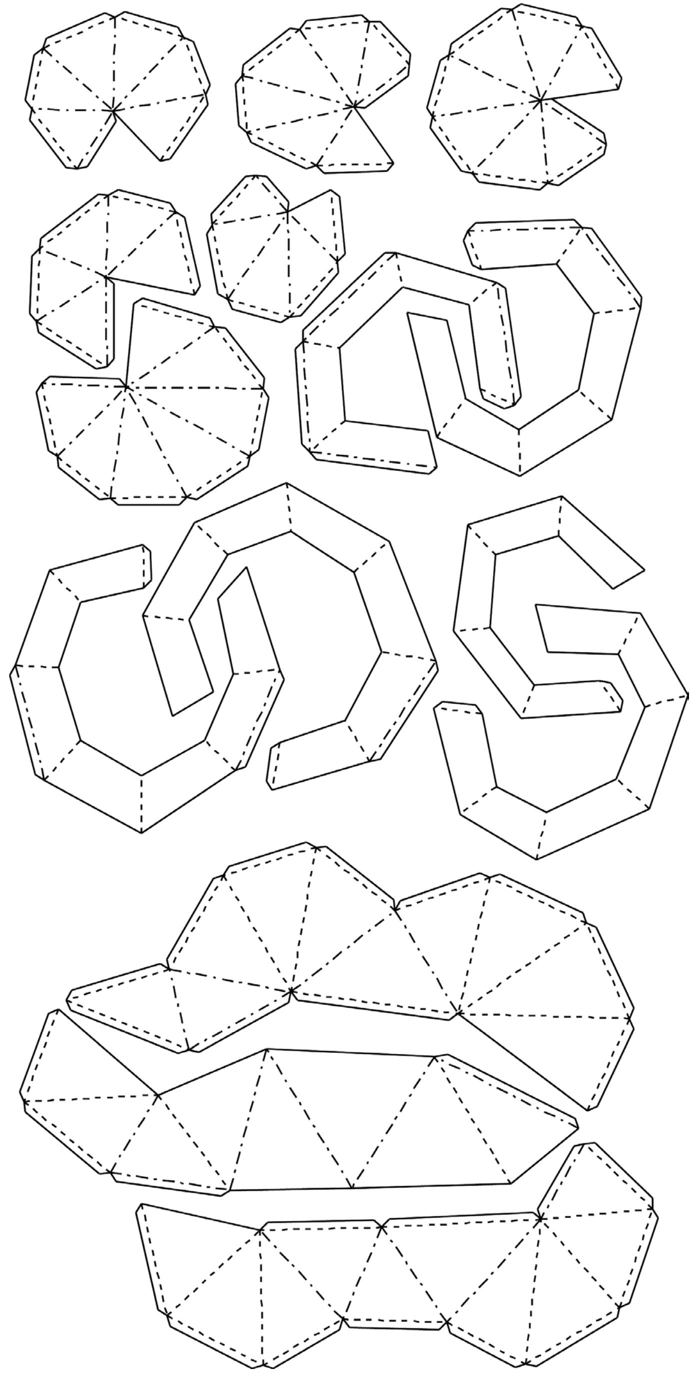
Digital Experiment 12.

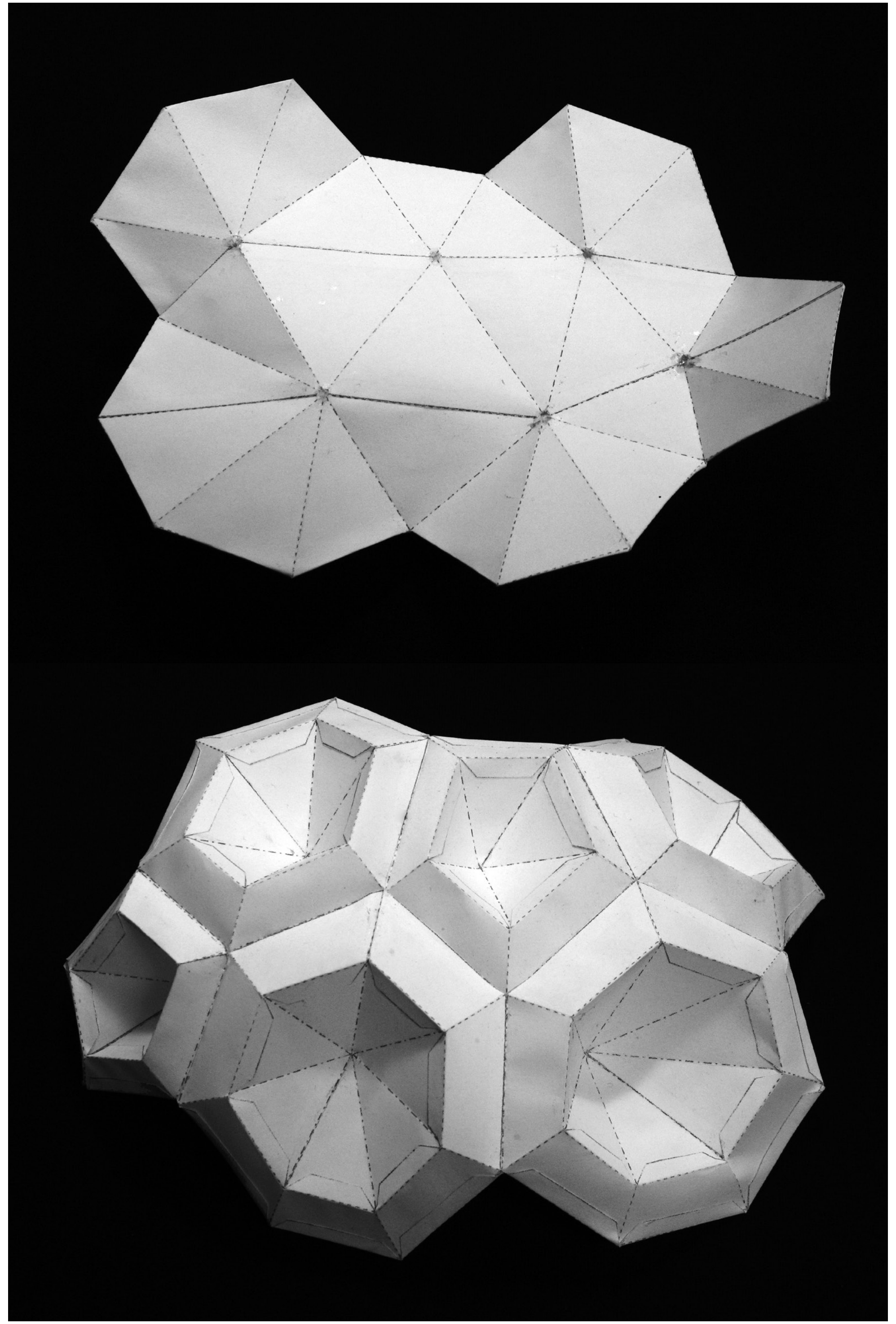
In this experiment the model from the previous experiment was developed to assess a method in which seams may be marked for separation in Pepakura. There are three major areas the twin walled pattern can be separated for reassembly. These are the two areas of the inner and outer faces of each individual component and the back face.

The goal of this experiment was to create a surface pattern separation and a assembly language that helps to clearly identify seams marked for unfolding. This language often comes from the form itself and has applications beyond the scope of this experiment. Different approaches were taken to determine which edges of the cone were separated. For example if the cone of the component is separated on its longest edge, the shape will be more spread apart. If it is separated on its shortest edge the cone will be more compact. The most appropriate strategy was to manually configure the edge separations in relation to how the shapes would be nested on the sheet for cutting. This is often the most time consuming aspect of unfolding for assembly as it is vital for reducing material wastage.

The most important factor that must be taken into account is to ensure that there are no overlaps of the surface. However it takes little effort to return to the virtual model and adjust the surface in order to achieve a greater consistency of material usage.







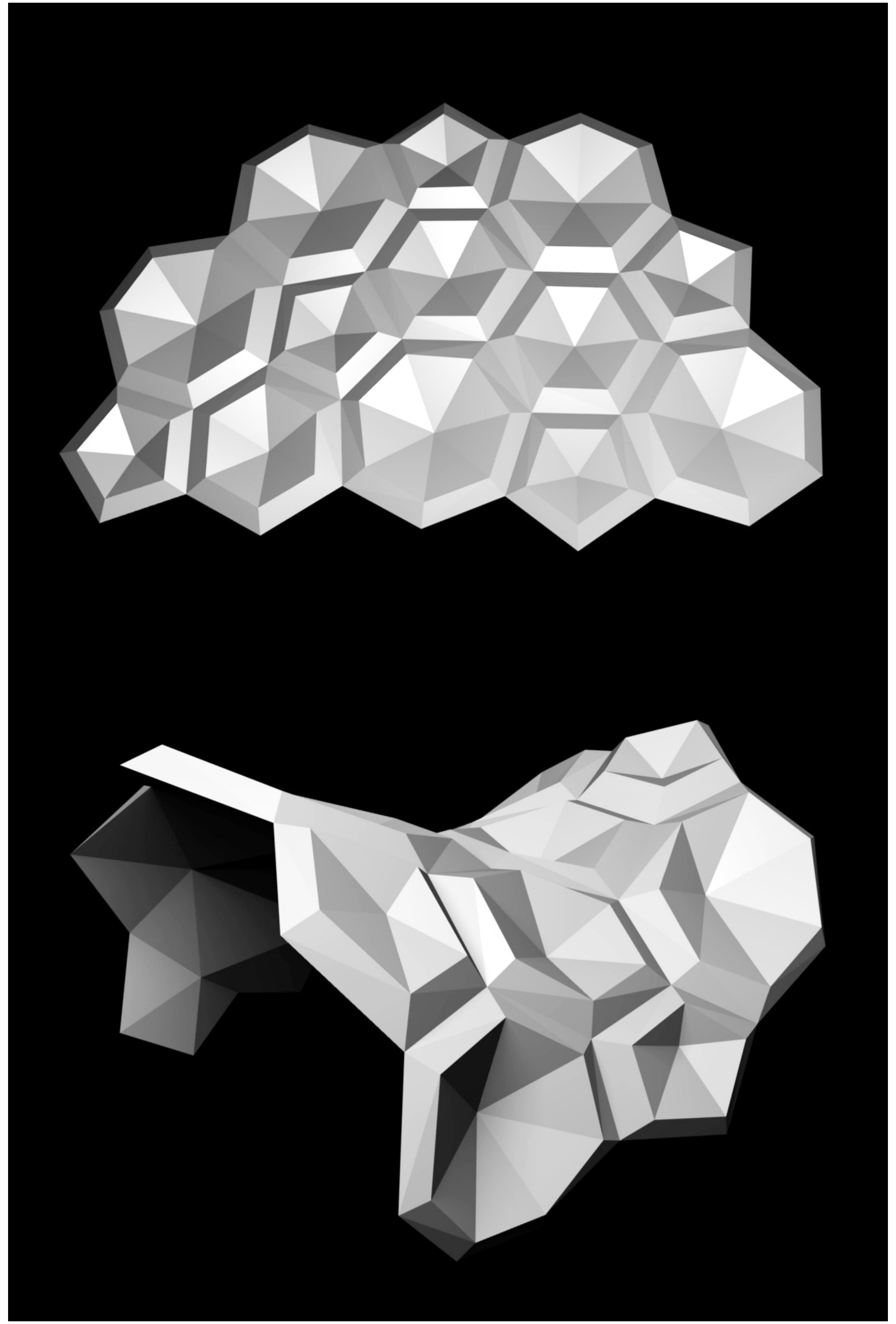
Surface and Space

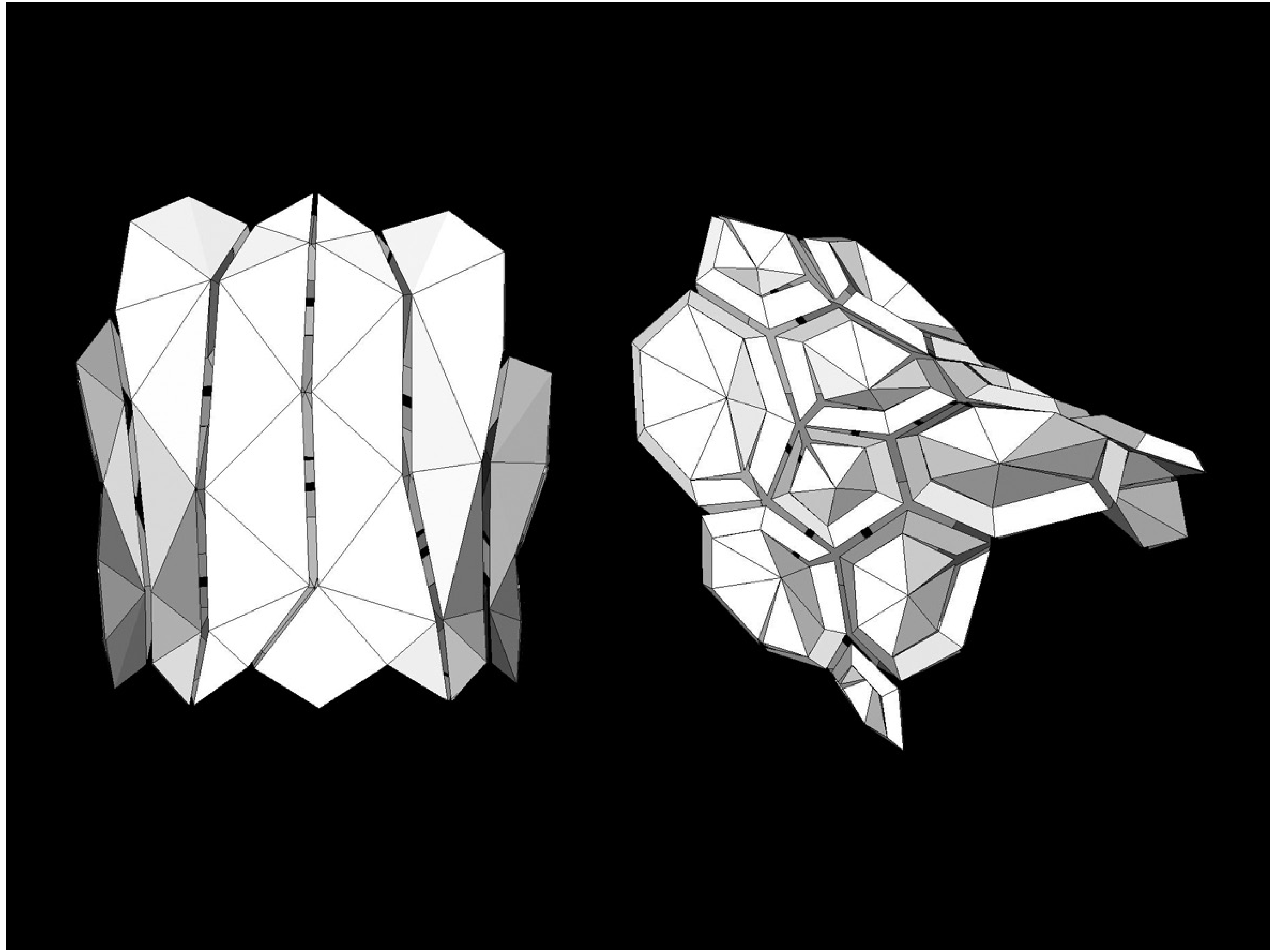
Digital Experiment 13.

This is the final model explored in the 'Digital Manipulations' stage of this research. This pattern was the major entry point into 3D stereoscopic environments. In this experiment a larger collection of components were pieced together, 13 in total. The combination of 5, 6 and 7 sided components were warped around its central point. It was then subtly warped again to form a wafer, or a leaf-like structure.

Although scale was not taken into account, the number of components and the maximum size of each would impact on the overall size of the structure. For example if this model were scaled to fit the maximum sheet size of 1.2 x 2.4 metres, the final structure would be approximately 3 metres in height. The notion of scale is investigated further in the next stage of this research: 'Immersive Environments'.

On the opposite page the seams were marked for separation in Pepakura. The issue of separation of components for reassembly is explored in greater detail in the following experiment.



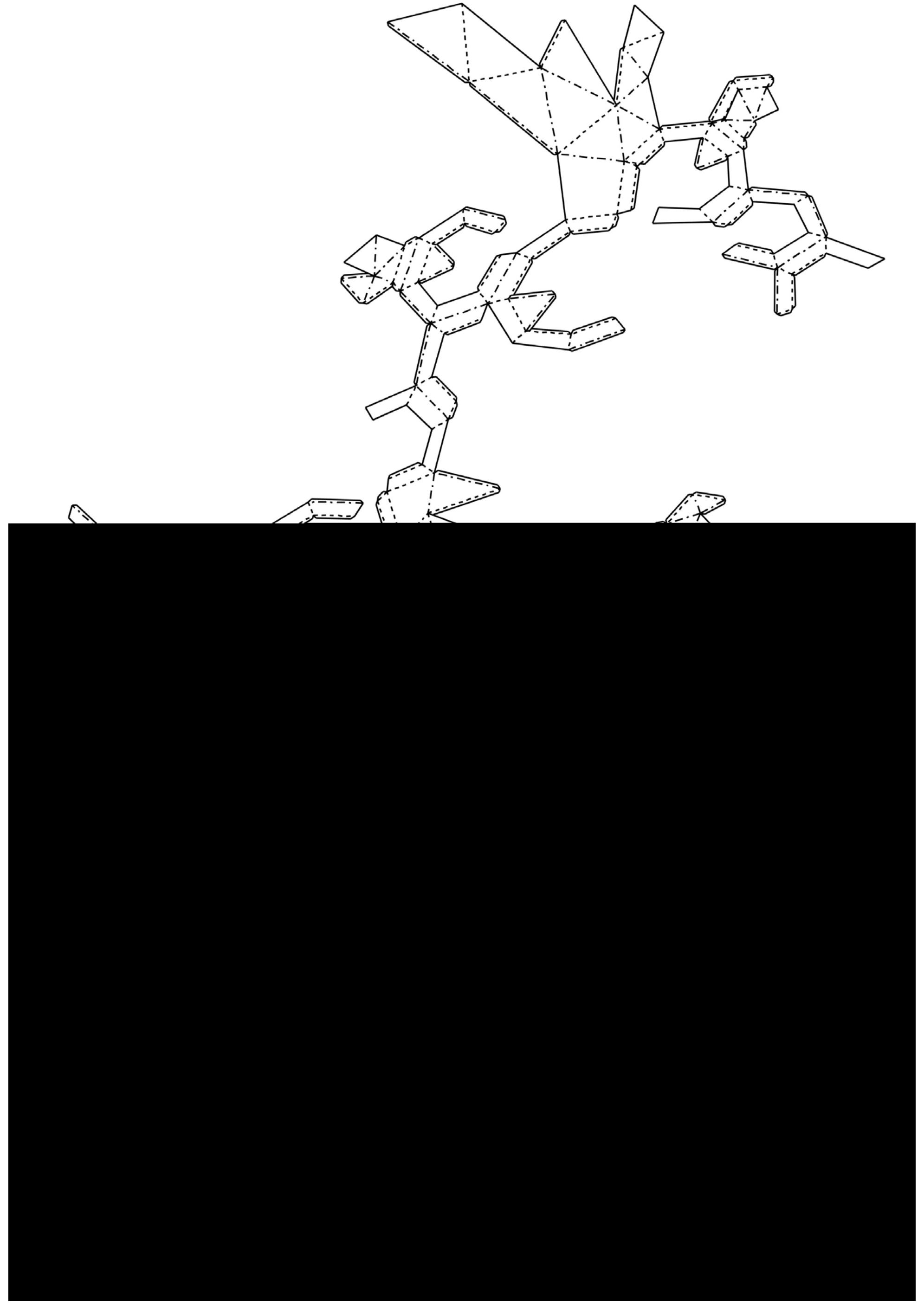


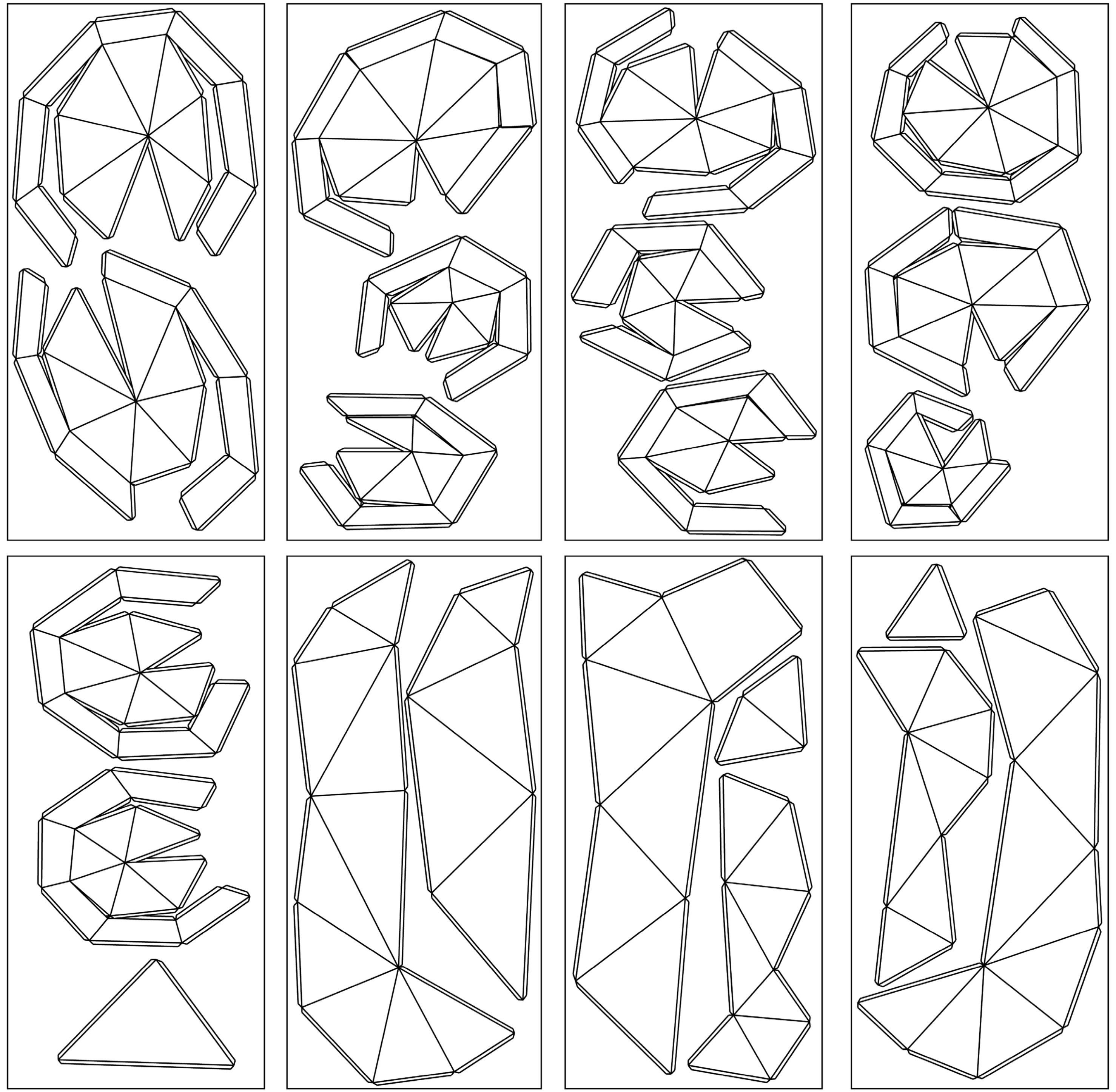
Pattern Layout

Digital Experiment 14.

In this experiment the form from the previous experiment was taken and unfolded for reassembly. The image on the left illustrates how the automatic unfolding within Pepakura does not create a pattern layout that minimises wastage. Nor does it aid in the understanding of how it may it be easily reassembled. Some of the edges were marked for separation and each of the component parts were reorganised to fit onto the scale of a 1.2m x 2.4m sheet material. Extensive manipulation of the layout of the separated parts was experimented with in order to reduce the amount of material wastage of each sheet. The patterns were composed in such a way to ensure that each of the 5, 6 and 7 sided components were not split apart.

After cutting and assembling this object in the next experiment, it was discovered that material thickness played an important role in the way in which the seams were marked for unfolding. It was found that leaving the interior part and the outer parts of the joined components created an inconsistency when all of the components were reassembled. For consistency between the folds of the assembled design, it was beneficial to separate the interior and exterior parts of each component.





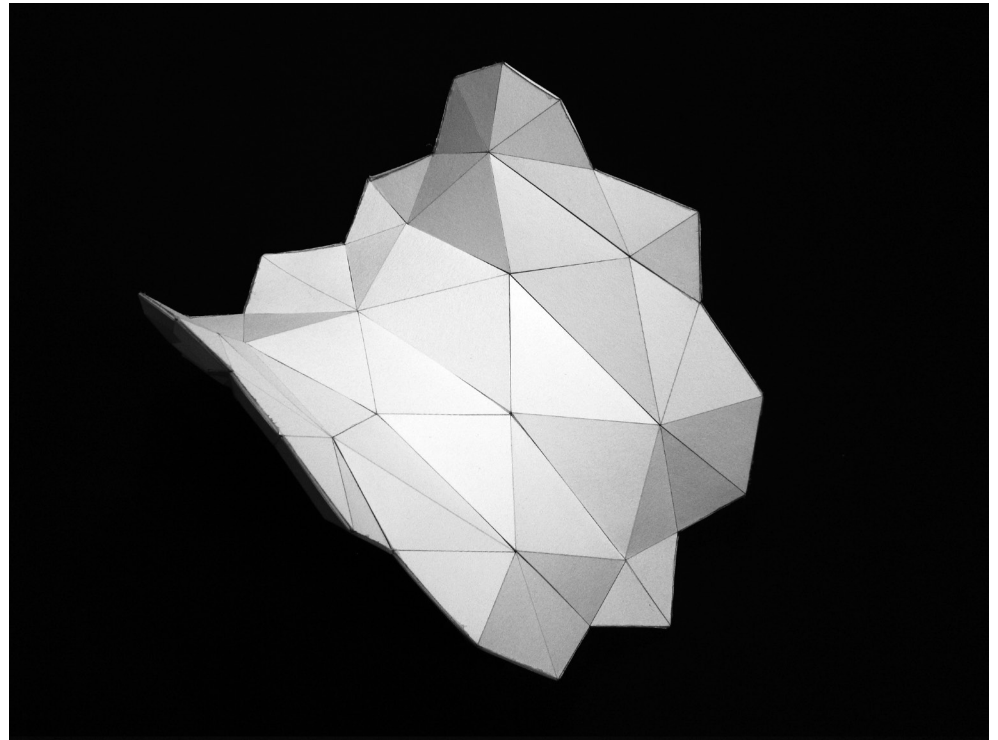
Surface and Form

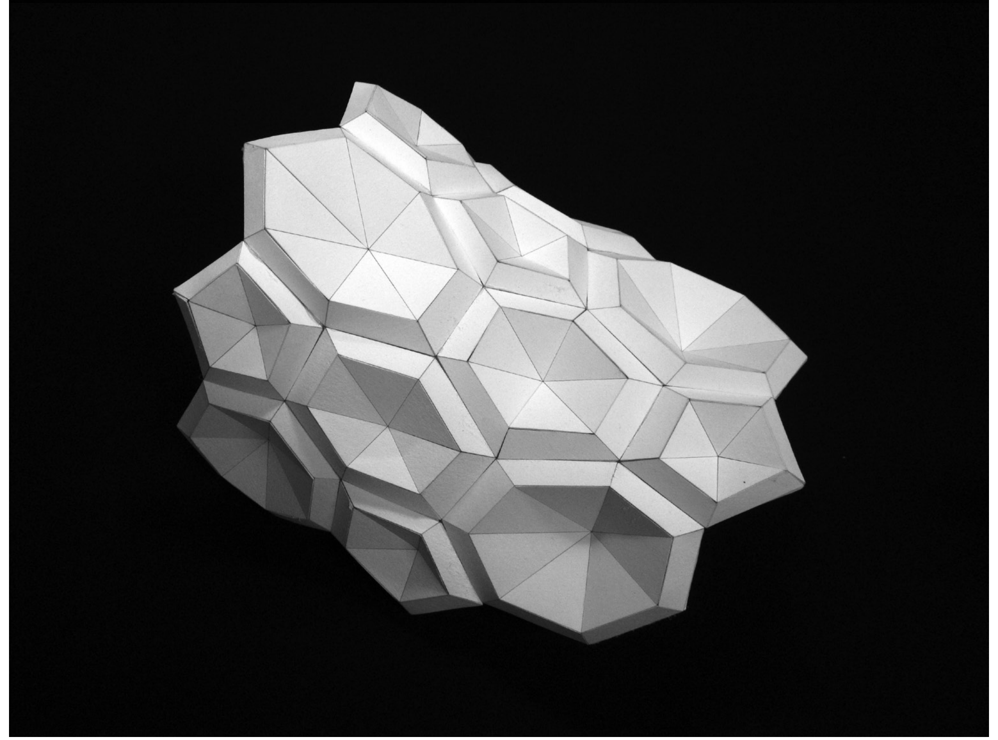
Digital Experiment 15.

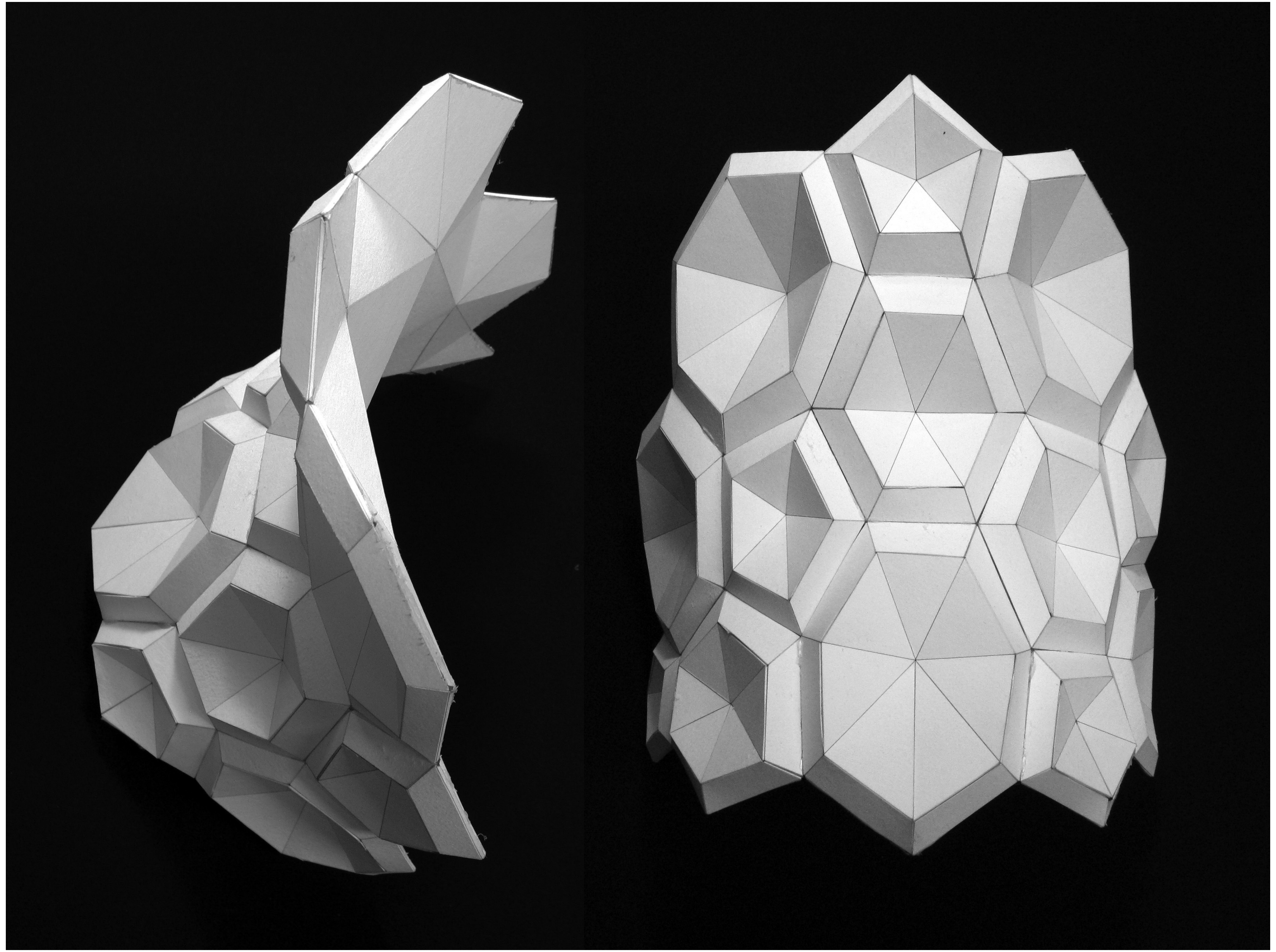
This is the final experiment within this stage of the research and addressed the analysis of the surface and form and ultimately structure, which is further explored in the third stage of this project; 'Immersive Environments'.

The patterns constructed in Pepakura in the previous experiment were able to be exported as vector files for laser cutting. Sheets of thin card were then laser cut and assembled. First, the interior and exterior parts of each component were joined individually and then all of the components were joined together. Second, the underside surface was joined in the same way. Third, the points triangulating the top and bottom surfaces were connected and the edges between the topside and the underside were joined.

It was found that the model had the quality of being stiff in structure. This confirmed many of the findings of earlier experiments involving twin walled designs which involved triangulating surfaces together to achieve rigidity and structural integrity. The aesthetic of the model achieves an inherently organic quality and a sense of organic symmetry despite being in an asymmetrical pattern. This is in line with the topic of biomimicry discussed in the Background.







Summary of Findings

In the experiments described in this Chapter, a series of 3D models, folded designs and their unfolded patterns were explored covering a broad range of concepts and strategies that could be applied in the next stage of this project, Immersive Environments, and implemented within the Final Design stage.

Entry into the digital medium began by developing 5, 6 and 7 sided shapes by using Blender and composing them into arrangements that would fit together with minimal gaps. In many ways, this digital method of shape alignment was similar to what was conducted in the later experiments of the Physical Folding stage. The opportunity to do this virtually however, was significantly more appealing as it was quicker to make, duplicate and precisely arrange the components. This resulted in faster working times and greater freedoms to explore the different variations of 3D tessellations. These could then be expanded into larger arrays.

The arrays, or digital sheet materials, were explored with Blender's modifies through a series of surface manipulations. Some of the main functions explored included surface modifiers such as soft selection push/pull, bevel, cast, warp, twist, and bend. The most expansive and interesting manipulations occurred with the warp function which could manipulate the digital sheet materials in a manner similar to forming a physical material, for example twisting a sheet of paper.

The resulting arrays of components were simultaneously explored as both 3D form and unfolded patterns. The unfolding software Pepakura provided a wide range of functions that aided in the marking of seams for separation and the layout onto flat sheets of material. Many of the experiments concluded with the making of physical models derived from the virtual model. Making strategies were essential for the separation of the digital materials into each of the component parts. This allowed for simpler methods of pattern separation, CNC fabrication and straight forward assemblies.

Outputs within this stage of the project were aimed at refining the structural qualities of the design and the effective representation of a physical prototype. From the strategies for investigation raised in the introduction of this Chapter, the following concepts were identified as key elements for success.

Digital manipulation of surface to create structure

The use of Blender provided a wide range of modifiers that could be applied to manipulate the surface of the form of the digital sheet materials. The warp tool effectively created a smooth bend that curved the surface collectively and produced minimal variations in the patterns consistency. This allowed for surface structures and tensions to spread themselves more evenly, and greatly reduced the distortion of the components. This assisted in creating a more coherent structure where there were no strains or unbalanced pressure on any one particular component of the array.

Structure was also created through the use of folds, such as the mid-folds within each component. The addition of the mid-fold resulted in cones that could be steeper in pitch, providing greater structure, although they had half the height of the same cone without the mid-fold.

Opportunities for creating structural integrity

It was found that the use of 5, 6 and 7 sided forms (as conical components) had the ability to support themselves through their own structure. The bevel tool in Blender provided the means through which to provide additional support to a surface. This is because most of the flexibility of the surface array is apparent in the edge joins of each of the components. The mesh of a surface could function as both the structure and the surface of the form. By bevelling the joins between the components, the mesh could function as both the structure as well as the form. The bevelled mesh could be made from a stronger material to add additional support and increase structural integrity.

Another method to achieve structural integrity was by triangulating the central points of the structure. This achieved rigidity through locking each of the components into a fixed position and greatly reduced the flexibility of the surfaces. This was one of the main findings of the twin-walled experiments which were developed for use in the Final Design stage.

Surface thickness of virtual / physical materials

The digital medium is without materiality and the flat plane is expressed as an infinitely thin material. It was found that the experiments in this stage needed to account for the material's thickness as an aspect of structure and as a constraint of working between virtual and physical mediums. The consequence of this is that the tolerance between the physical thickness of the material and its virtual counterpart needed to be considered during the unfolding step.

In relation to surface thickness, it is important to define the optimal thickness that a surface would support itself without buckling or deforming. This may mean thicker modules on the bottom of the design where forces meet the ground, and thinner on the top surfaces to reduce stress lower down. Or it may mean thinner material on the interior wall of the structure and thicker material on the exterior.

Digital manipulations which allowed for printing and assembly

The approach within a mesh modelling environment was to make modifications that altered the entire sheet material so it retained a homogeneous form. Those surface manipulations which reduced the amount of change in each edge length of the individual components and therefore minimising the distortion of the edge lengths, made it easier to contain each of the components within the maximum sheet size.

Marking seams for separation and minimising material wastage

The way in which surfaces are marked for separation must result in pattern layouts that are easy to interpret, and thus easier to rebuild. It was found that in order to reduce the amount of material wastage of each sheet, it was important to nest the shapes as closely as possible. A digital trial and error process involving marking the seams for separation helped to ensure the minimisation of material waste.

The modular construction system of using 5, 6 and 7 sided components enabled one or more of the components to be added, removed or replaced. This versatility was one of the main benefits of using this design strategy.

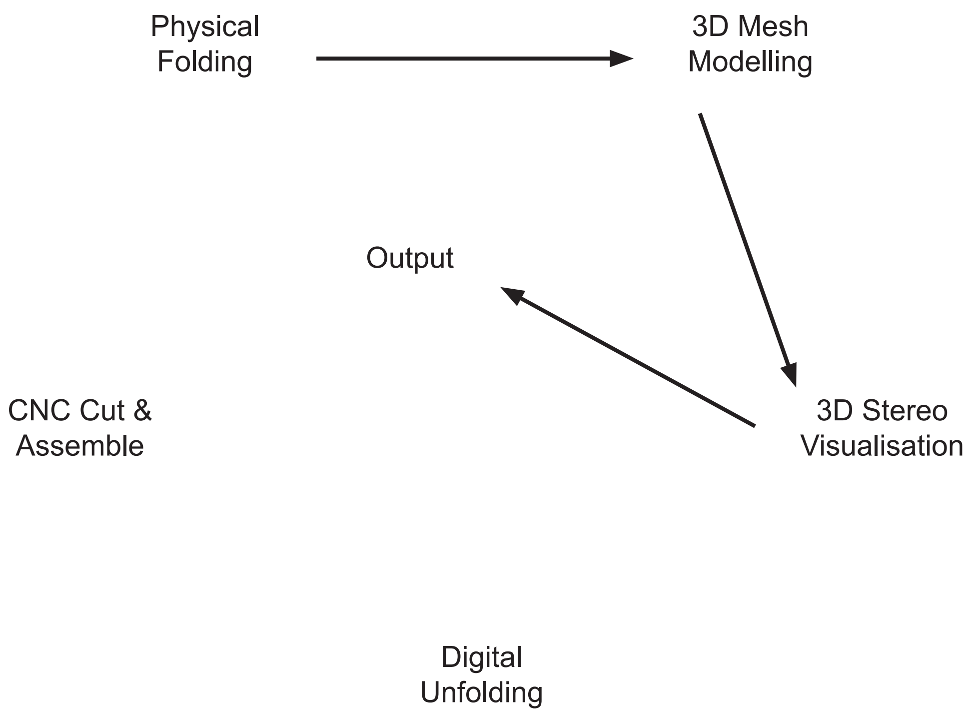
Immersive Environments

The third stage of this project presents a series of experiments and photographs demonstrating the opportunity to explore space and structure by exporting the 3D models and visualising them with a 3D stereoscopic dual projection system.

As illustrated in the diagram on the right, the forms that were first developed through physical folding, underwent further manipulation digitally, and were then visualised in 3D immersive environments. This was the last set of experiments that investigated the transition between the small and intermediate scales developed in the previous stages, and the larger scale explored in this stage.

3D stereoscopic environments were used to visualise large scale spaces. These would next be translated to physical reality in the Final Design stage of this research. The act of visualising was itself an output in both these stages as the intent was to intertwine both the physical and virtual experiences.

These digital experiments were aimed at developing intimate relationships between the method of digital modelling and the virtual representation of physical space in 3D. The results from this exploration were taken into the Final Design stage of this project where it could be evaluated based on the virtual / physical transition and the accurate representation of the design's formal and spatial qualities.



Introduction

This stage of the project introduced the use of a dual stereoscopic projection system to aid in the understanding of virtual model making and the transition of the designed object to physicality. With a 3D stereoscopic projection system, designers are offered the possibility of diving into the object, moving through space and analysing the scale of the object in relation to the human body. This is not a feature readily available with the use of 2D computer monitors. Even with the relatively recent development of 3D monitors and 3D TVs (2010), the prospect of immersing oneself within a virtual environment is still not comparable to the immersive quality achieved with the larger screen of a projection system. The hardware and software requirements to create an environment that immerses its users are identified on the follow pages.

In this thesis the 3D environment provided the context for a more focused research project. 3D models that make the most of stereoscopic display capabilities are the ones that have spaces in which to enter, but also have identifiable faces in which to separate the walls of the surface from the structures of the fold. The basis for an unfolding theory developed for and within 3D environments, is taken from the perspective of the fold as a process of discovery and a practical method of creation. Movement is an integral part of the process of folding. This suggests that 3D stereoscopic projection could be used as an environment that encompasses movement as a key element of the display, which may ultimately heighten the visual experience.

Immersive environments also present the opportunity to explore the interrelationships between the virtual and physical to create an interlinked experience. Throughout this stage, the purpose of the research was to investigate the opportunities to visually represent physically folded structures within 3D environments. The experiments explored how the cross-over between virtual and physical design methodologies would lead to a final composition that could in turn be used to compare the qualities of a virtual model with its physical counterpart.

In this stage outputs were aimed at enhancing the designer's engagement with form and space by creating interactive experiences that could be shared with an audience. This experience would reveal knowledge about a design that could be directly communicated through a visualisation, rather than the use of more conventional 2D methods (for example a slide show presentation). The intention was to create an experience that engages with the user's creative imagination and creates a more meaningful dialogue between a designer and their audience.

The strategies used for the investigation in this stage are set out on the right. This stage explored how the process of exploring folded objects in 3D stereo environments could open up opportunities for understanding, designing and developing physical structures and spaces, and exploring space at the human scale. The strategies for investigation guided the design of a virtual experience that could be interlinked with the physical component of the Final Design.

Strategies for Investigation

• Investigate software that would provide the capability to interactively engage with 3D form and spaces.

• Investigate and visualise folding processes in 3D in order to have a better understanding of the same process physically.

• Investigate the properties of navigating through the space with remote controllers.

• Investigate the surface qualities of faceted forms and how they may be represented in a virtual environment.

• Investigate both the inside and outside of a form and the opportunity to use wire frame to see through closed surfaces.

• Investigate the lighting of forms, surfaces and spaces to create more realistic representations of a design.

• Investigate the situating of a virtual object in physical space and the qualities of spatial inhabitation.

• Investigate the scale of a virtual component in relation to its physical counterpart.

• Investigate and identify faults in the model that would require further resolution.

• Investigate visualisation techniques that reveal new interpretations of physical spaces beyond the original intent.

Dual Projection System

Investigating the hardware and software requirements for visualising 3D models.

The aim of the research was to identify software solutions that could provide an interactive experience and represent physicality in a virtual space. Currently there is a wide spectrum of 3D technologies from the low end anaglyph red/blue illusions to the higher end immersive displays. The setup in the Media Lab at the Victoria School of Design in Wellington is somewhere in between. Two projectors are stacked on top of each other and a polarized filter is fitted over each lens. The images are then projected onto a silver screen and polarized glasses are worn to achieve the 3D effect. This is referred to as a dual projection system.

The system works well, but is less sophisticated than the 3D system HitlabNZ has developed at Canterbury University. Its 'VisionSpace' is New Zealand's most advanced stereoscopic environment. HitlabNZ has three screens with rear projection, infrared tracking and its own custom software: Visionspace. The additional screens and tracking systems make for a significantly more immersive experience. There is the sensation of walking around an object that does not exist in reality. Even though the setup at Victoria University is relatively simple, due to the cost of the projectors, screen and computing hardware, this type of system is still out of reach of most DIY enthusiasts. It also means that there is very little documentation online and no appropriate software application to make dual projection 3D work well.

Industry standards in this area were slow to develop and it will be a while yet before commercial 3D software companies develop methods of dual projection stereoscopic support. The most notable example of a similar system used commercially is the IMAX screens used in cinemas across the world. This however does not give software developers the incentive to create 3D scenes for the exploration of virtual environments as they target a different audience with a different experience.

The development of industry standards has dictated the direction of software developments in 3D stereoscopic displays. At the beginning of this research (in 2008), the most problematic issues facing stereoscopic displays were the lack of standards in both hardware and software systems. The industry has since unified its approach with the commercial release of 3D TVs in 2010. Nevertheless there is still competition between companies providing Active, Passive and Autostereoscopy displays.

In comparison to 3D TVs which are typically anywhere from a 30 inch to 60 inch screen, a projection system provides a significantly more all-encompassing experience. At some institutions, such as Allosphere, stereoscopic environments have been built which completely enclose the viewer with multiple projection screens. Ideally the most immersive experience is one where the user feels as though the boundaries between the virtual world and the physical world are merging and the virtual world is indistinguishable from their physical environment.

The prospect of designing within these spaces is one of the most promising aspects for the future applications of stereoscopic projection technologies. After the initial capital investment in hardware, the area that is in the most need of development is software that allows a designer to not only visualise space in 3D but to interactively manipulate the space.

For the purposes of this research, the ideal software solution would be to introduce a system that would allow compatibility between Blender and Pepakura and display in a dual projection system. Because these 3D software applications were not compatible with a dual projection system, alternative methods were investigated. The following are a selected list of software that was experimented with to achieve dynamic 3D form and space visualisations within stereoscopic immersive environments.

Blender / Maya / 3Ds Max / Houdini

With a dual projection system, viewports in 3D modelling software can be split off from the main screen and projected separately. Left and right cameras were made with view port (a) aligned to the left camera and viewport (b) aligned to the right camera. Care was taken not to disrupt the view of the camera on either screen. A full range of modelling could then take place with all of the necessary toolbars on the desktop screen.

After experimentation with this method, it was realised that it was not truly an immersive visualisation. The problem was the inability of the algorithms used to process real-time object orientation to control the camera rigs within a 3D scene and the simultaneous focusing of objects near and far. The use of a divided viewport was a method that would be replaced during subsequent 3D product upgrades in order to keep up with mainstream content needs, such as the use of 3D capable desktop monitors and TVs.

Verse-Blender-VisionSpace, with Connector and Quel Solaar.

This software combination was connected together to enable 3D modelling within stereoscopic immersive environments. Blender was used to model an object and send it to the verse server (ie an internet protocol that allows different software to communicate through a network). 'Connector' was used to view all of the models loaded to the verse server. 'Quel Solaar' was used to add colours and materials. HitlabNZ's VisionSpace pulled models from the verse server for display. It is a sophisticated stereo-scene that can be developed to include additional hardware functionality such as infrared tracking system and wireless controllers. This software collection was explored as a method in which to incorporate collaborative 3D modelling within stereoscopic environments. However, after experimentation with this software, it was determined that this method of 3D visualisation had a number of technical and computational issues. While its collaborative aspects are its most interesting features, it is an ad-hoc collection of software that was not found to be suitable for this research.

Quartz Composer/ Visualiser

This software generates real-time animated media that is compatible with dual projectors. It is a 'node' based software (ie software which is based upon the connection of 'nodes' rather than simply lines of code) that can be used to create high quality, real-time 3D visualisations and animations. It does not however incorporate simple object viewing functionality or any form of 3D modelling. This software showed a lot of potential for creating 3D content, but was not suitable for ongoing use in this project because of its lack of functionality.

MaxMsp/Jitter - Stereoscopic Model Viewer

MaxMsp/Jitter is a 'node' based software that is intended to connect hardware and software applications with a great deal of functionality and customisation. Through the use of this software platform, a Stereoscopic Model Viewer called a 'patch' was specifically developed for the dual projection system used at Victoria University. During this research project new elements of functionality were incorporated within the patch, including a file loading system and navigational control.

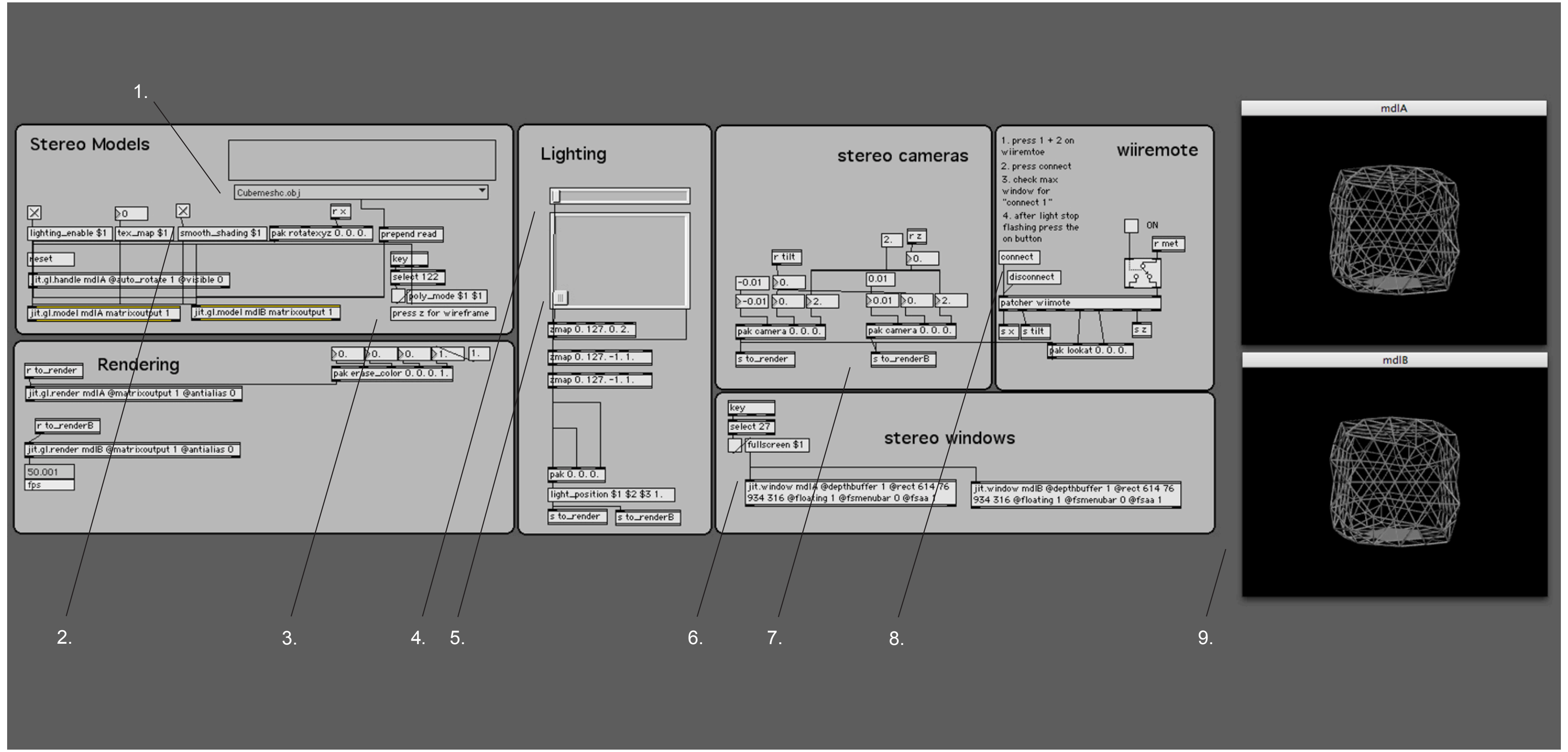
The patch developed for this research does not allow for 3D modelling. However in the future, connecting MaxMsp/Jitter with Ogre (an open source game engine) may allow for a type of 3D modelling, in which highly customised animations could be created, with low cost computational requirements. Unfortunately this required extensive development that was outside the scope of this research.

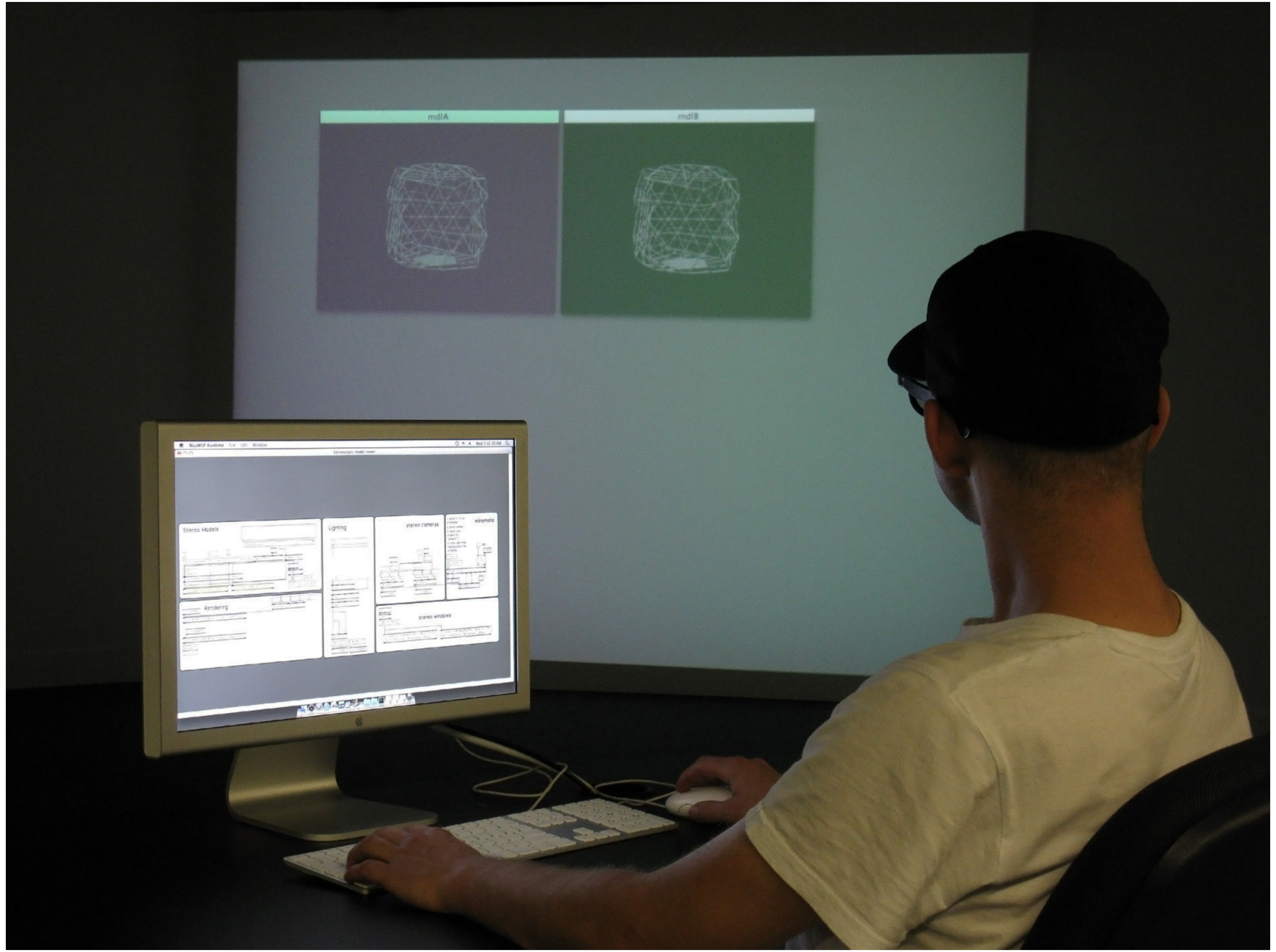
The patch imports object files (OBJ. files which are text files listing a series of x, y, and z coordinates in space) which are usually accompanied by material files (MTL.). This means that the patch has the capability to imports colours, materials and UV maps. Most importantly, it was found that it could run smoothly without stalling and was therefore more reliable than the software discussed previously. Stereoscopic Model Viewer was selected for visualising form and space for the duration of this research. A screen shot of the Stereo Model Viewer software is shown on the following page.

3D Visualisation Software

Software Interface for Viewing 3D Models with a Dual Projection Setup.

1. OBJ. model selection menu.
2. Smooth/ flat shading toggle.
3. Toggle for viewing the model in wireframe.
4. Lighting intensity.
5. In-scene light positioning.
6. Full screen toggle for stereo windows.
7. Settings for stereo cameras.
8. Wii-Remote connection toggle.
9. Left and right stereo windows.





Software and Controller

Functionality of the 3D Software and Wireless Controller.

The Stereoscopic Model Viewer loads models into a 3D scene. Two side by side cameras record an object within the scene and send the video to each of the stereo windows (a) and (b). These windows are then dragged onto each of the projection screens, i.e. window (a) for the left screen and window (b) for the right screen. Because the projections are laid on top of each other they appear as one image. The camera separation mimics the separation between the viewer's eyes. So when the projection is viewed through the polarized lenses, the viewer is seeing only the window (a) with their left eye and window (b) with their right eye.

The process to load models commences by selecting an OBJ file from the drop down menu containing all of the files which have been placed within a folder on the desktop. All of the models are preloaded at the start of the program which increases the speed at which one is able to switch from one model to another. The size of the model also greatly influences the speed at which it loads as well as the lag experience when rotating it. The patch functioned best with models that were less than 5 Mb. However, it is capable of opening models in excess of 100 Mb's, however they are difficult to navigate around and the fluidity of the visualisation is reduced.

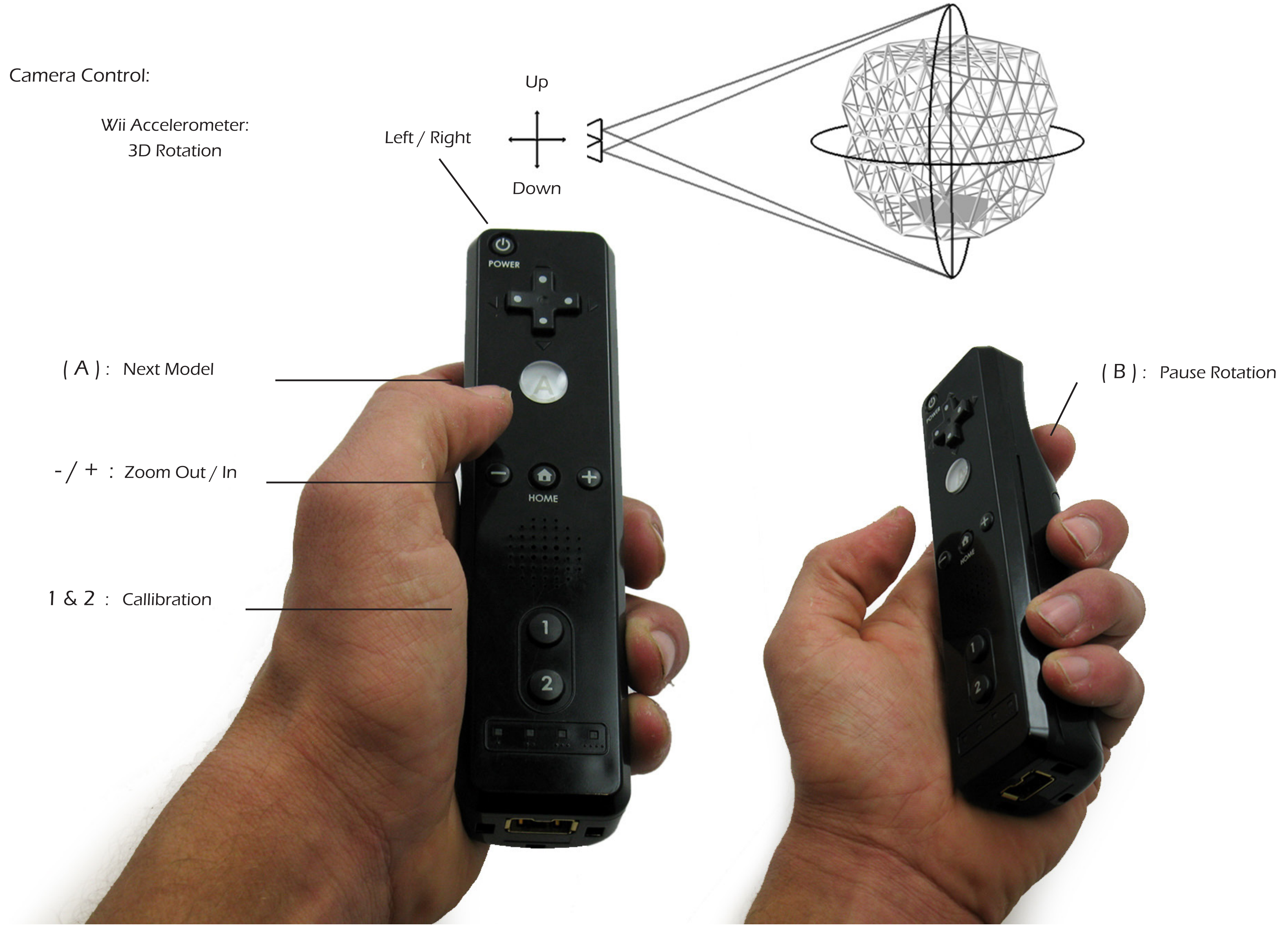
Rendering and lighting functionality was incorporated within the patch to better simulate how a virtual model may be simulated as a physical form or space. The density and orientation of the lighting is adjustable by moving the sliders in the lighting window. Typically the default settings are the most appropriate for most visualisations. The surface would become unreadable if the lighting did not illuminate each facet evenly, and had a high degree of contrast between light and dark areas. In this case toggling the smooth shader allowed an extra degree of customisation to experiment with how to light a surface. In the event that there are interior surfaces or spaces within an object and obscured from view, toggling the wireframe mode allowed for only the mesh of the surface to be viewed.

During the initial phase of this software investigation it was apparent that a navigation controller would be vital for the successful exploration of surfaces, forms and spaces. A great deal of investigation of the interrelation between the user within stereo space and the models projected onto the screen was explored. Considerations taken in account were infrared tracking, face tracking, motion sensing and game controllers.

The popular Wii Remote game controller was identified as the most appropriate tool for navigation. This is because it was a wireless device that had motion sensors and buttons that could provide a range of functionality and was compatible with MaxMsp/Jitter. Most importantly, its use only required the use of one hand in which to control the orientation of the object and the position of the person within space. This would leave the other hand to point and gesture throughout a demonstration, making it easier to communicate with an audience and interact with the design. It was important to have the user engaging with the design in front of the screen, and not locked behind a computer using a keyboard and mouse.

Movement was predominately achieved with the Wii Remote through the accelerometer inside the remote. This meant that it could be twisted in the user's hand without pressing a button and the model would spin in relation to the degree to which the remote was twisted. This provided a very fluid movement when engaging with either form or space. Additional functions incorporated into the Wii Remote were the ability to zoom in and out and move the object from side to side and up and down. The holding of the trigger button paused the movement of the model. These functionalities are illustrated with the image on the right.

During the later stages of this project, functionality to cycle through different models was added to the Wii Remote. This allowed the capability to create visualisations in which a model could be animated through a series of frames. This is similar to an animated stop motion except that the functionality of navigating the space is not disrupted. A model can be spinning around, and a new model can be loaded without changing the orientation of the model. This presented the opportunity to rapidly explore the revisions of design and present a more refined alternative to developing surfaces in real-time. The possibilities of using such animations would help to visualise the construction and deconstruction of surface and aid in the understanding of translating virtual form into physical space.

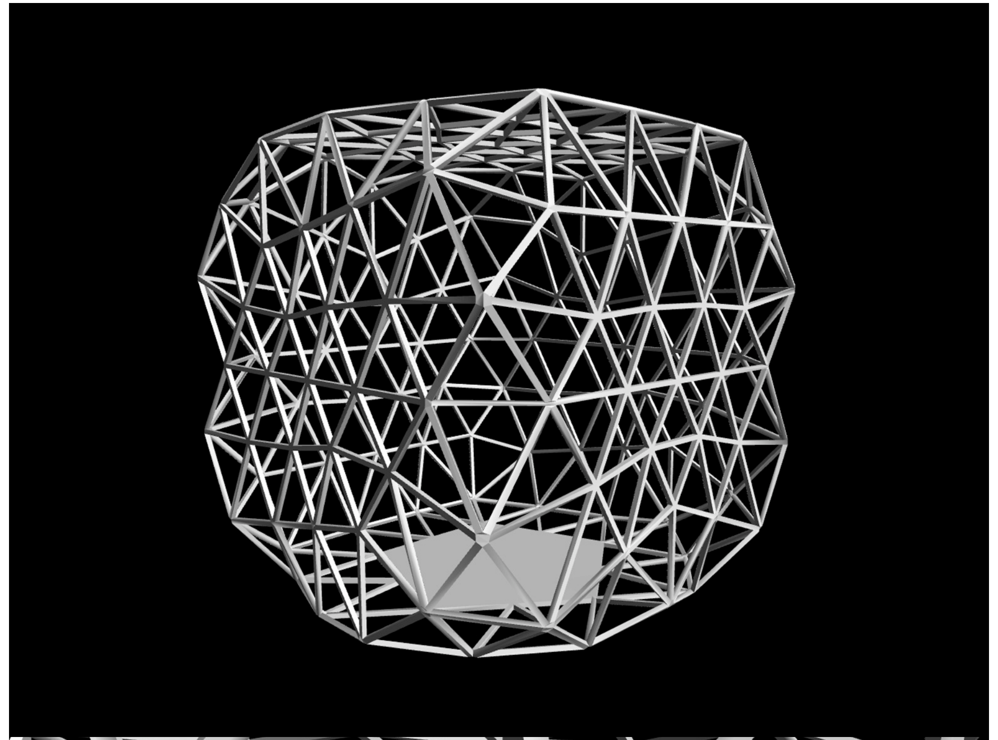


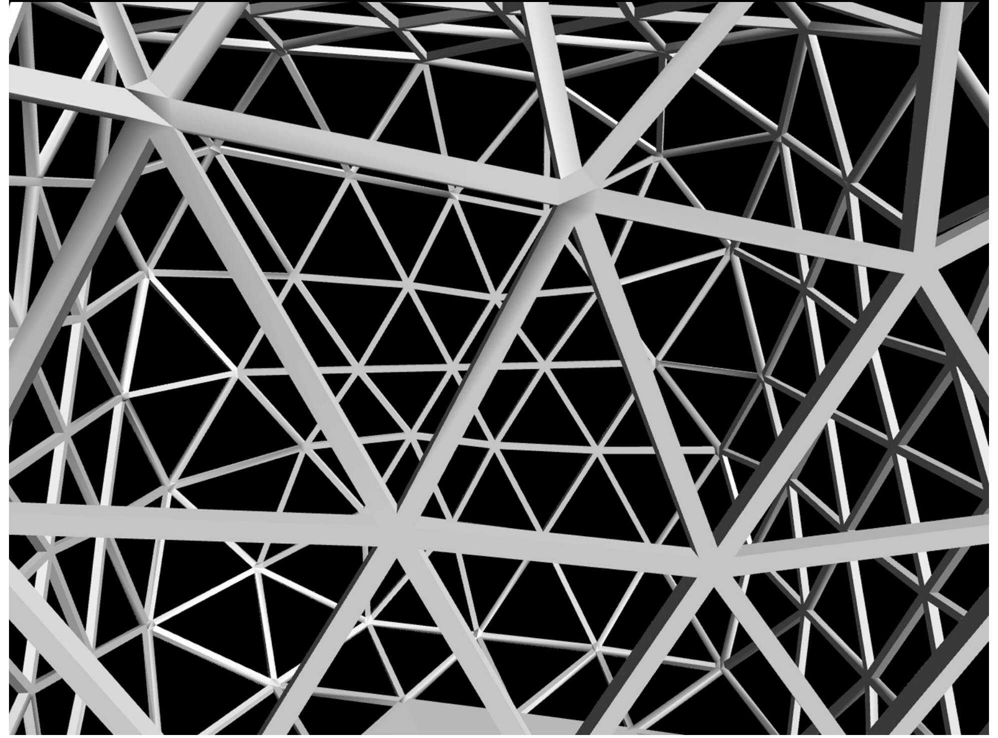
3D Space Visualisation

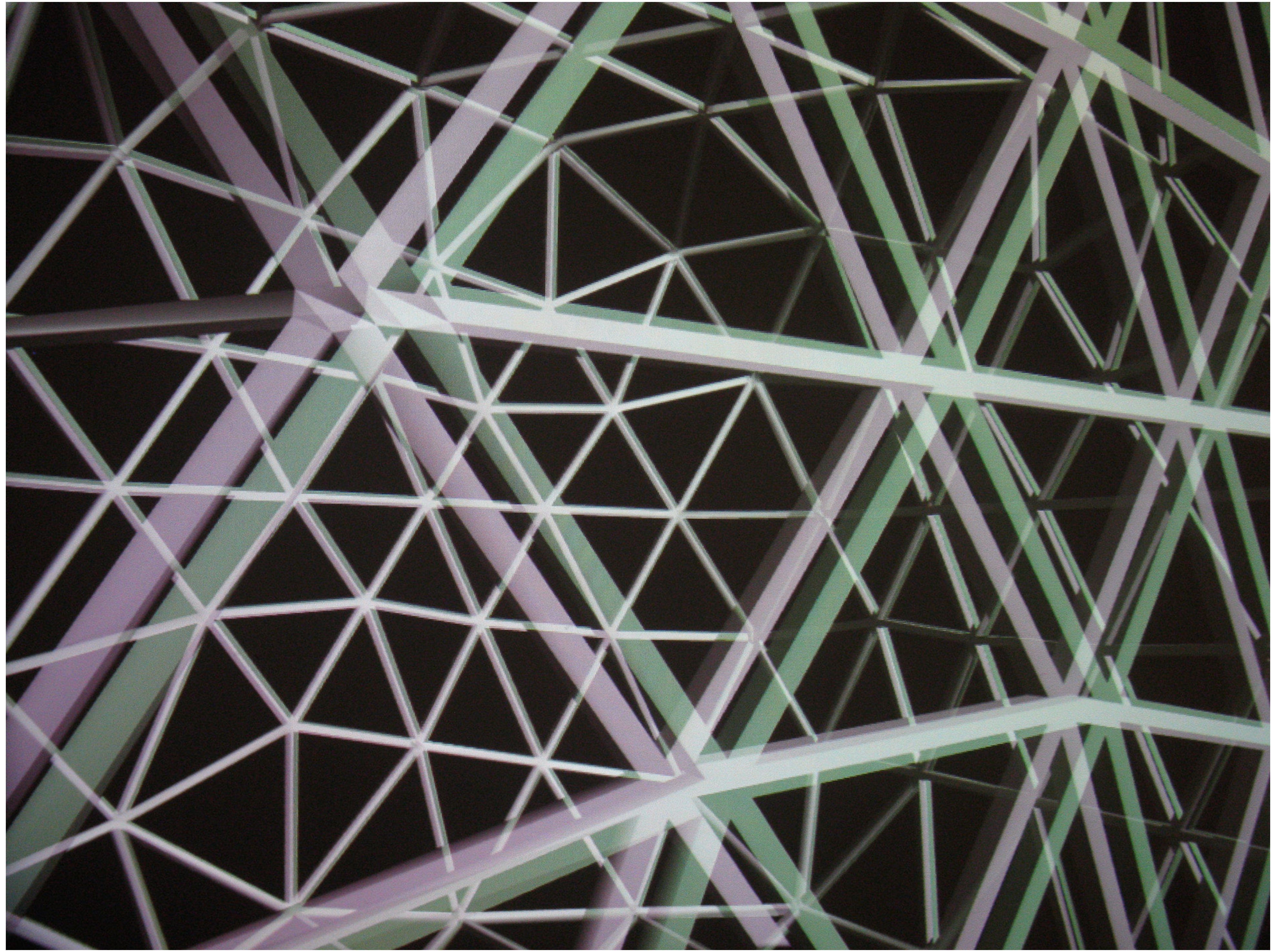
Space Experiment 1.

This model was introduced early in the project as a proxy for testing the qualities of immersion from both within the cube and looking at the cube from the outside. The double lines, (one lightly coloured red and the other green) indicates the camera separation viewing the object before glasses are worn. The greater the separation, the more the surface will appear to jump out at the viewer. A lack of separation means that the object will appear to be flat on the screen. (However, unfortunately it is not possible to document the effect of being in a 3D space with a photograph).

For the purposes of this research, a delicate balance must be created in order for the viewer to refocus their eyes as they would in real life. This creates the illusion of depth because if one refocused the object in both the foreground and the background, the object would become blurry. If the object is always in focus, the experience will not become spatial and the feeling of immersion within space will be lost. For this reason a great deal of research was undertaken to create objects that would be suitable for 3D stereoscopic immersion.





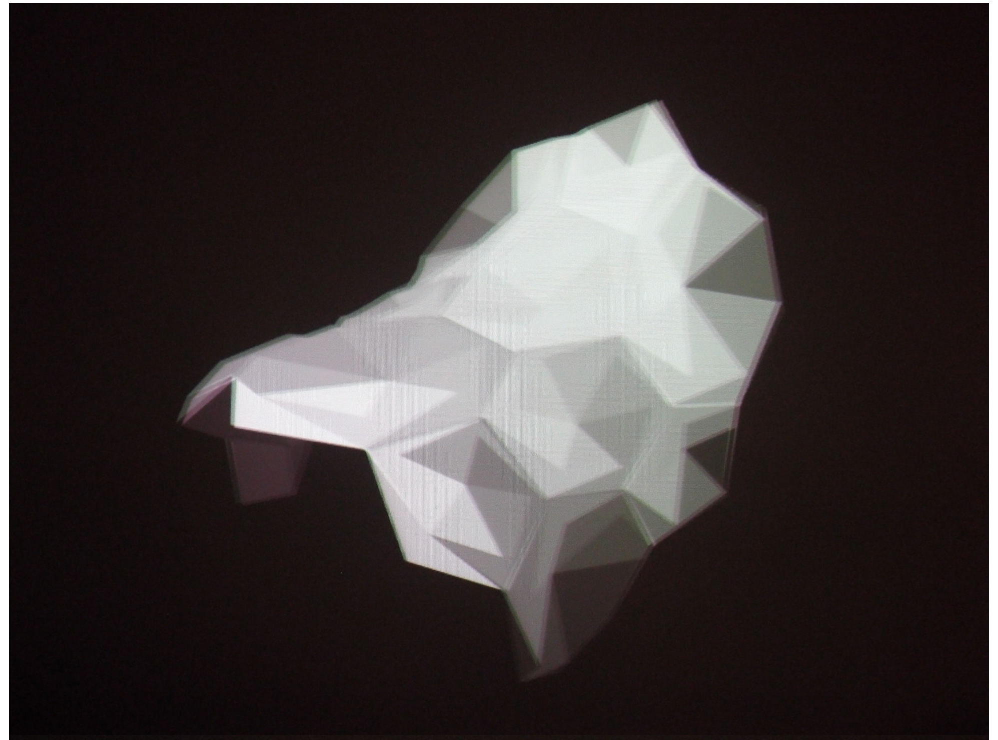


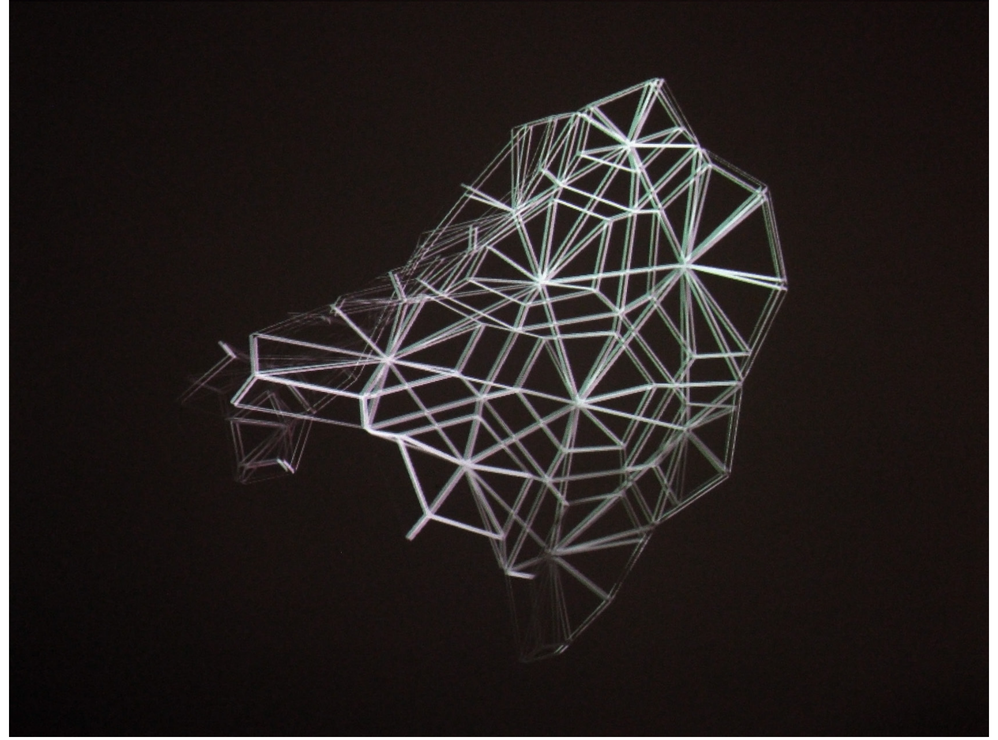
Surface Visualisation

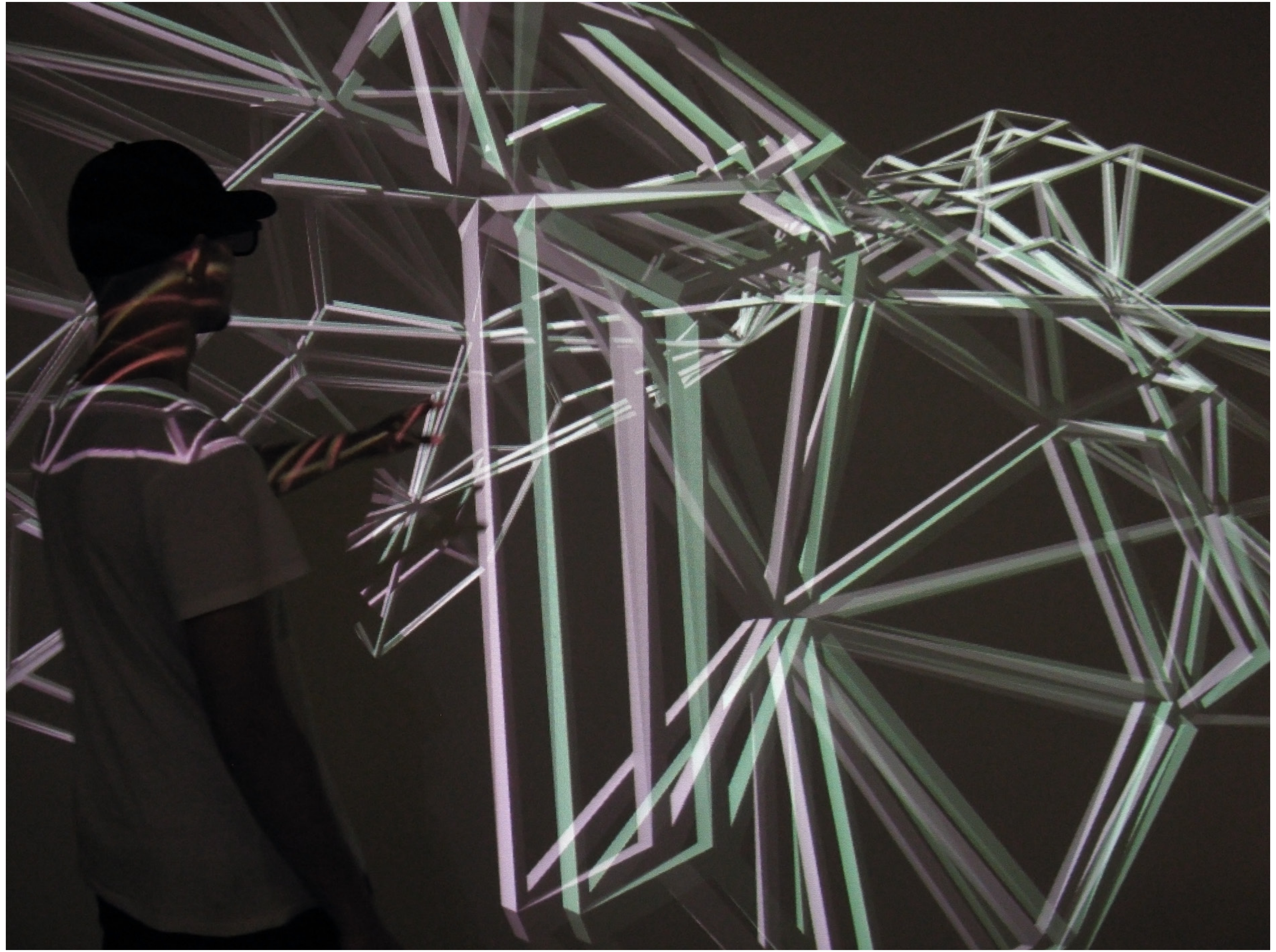
Space Experiment 2.

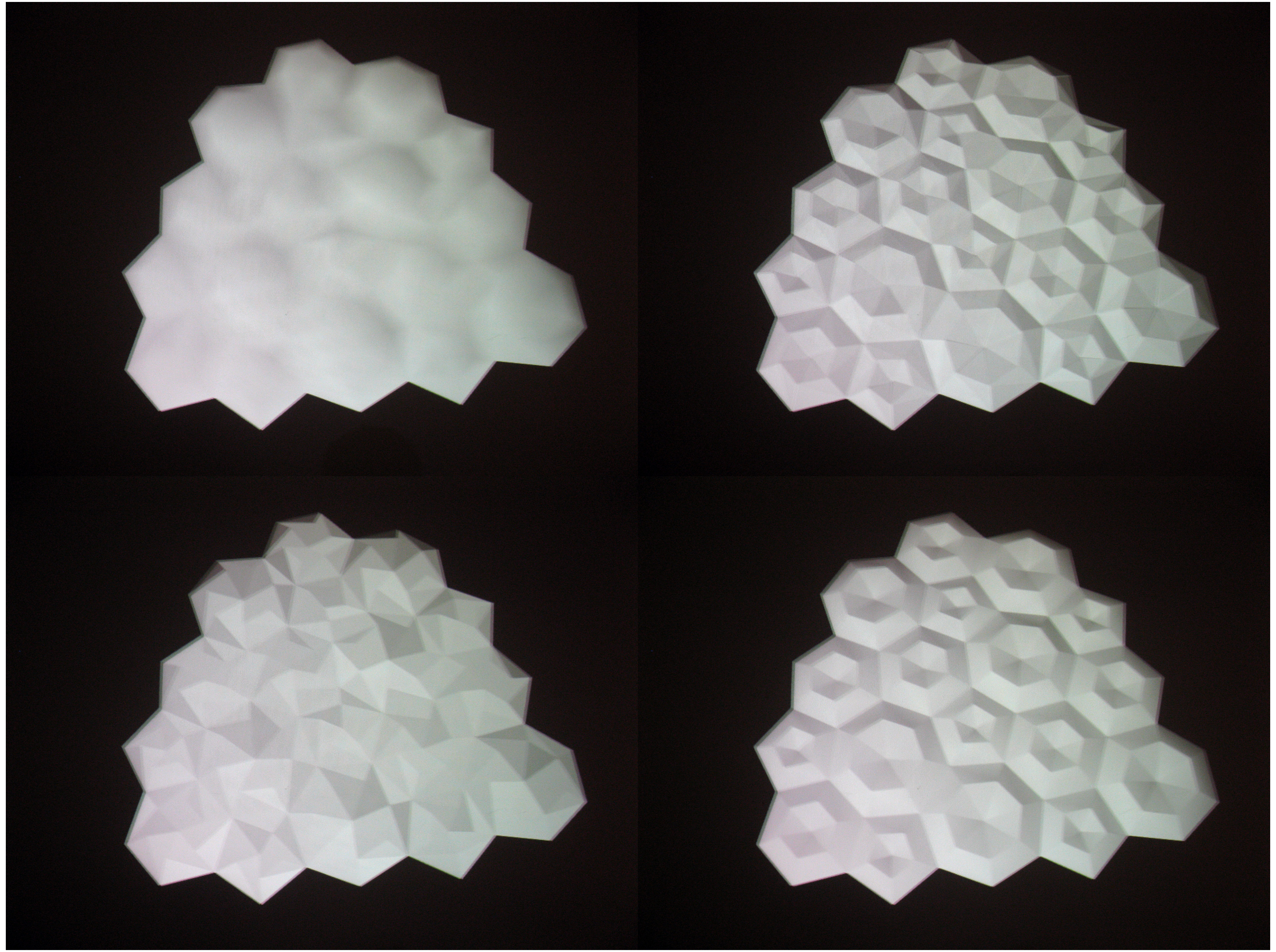
In this experiment the final model developed in the digital stage was loaded for viewing. Initially the model chosen was not immediately suitable for visualisation as its surface mesh was improperly faceted, which resulted in a visualisation that did not represent its true form. To overcome this issue the mesh's edges were initially converted into a truss in which to explore the connection points between the top and bottom surfaces.

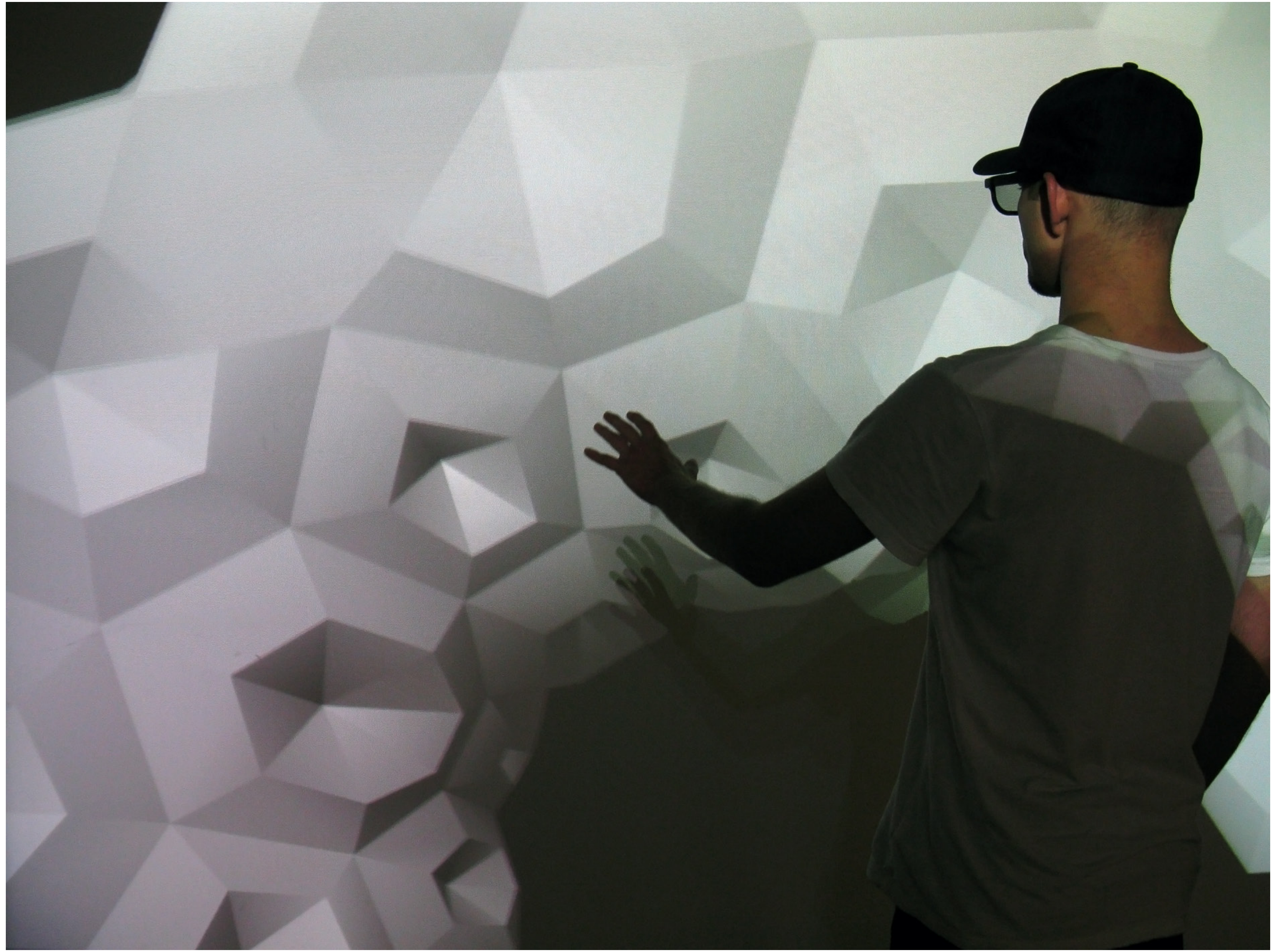
On the following page, four variations of surface qualities are shown to illustrate the different methods in which a surface may be textured. The top left is a smooth surface and bottom left is an unsmoothed surface. In order to correct the texturing for viewing with the stereo software, the only method available was to bevel the edges of the surface in Blender so that each face was recognised as being separate from each other face when the lighting and textures were applied. The bottom right image on the following pages indicates the effect of an unsmoothed surface with a bevel, which created the most desired surface representation for folded surfaces. Unfortunately, the bevel resulted in polygon count that was tripled, although the bevel was necessary for an accurate representation of the physical model. There was therefore a disconnect between the model used for outputting to the physical and the model used for 3D visualisation. This disconnect was later addressed in models by including the bevel as a key aspect of making a faceted form for visualising with the Stereoscopic Model Viewer.









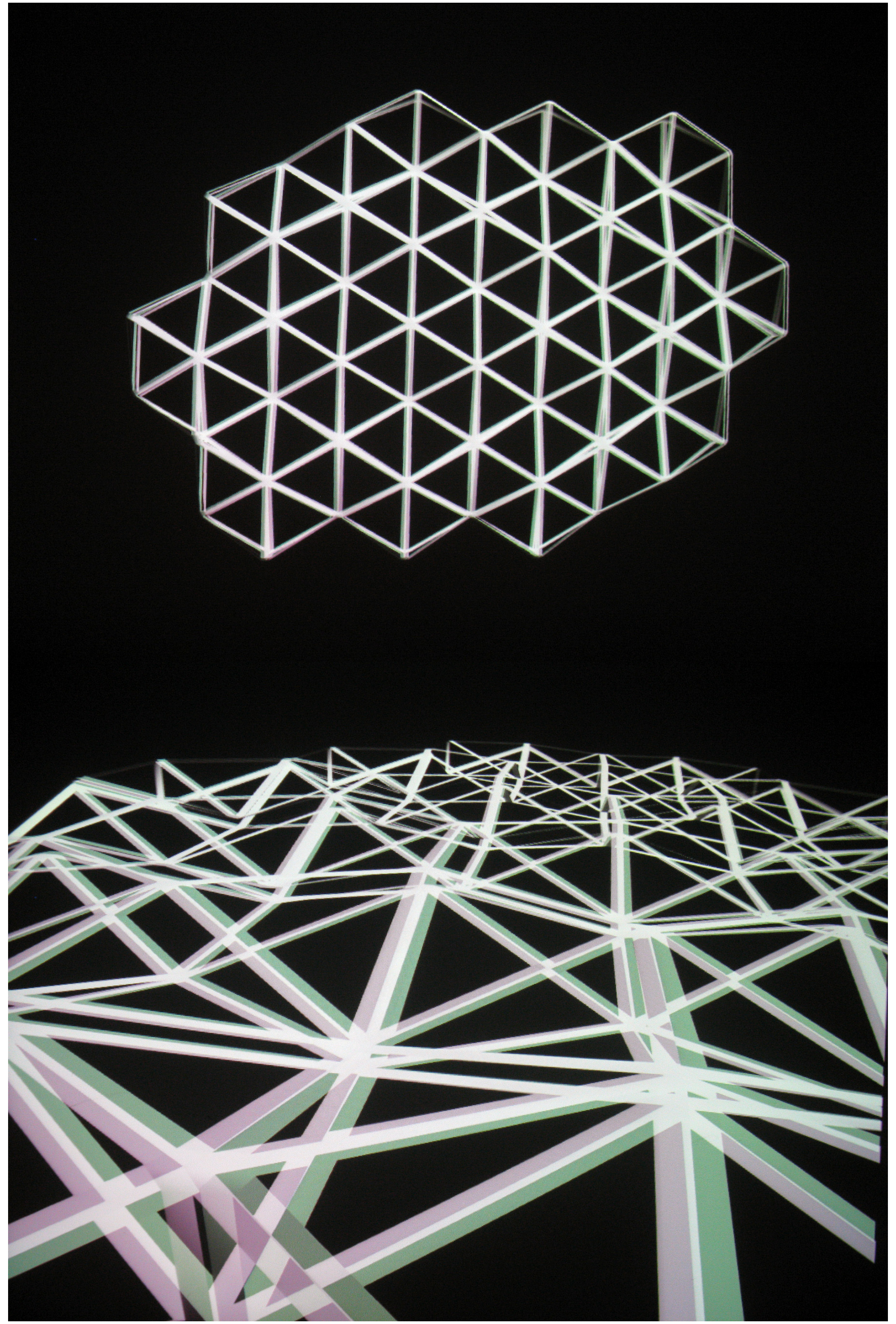


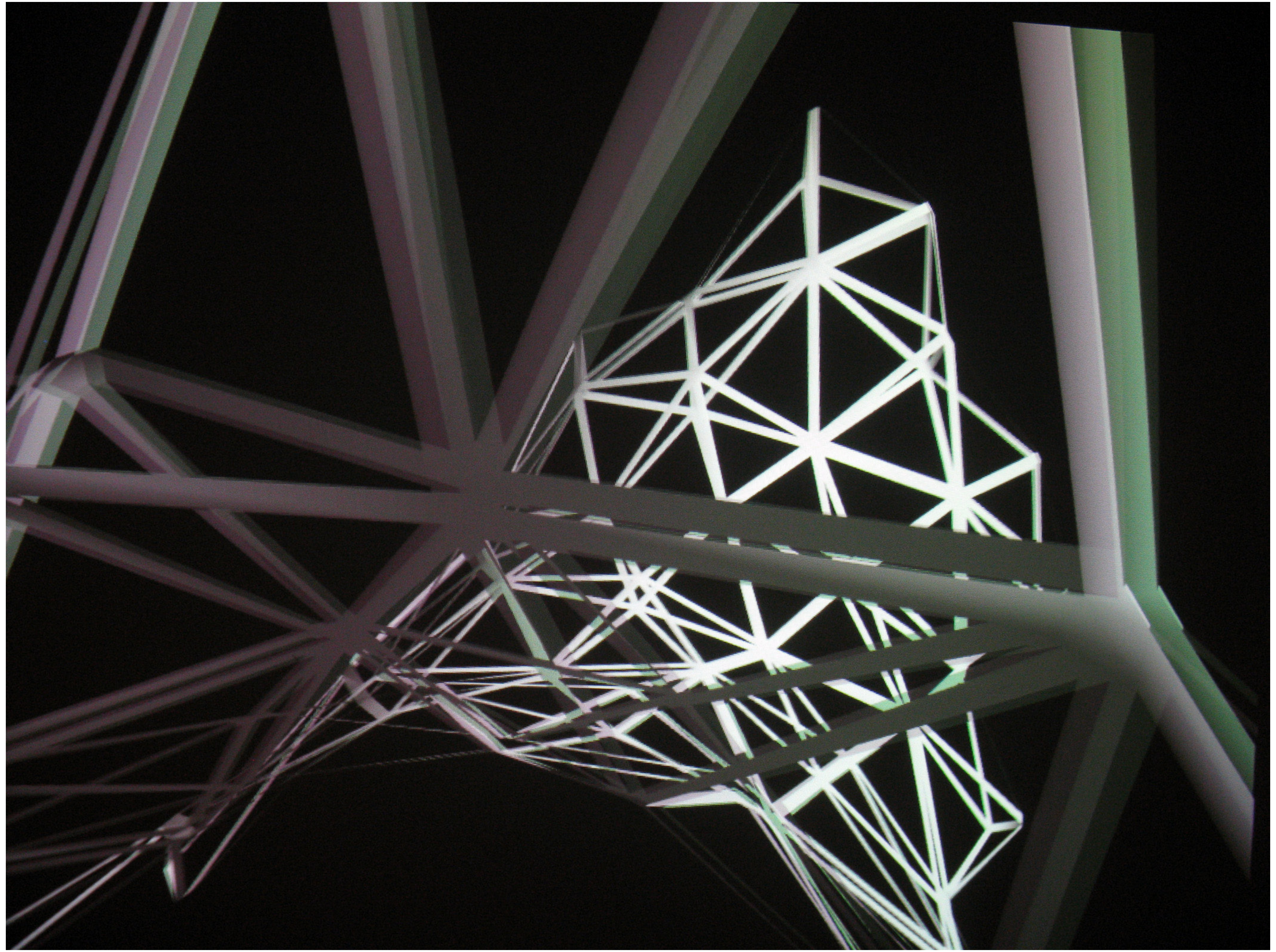
3D Truss Manipulation

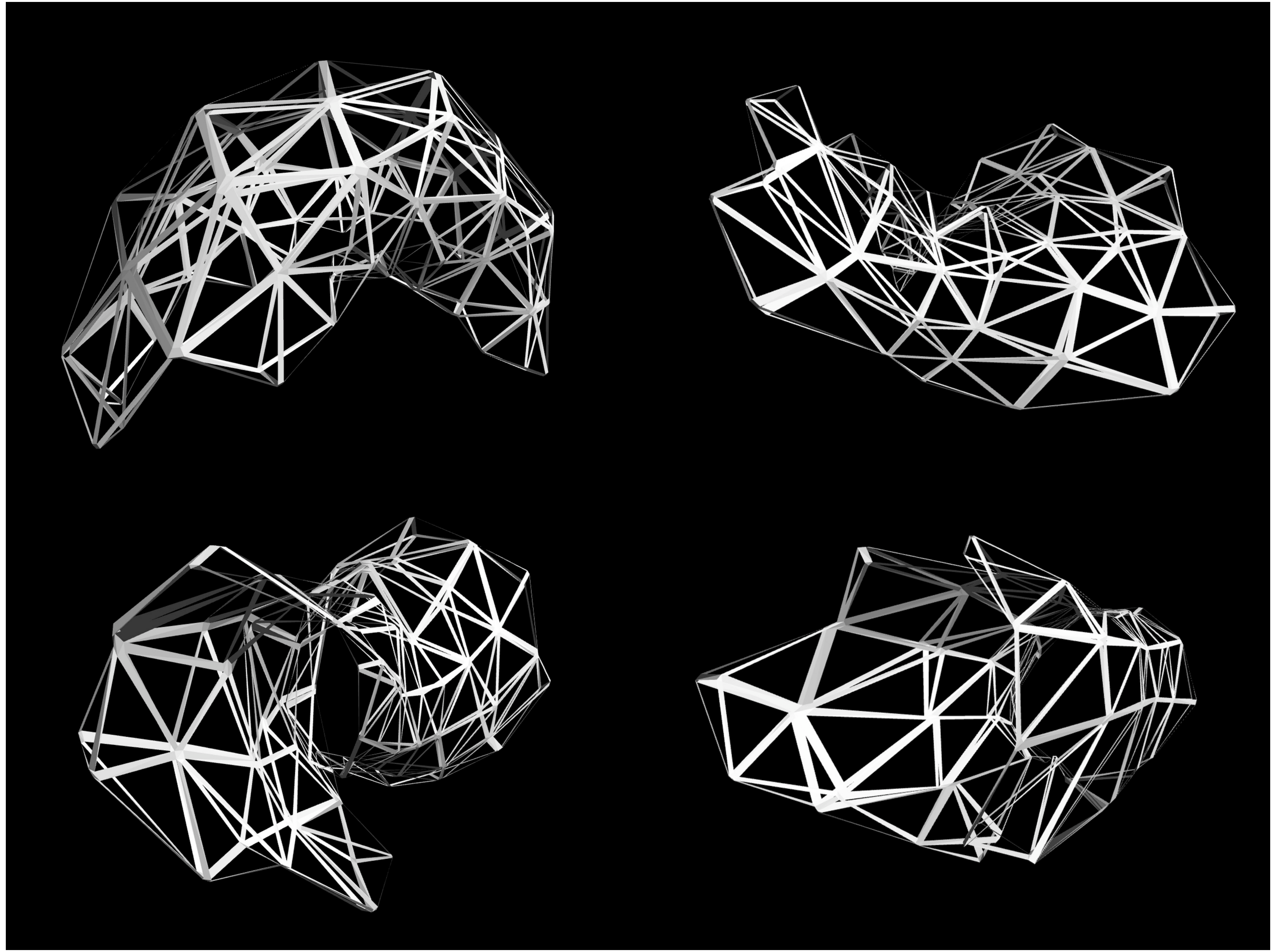
Space Experiment 3.

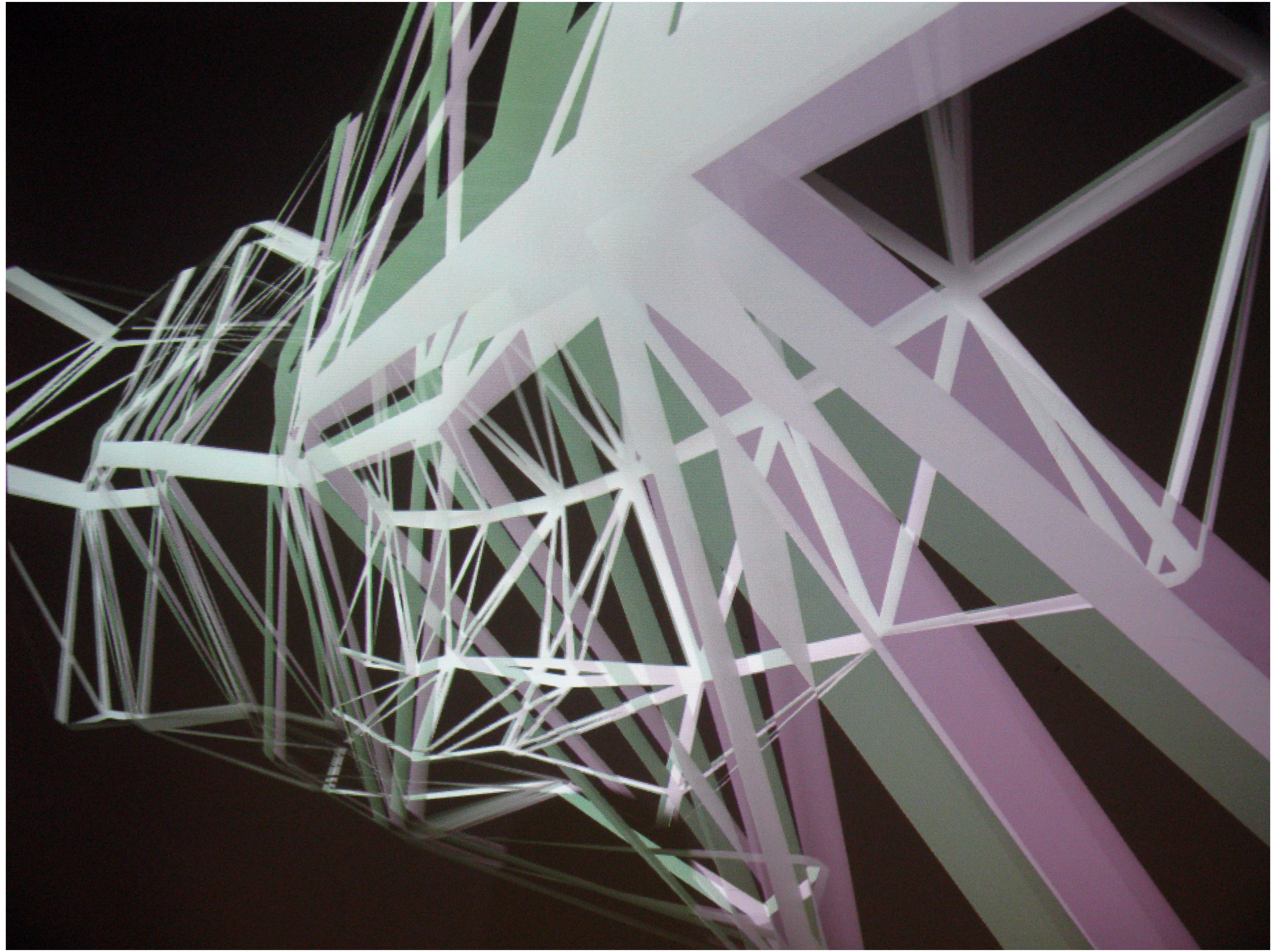
In this experiment the hexagonal truss developed in Digital Experiment 10 was expanded upon in order to create a wider variety of spatial forms that may be explored from any orientation and at any scale. The spatial forms on the right and on the following page were the first exercise in warping digital sheet materials in order to create forms that were inherently structural in their makeup and yet do not explicitly focus on physical reassembly. These were a series of warps with the same flat truss pattern made from the pattern illustrated on the top right of this page. Creating shapes with the truss as its main feature is beneficial for visualising form and space. It allows one to look past the surface, through its interior space, and into the nothingness behind it.

The disadvantage of this type of truss construction is that it does not lend itself to reproduction with physical sheet materials. It is however an excellent method of visualising the structure of fold lines and providing a greater understanding of the interior volumes of a space. It lends itself to engaging with spaces that are difficult to perceive as a flat 2D rendering.







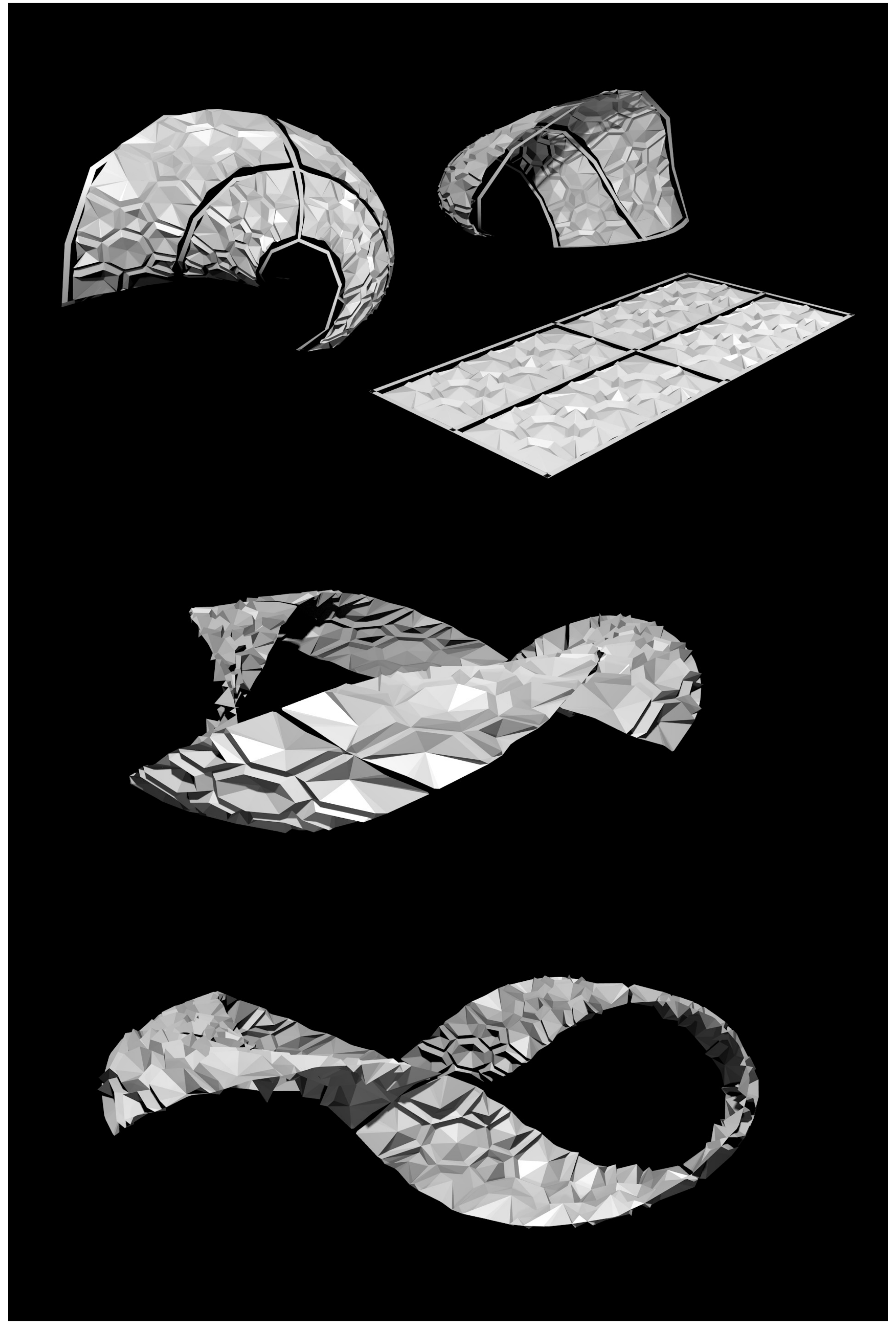


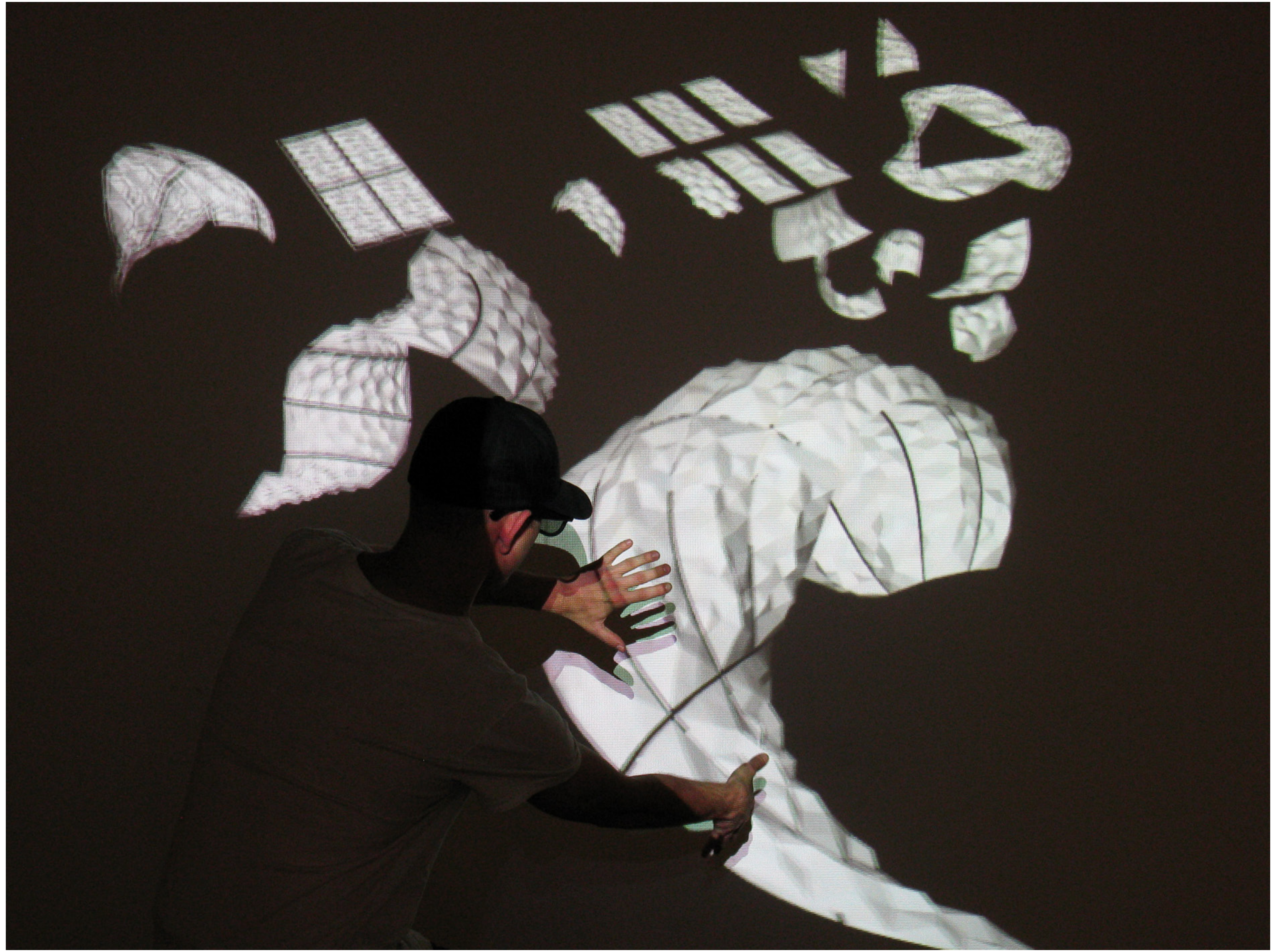
Spatial Sheet Warps

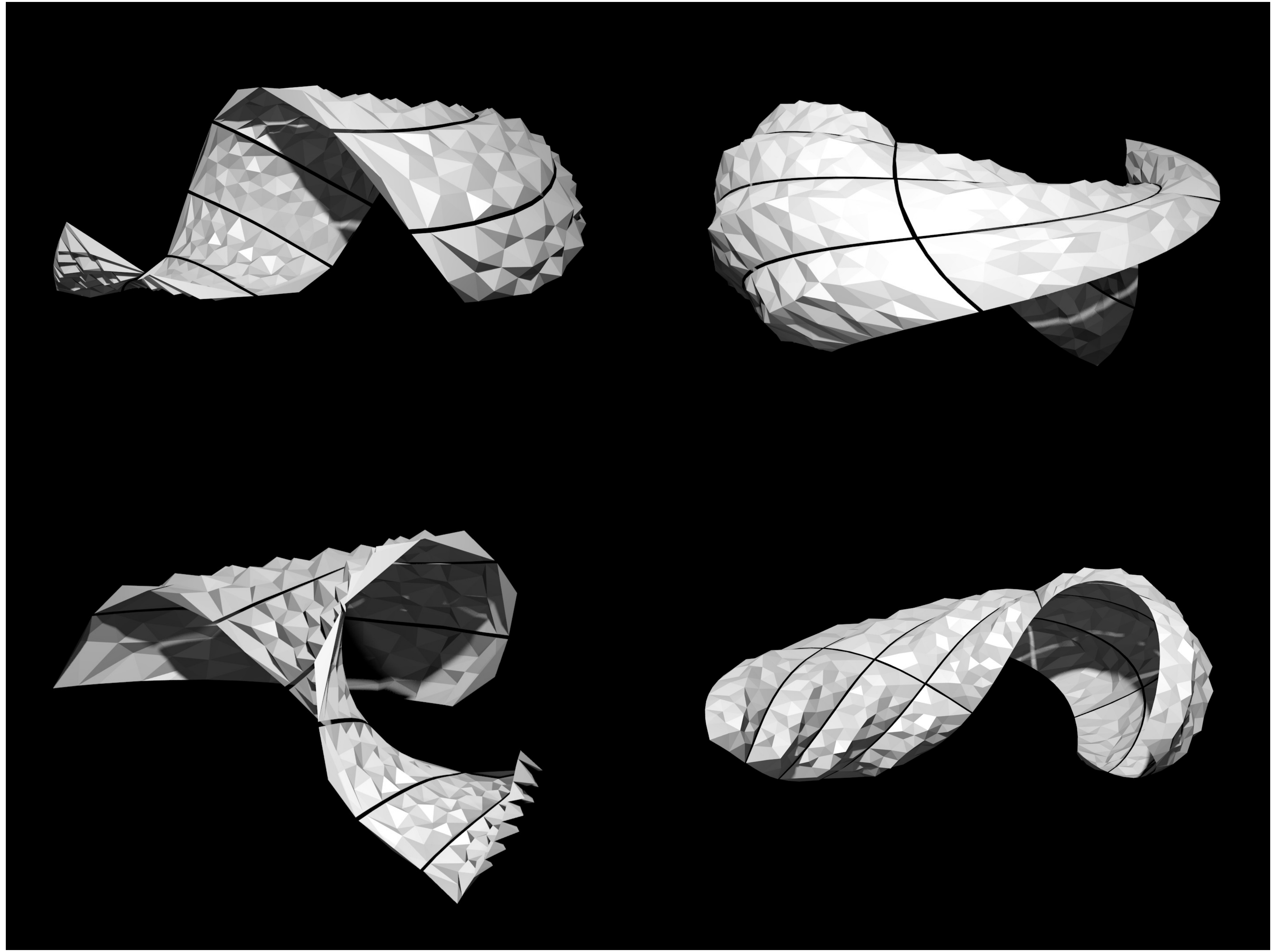
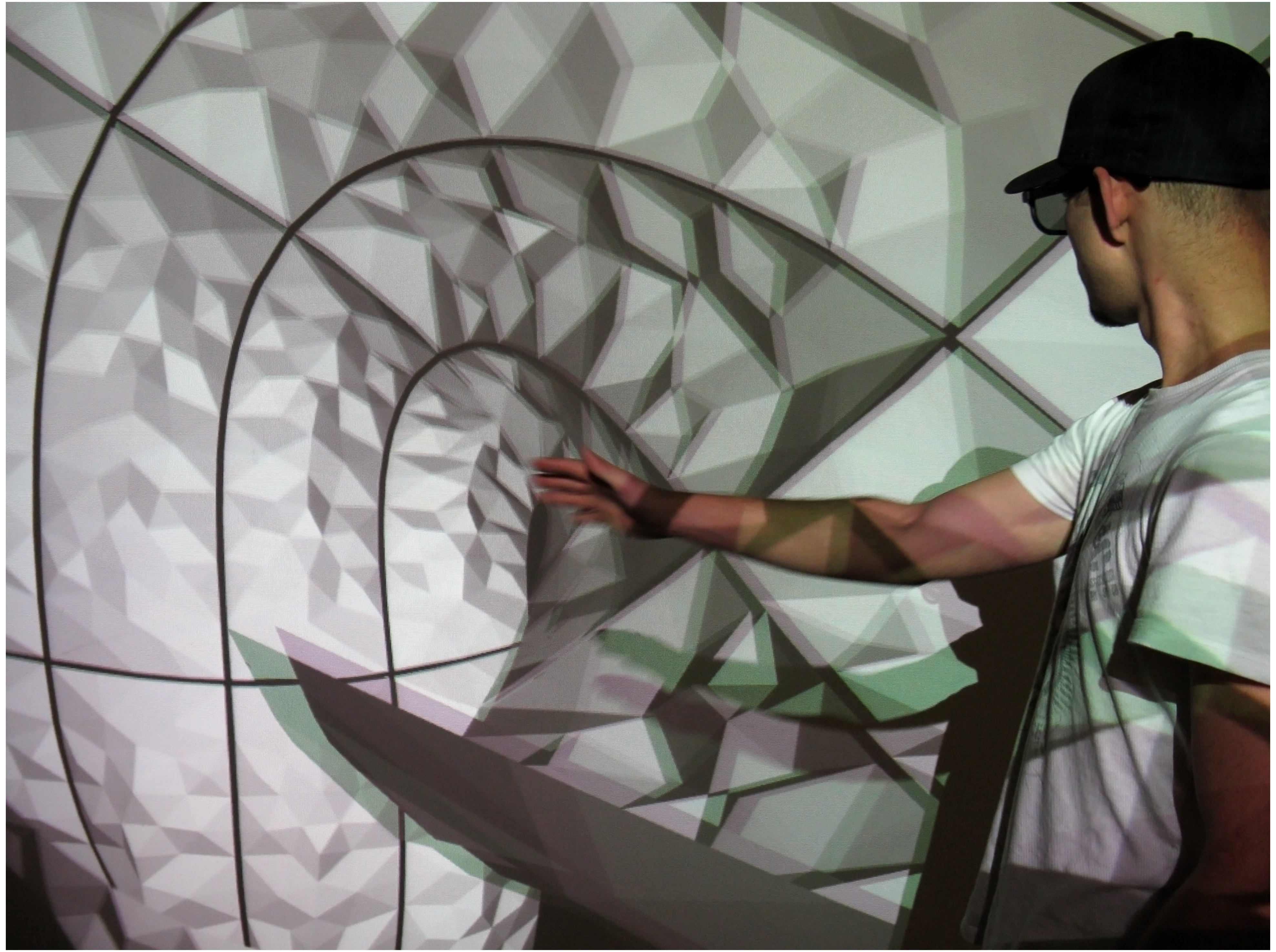
Space Experiment 4.

In this experiment the digital sheet materials developed in Digital Experiment 8 were connected together to explore the opportunities for creating surface mesh that was large enough not to distort the integrity of each of the 5, 6 and 7 sided components. Large arrays were composed, then warped, duplicated and then warped again. These models were segmented to allow for additional supports that could be added later, such as steel frames or plastic piping. In the development of large scale physical models, supports are necessary factors which need to be considered for an accurate transition to physical reality and representation of the virtual model.

The image on the far right was the first experiment in this stage to combine all of the models together for visualisation within immersive environments. Dubbed the 'graveyard', each of the models sits together indicating the progression of each model's development. This was not a visualisation of just one model but of a number of models. A scene is thereby composed in which there is a hierarchy between the early models and the final developed models. This was an effective method to communicate to others the process through which each of the surfaces was manipulated.





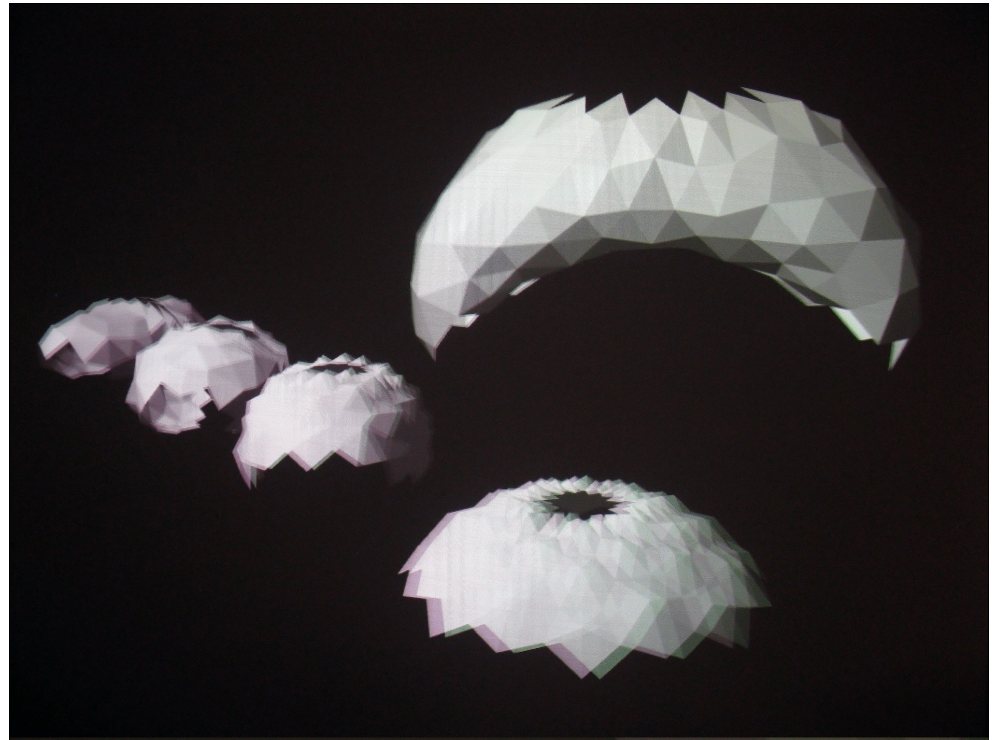
Inside and Outside

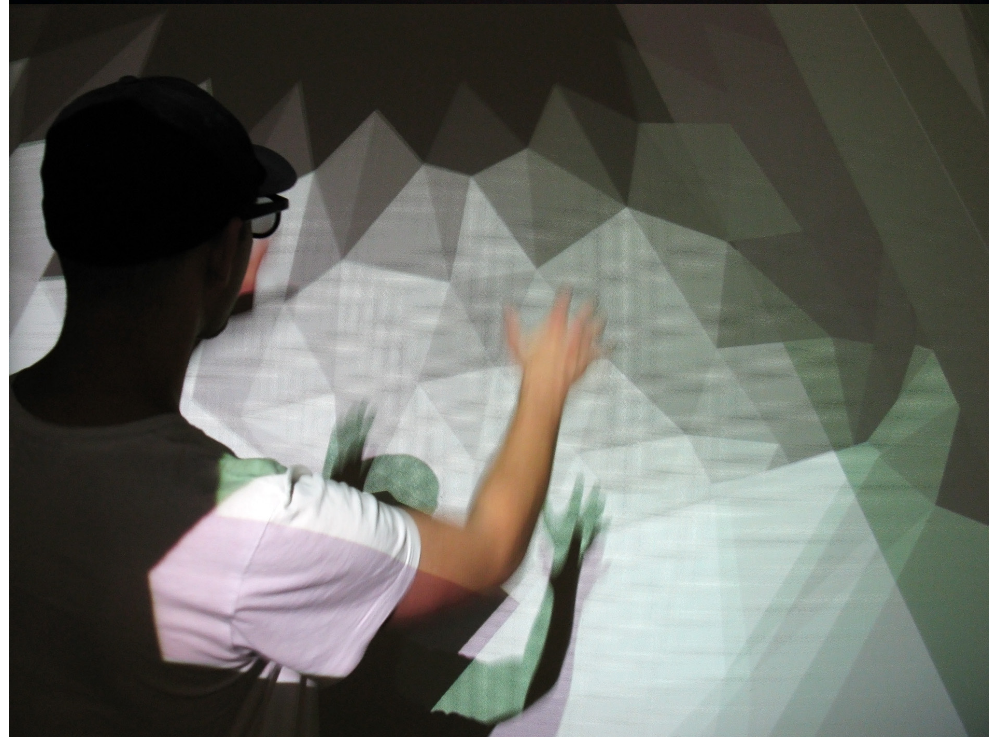
Space Experiment 5.

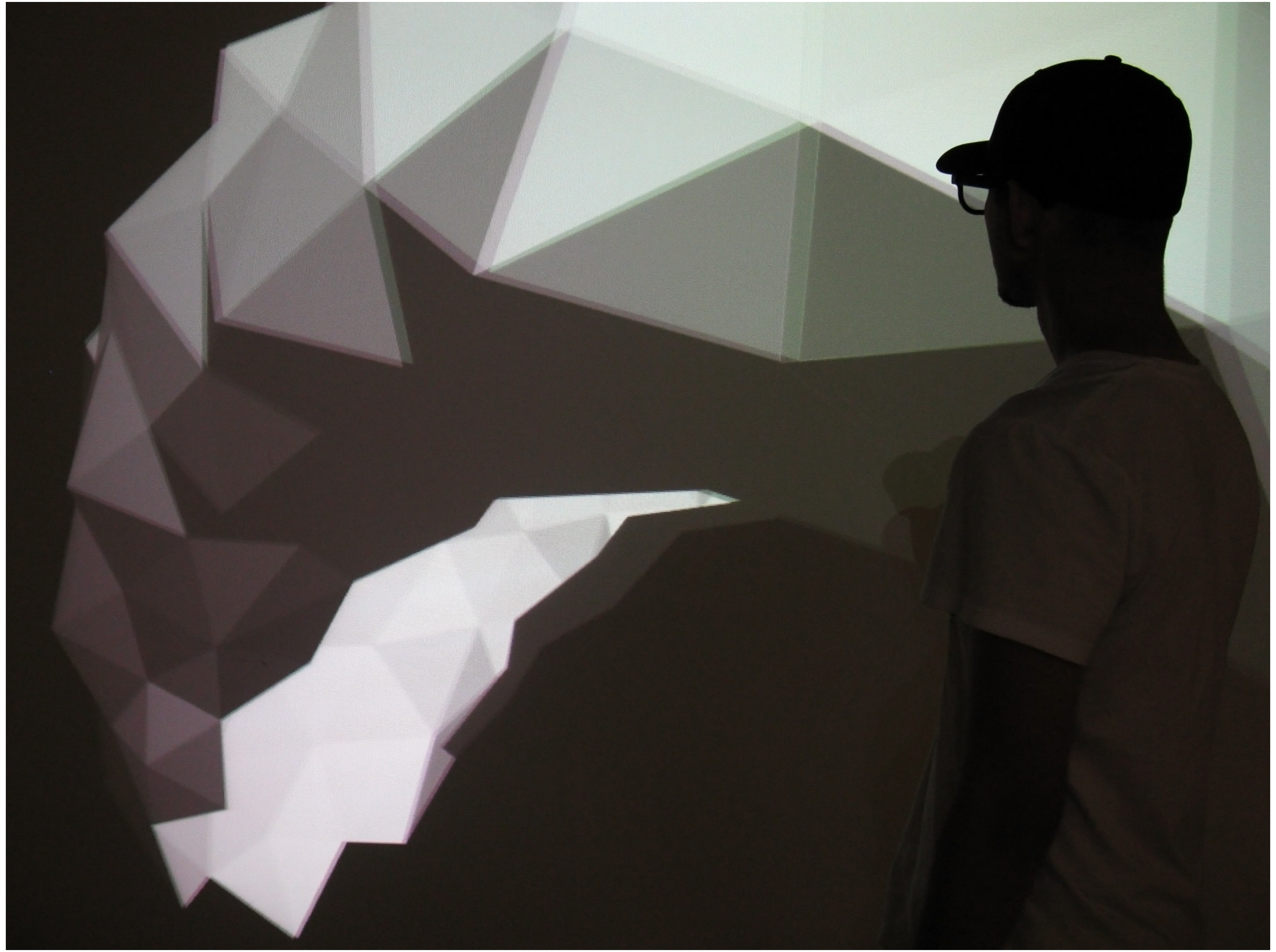
In this experiment, the exploration of the digital form developed in Digital Experiment 7, was explored as an opportunity to navigate the interior of the form as space. Observing the object from the outside, it looks like an object, in comparison to observing it from the inside, where it can be viewed as space.

Stereoscopic exploration inside a form allows one to look past the exterior physical form into the space within. Looking from both outside and within provides a holistic understanding of the design. In comparison, a purely external 2D visualisation provides only a single sided exterior perspective of the object.

In the image on the far right, the form was lit from within in order to emphasise the importance of finding gaps in which the user would perhaps choose to navigate through. Rather than walking directly through the walls of a closed surface, the intent was to navigate through the gaps in the surface. This image is meant to evoke the desire to explore the internal space of the form by entering from the underside. For the following experiments, it will be important to consider lighting as a key element to create spaces which are compelling to enter.







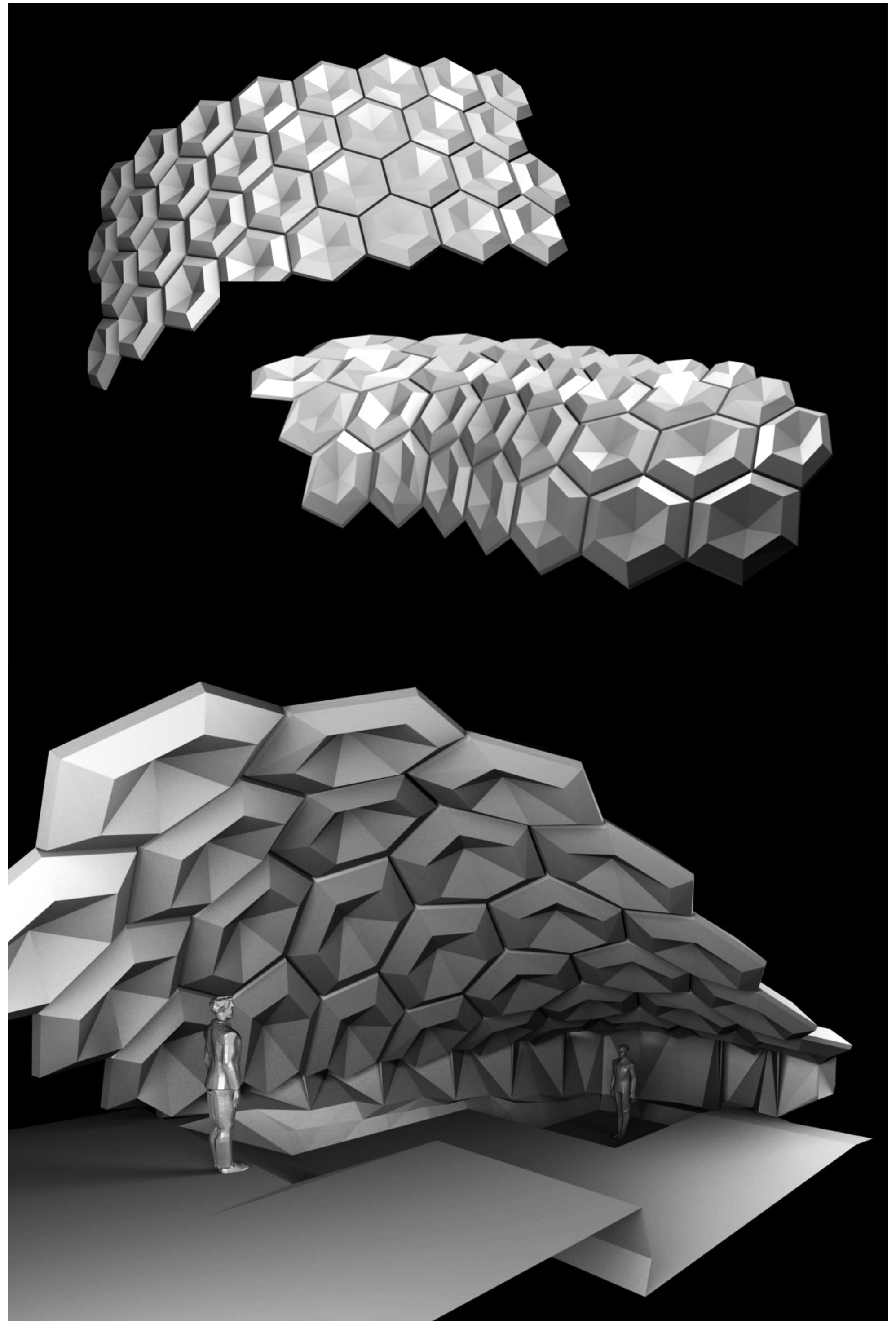
Surface Scale

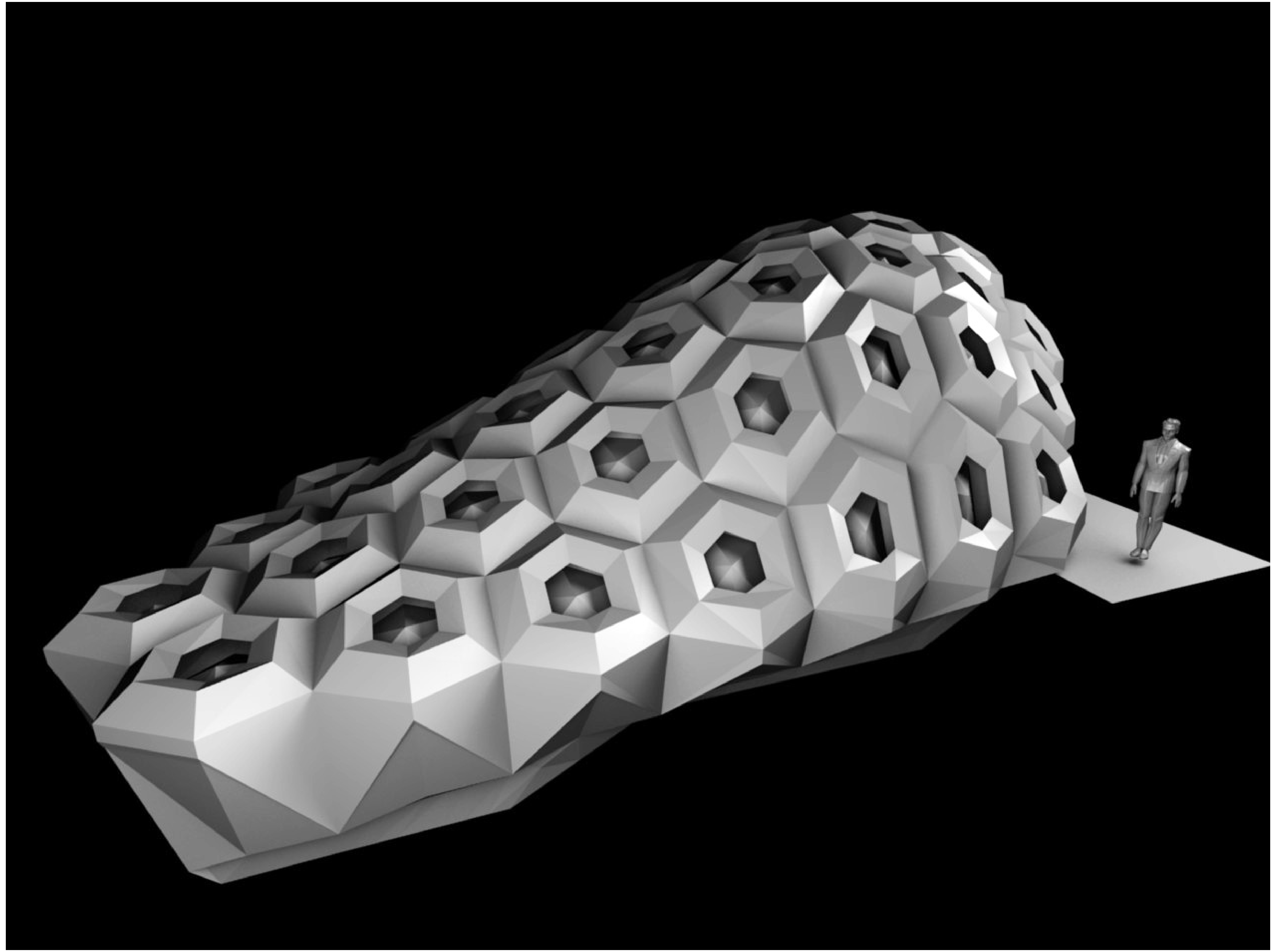
Space Experiment 6.

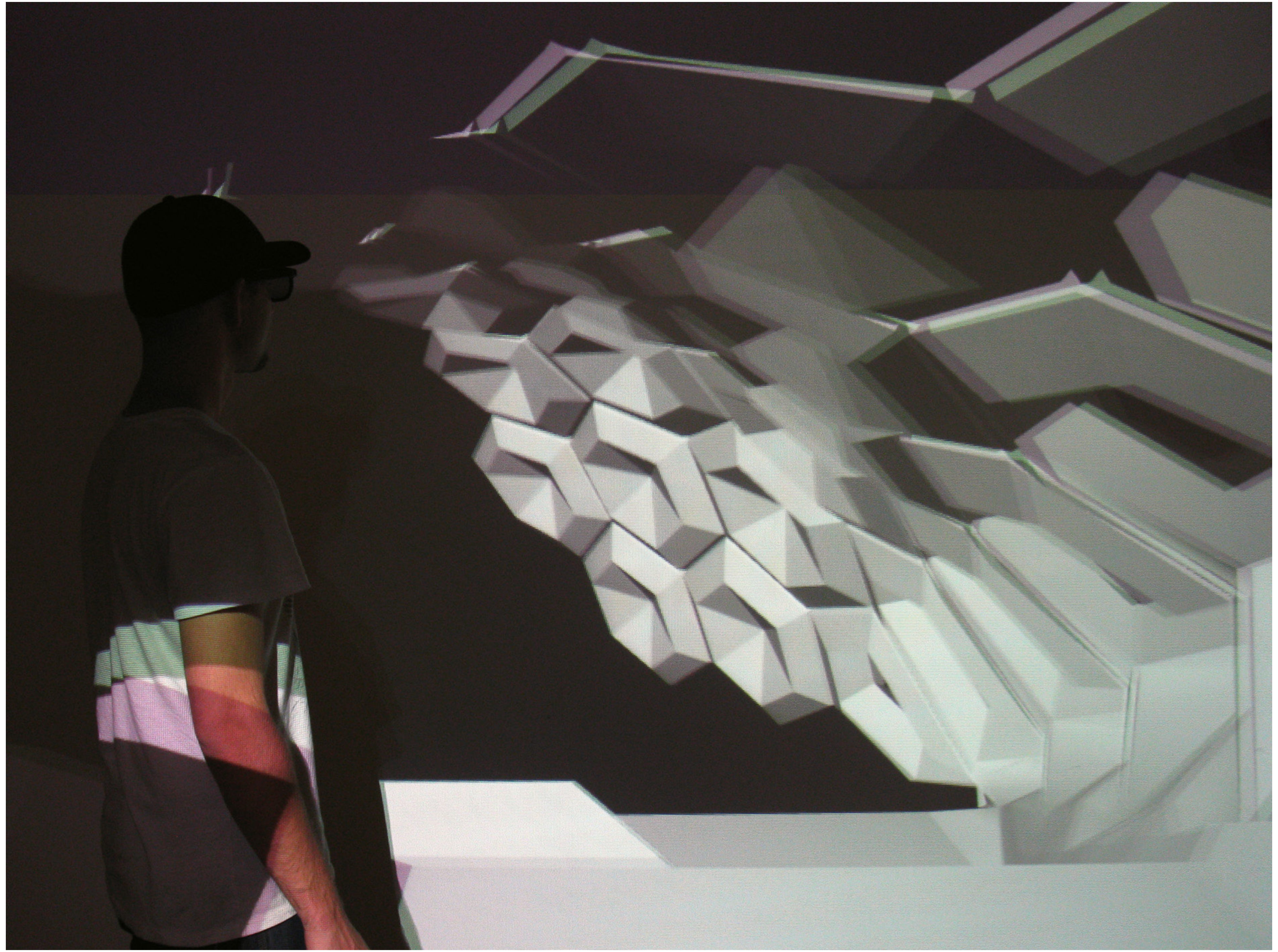
In this experiment the notion of scale was explored by introducing a 6 foot person to the design. The addition of a person can provide a reference as to the scale of the surface and the space. In addition, a cascading floor was added and holes for light added to the exterior surface. The idea was to develop the design to make it more real in terms of a surface exploration.

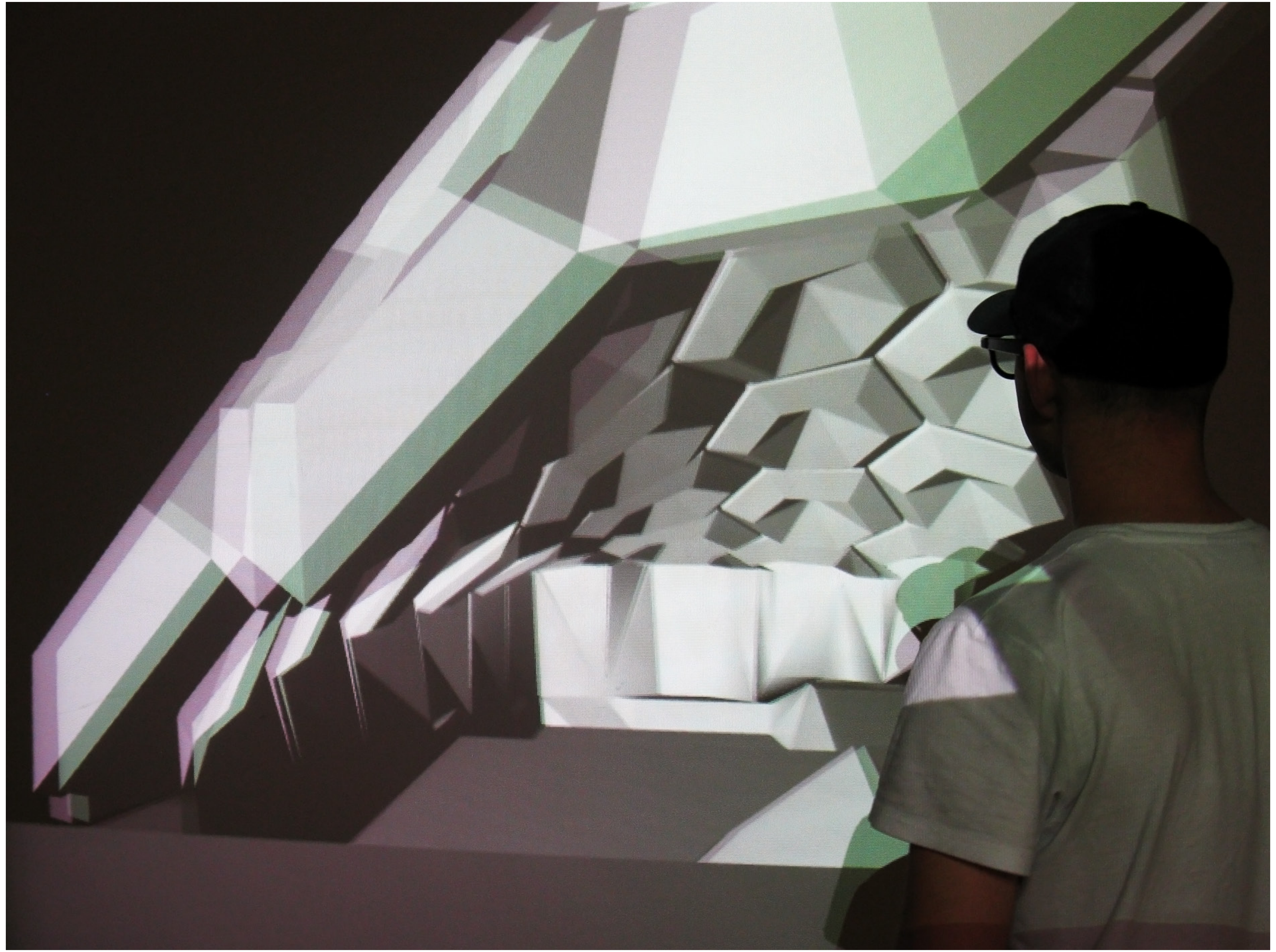
This was an attempt to create a functional space in which a person could inhabit. The model is composed solely of six sided components. It has been dubbed the 'Pineapple Pavilion' as its appearance draws on the exterior husk of the fruit. It shows the variety in which surfaces can be shaped and additional elements can be added to create a more holistically defined space.

Once the model was displayed within a stereoscopic environment, it was found that it was difficult to envisage the scale of the object, even with the addition of a human form. This is illustrated in the image on the following pages.







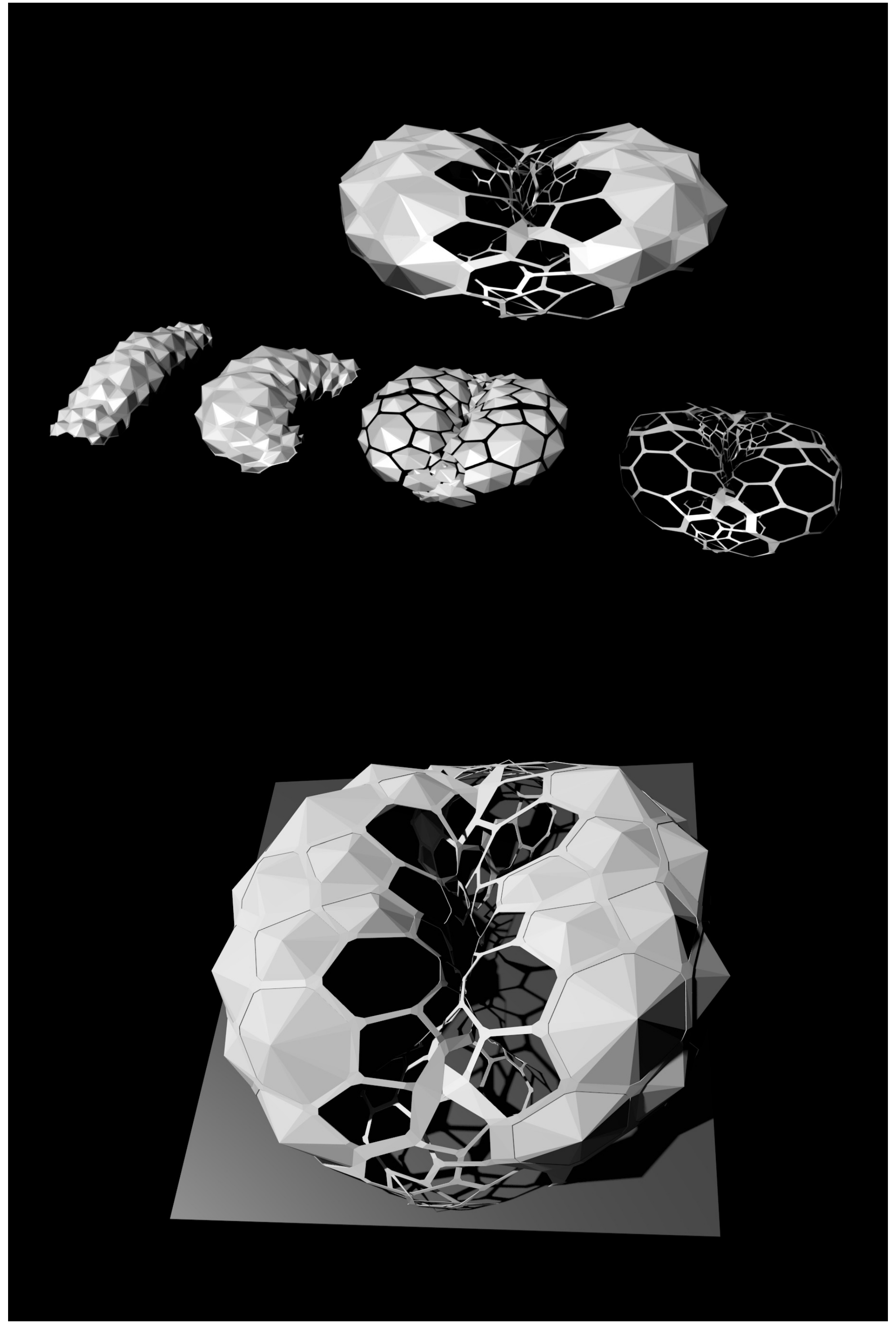


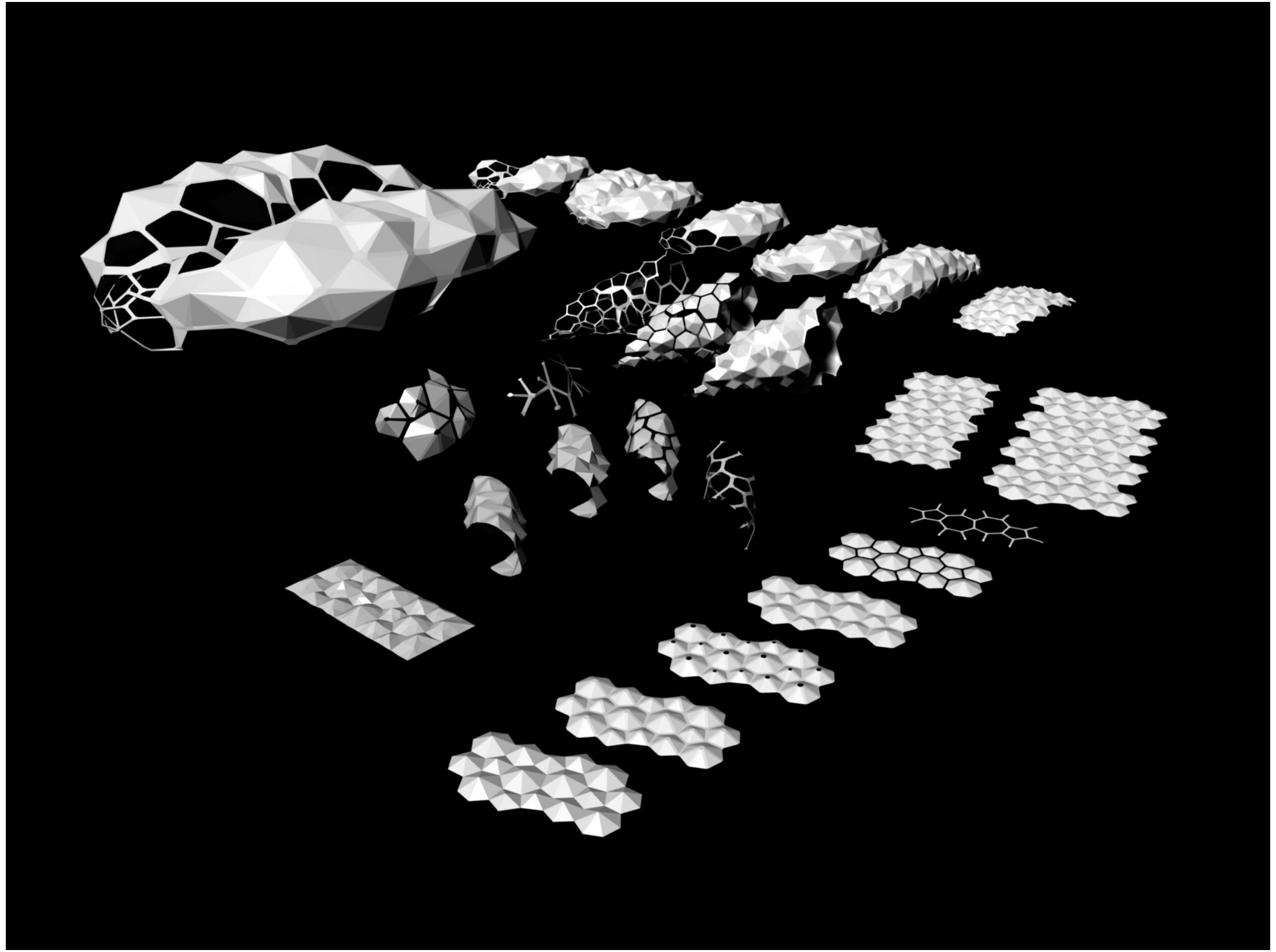
Organic Structures

Space Experiment 7.

In this experiment the notion of organic structures were explored as a formal configuration to embrace the immersive qualities of 3D stereoscopic projection. The idea was to use the bevel structure developed in Digital Experiment 9 to create a larger inhabitable structure. In this instance the bevel plays the role of tying each of the 5, 6 and 7 sided components together. It would be cut and constructed from a sheet of thick steel. This experiment is largely hypothetical in its use. It does however indicate the potential to combine folding materials with structural supports and to clearly separate these visually.

The continued use of the 'graveyard' illustrates each of the transformations that were necessary to achieve an interlocking structure in which the surface mesh does not intersect. It illustrates the comparison between internal parts and bevel structures. This experiment was successful in highlighting the opportunities of developing an organic structure that is more suitable for development within 3D environments than conventional 2D renders. This issue was addressed further in the next experiment.



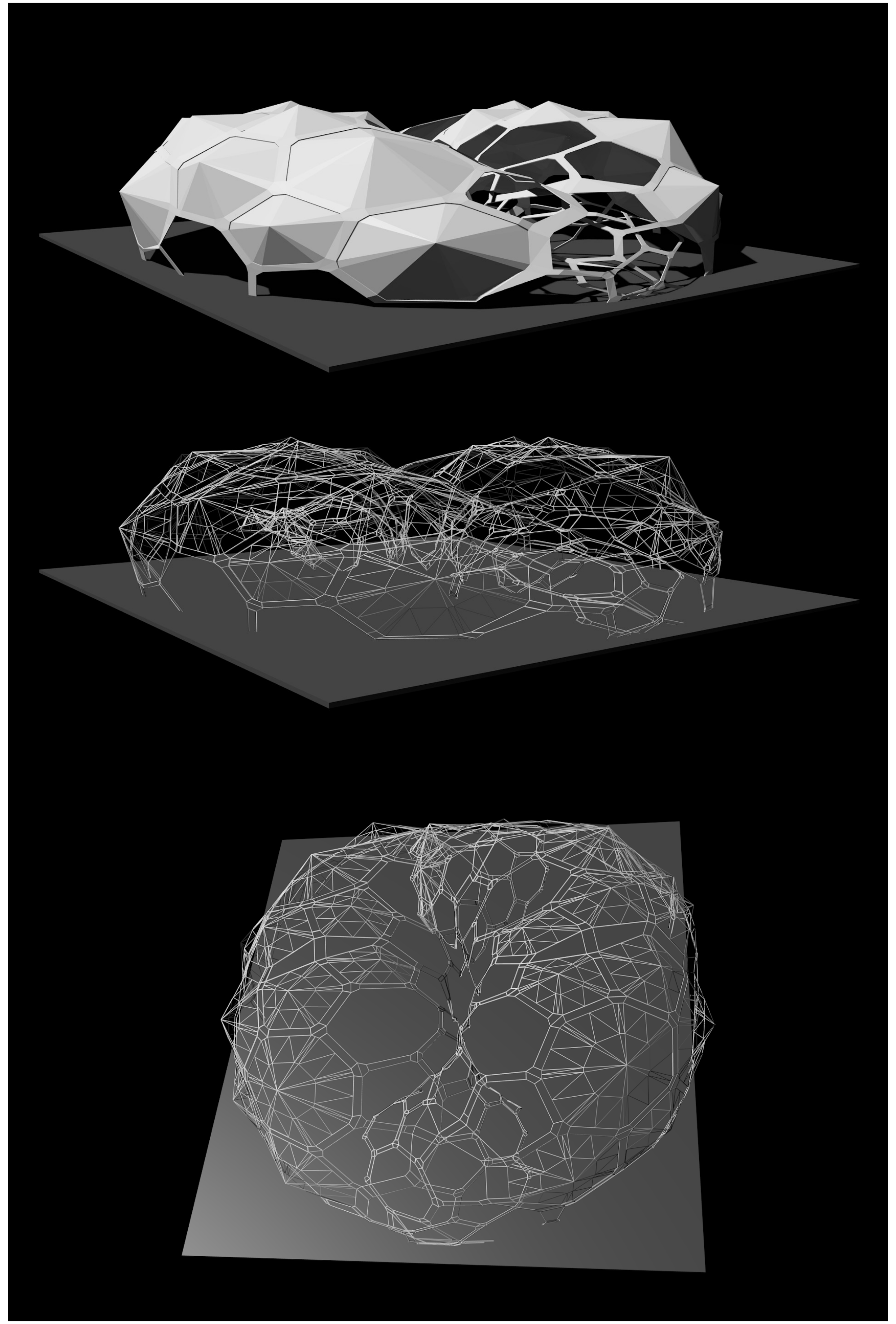


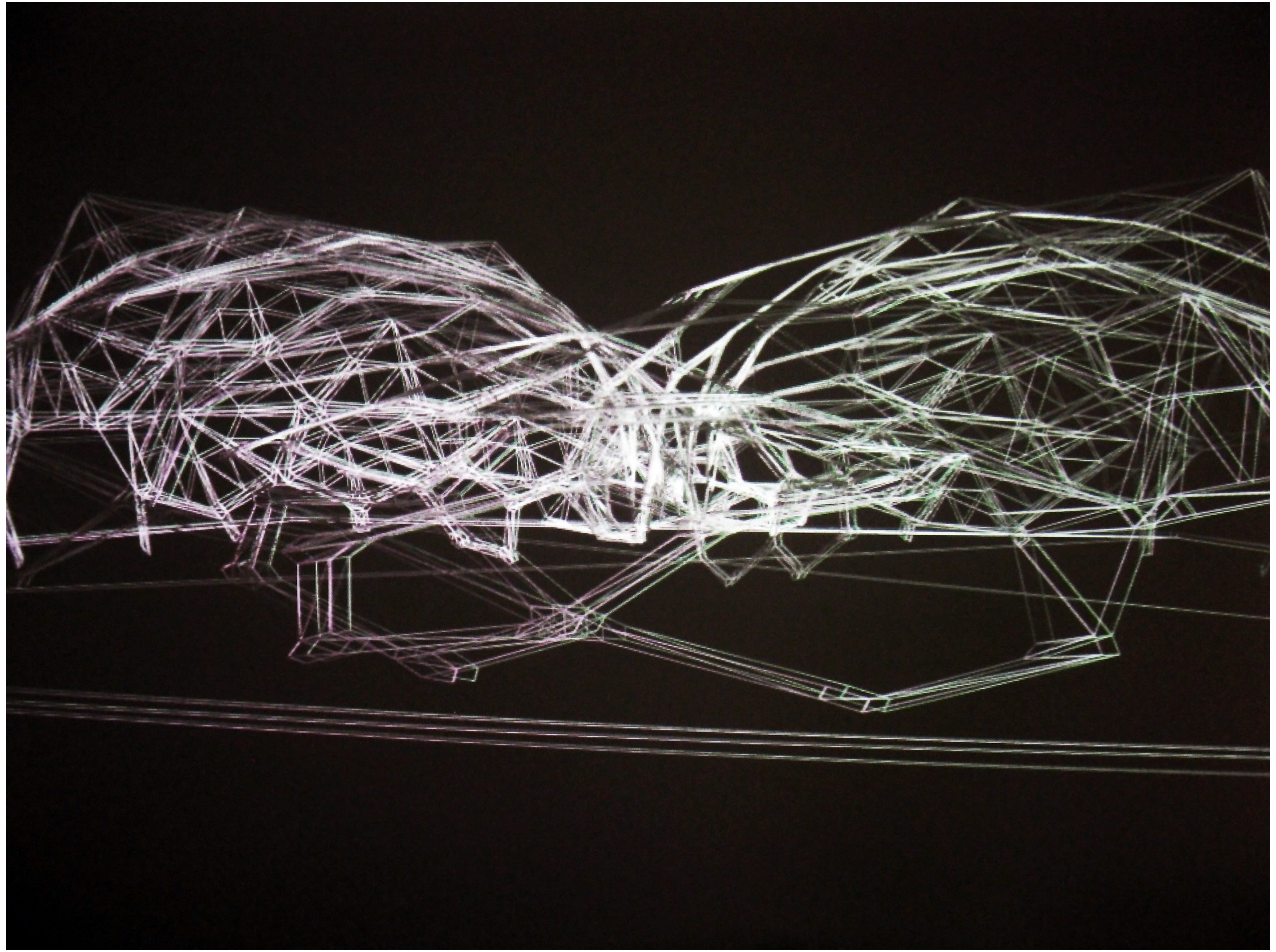
Mesh Visualisation

Space Experiment 8.

In this experiment a wire mesh was introduced to indicate the difficulty of interpreting organic forms and spaces that are rendered in 2D. From the images to the right it is very difficult to perceive the depth of each interlocking truss. The images are so unidentifiable that one questions which surfaces are in the foreground and which are in the background.

This highlights the importance of utilising 3D immersive environments to explore spaces that are not immediately identifiable. In 3D, the frames are separated from each other and the depth is clear to see between each of the interlocking surfaces. In a model such as this, with interlocking components, it is vital to explore the space both to look for mistakes as well as begin to interpret how elements may be added or removed to prepare for the transition to physicality. In any case, it is difficult to see how a form such as this could be inhabited and it is just as hard to capture that with a photograph.





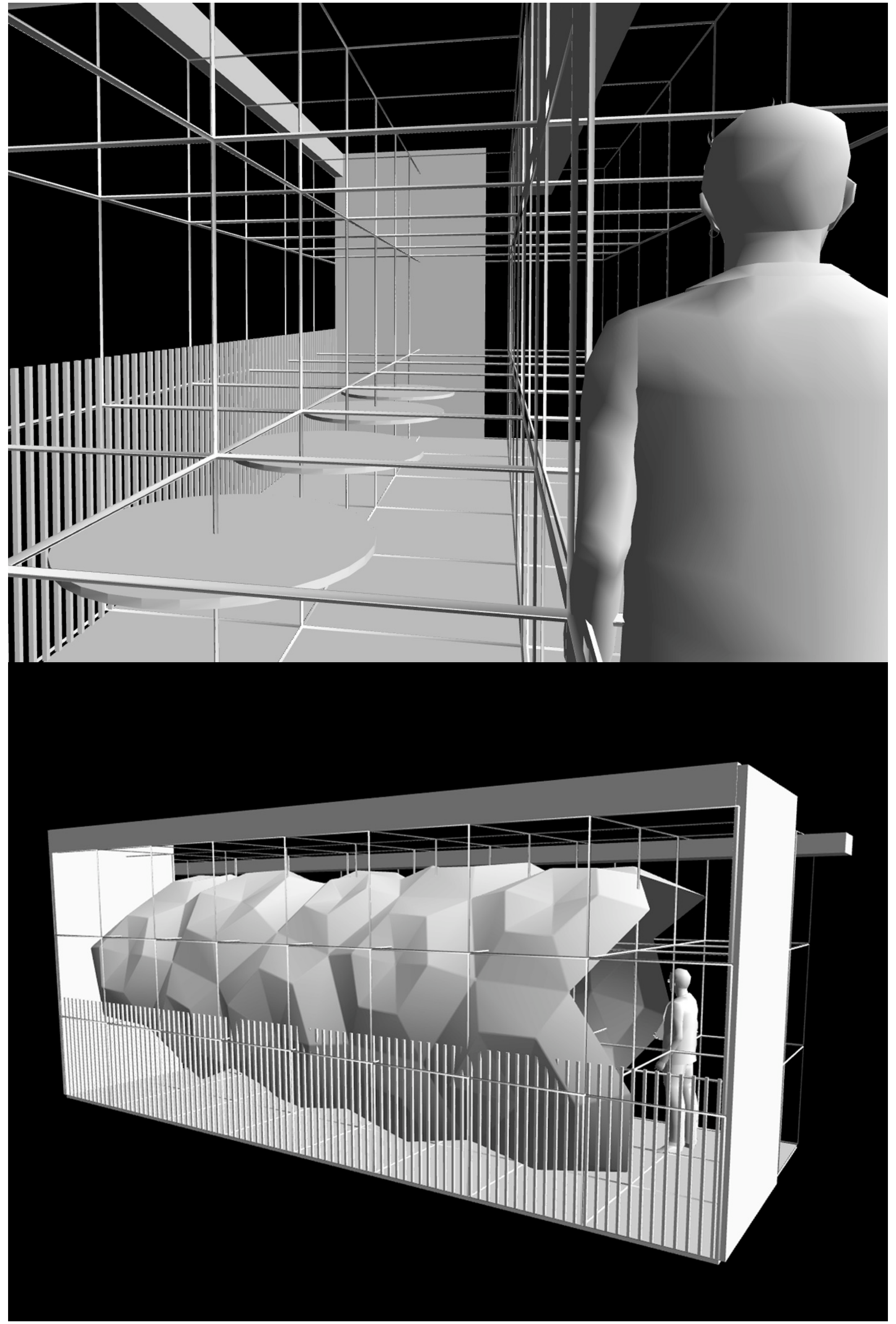
Situating the Object

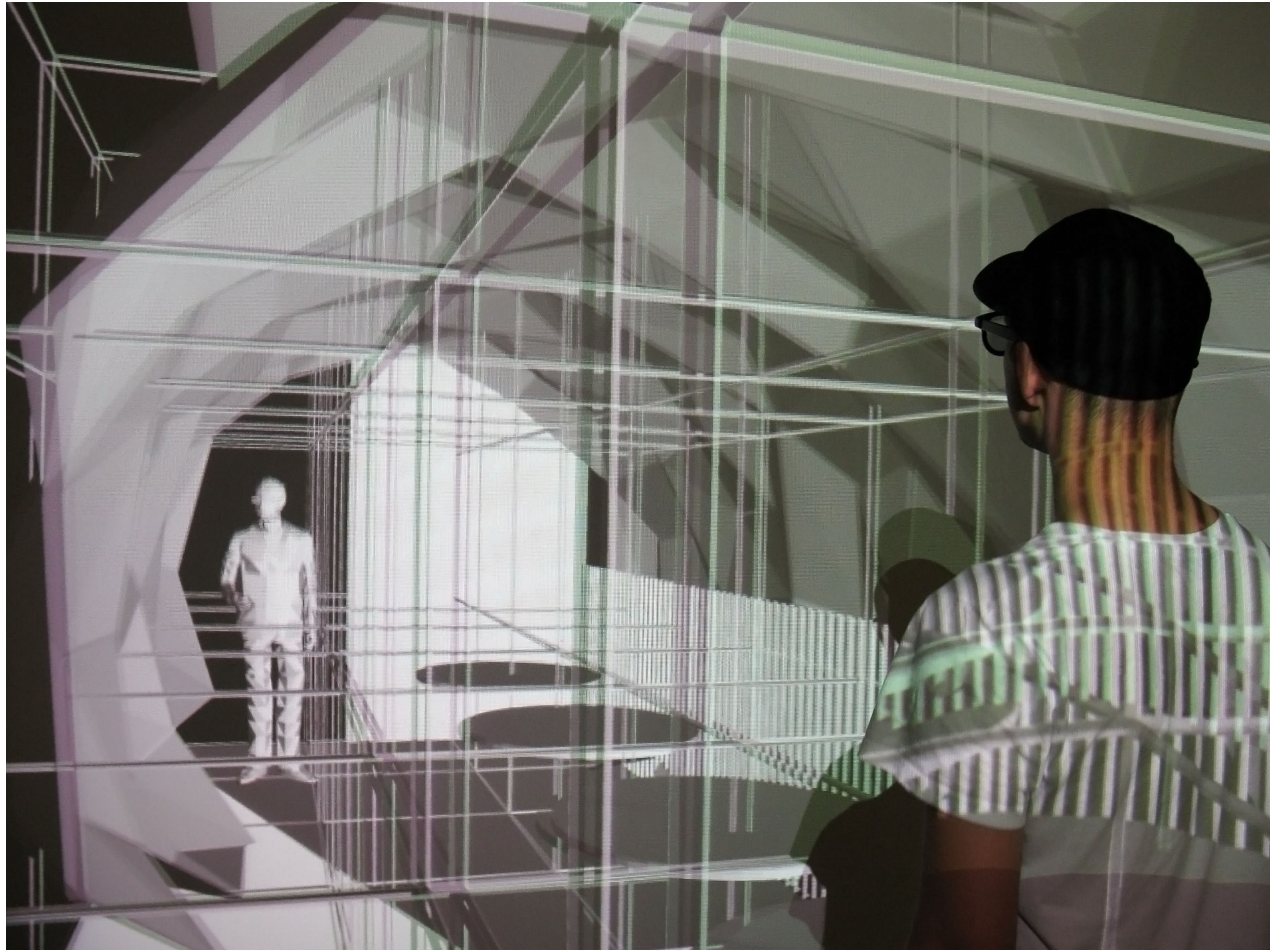
Space Experiment 9.

This experiment was an attempt to situate an object within a real physical space or site, and the first attempt to situate the final composition within a tangible space. In this case a walkway adjacent to the stereo projection space was chosen because of its immediate vicinity to the projection environment. Therefore it would be easy to visualise the physical walkway space within a 3D immersive environment. The walkway was measured and 3D modelled. Then a 3D grid with spacing of 1 m was added to indicate the size of the space and to assist in the development of a suitably scaled model.

The idea of using a walkway was developed from the notion of walking through a virtual space and walking through that same space physically. From this, a comparison could be made between both virtual and physical spaces and the relationship between them.

Situating the object within a tangible space helped to ground the form. However, because the walkway already had a function, it could not have a separate function independent of its function as a thoroughfare. This limited the possibility to convey its own meaning without the walkway dictating its own purpose. For this reason it was more important that the composition directly engage with the 3D projection space and let it find its own meaning acting between virtuality and physicality.



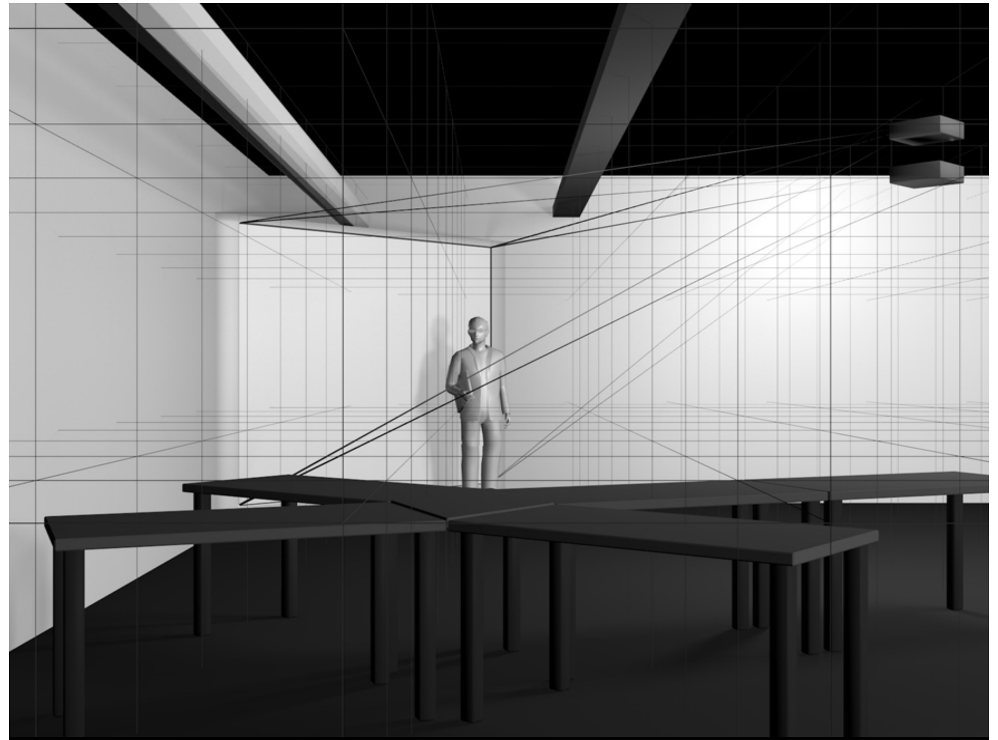


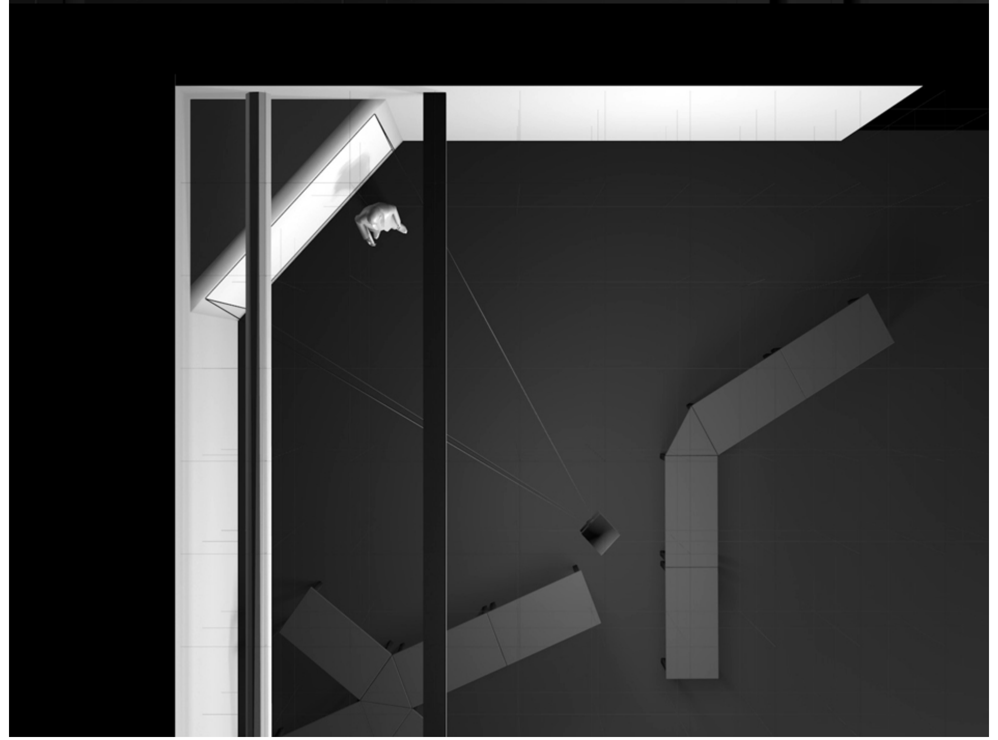
3D Stereo Space

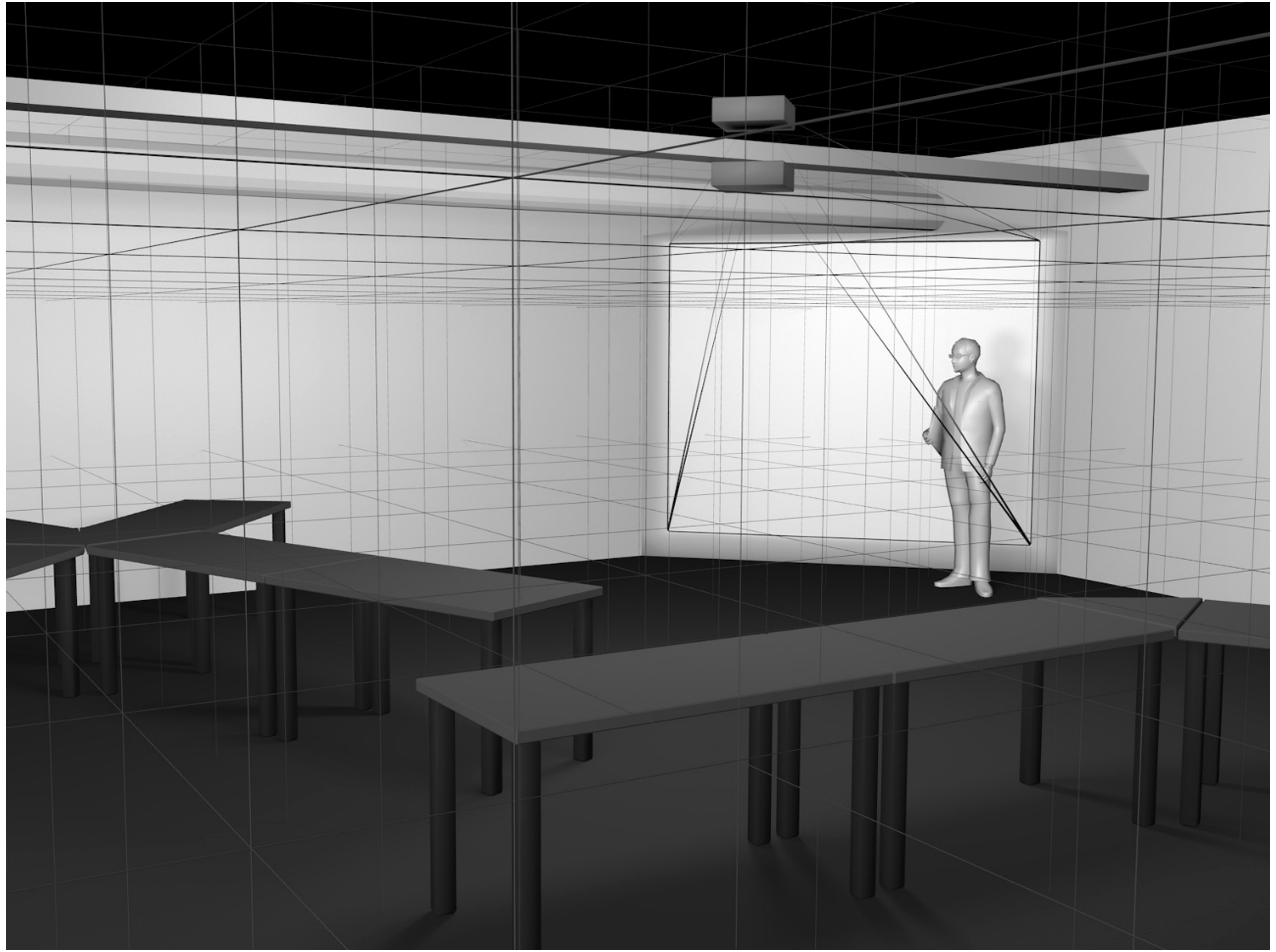
Space Experiment 10.

It was decided that the location for the final composition would be within the 3D stereo projection space so that there was an opportunity to directly engage with the 3D projection. In this way the inter-relationship between virtual space and physical form could be explored together as a single experience. In other words there would be an opportunity to blur the boundaries between the two realities and make a statement about the benefits of working between these two mediums.

The space for the final composition was measured and 3D modelled in Blender. A 1 meter 3D grid was added to better understand the depth of the space. A projection screen was the central aspect and would be the focus of the space. The final composition had to work within the confines of the room, which had maximum boundaries defined by the ceiling, walls and floor. The existence of tables and other aspects of the room were permanent, including the ducting for wires and the projectors themselves. These were the major constraints of working within the confines of the room.







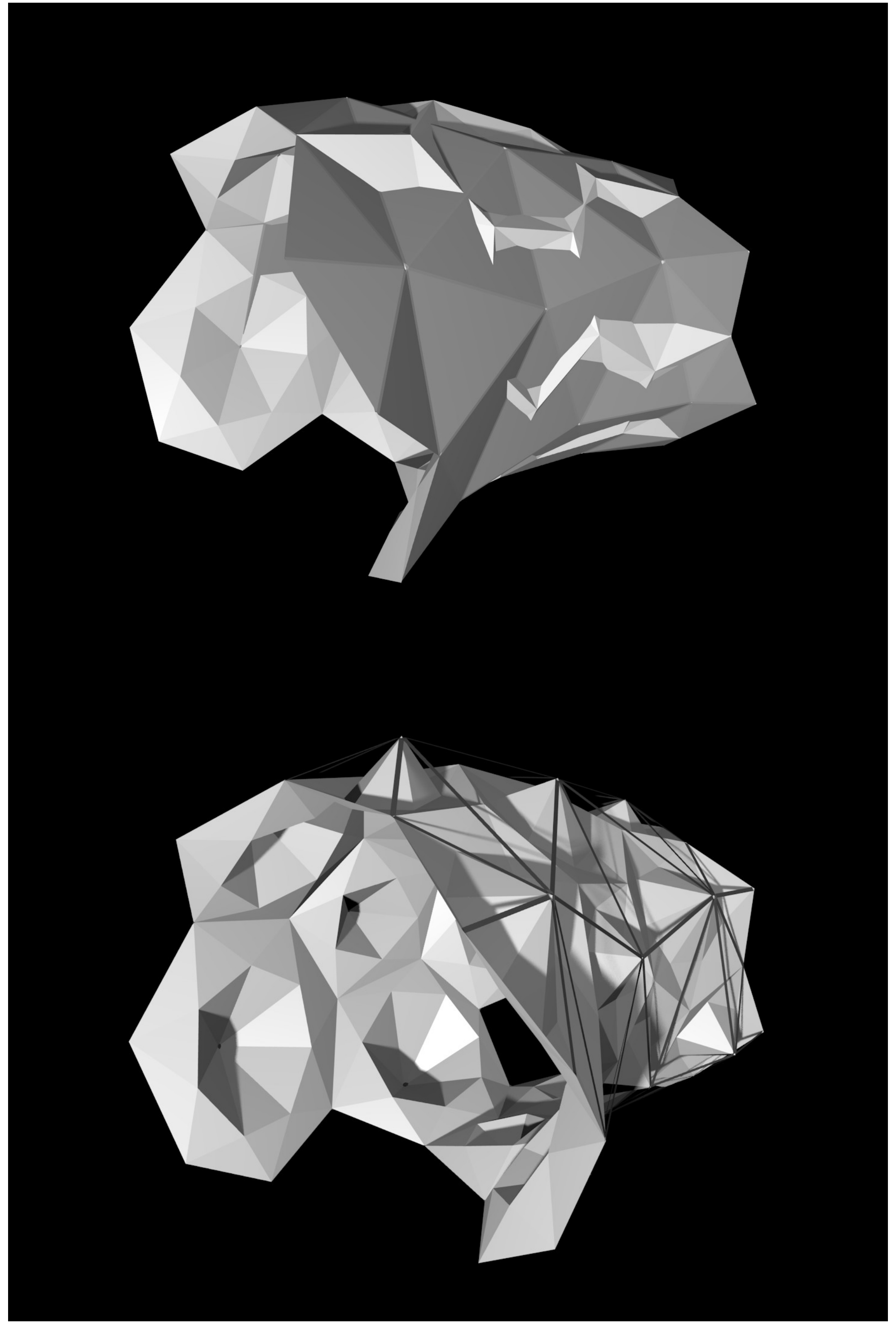
Form Development

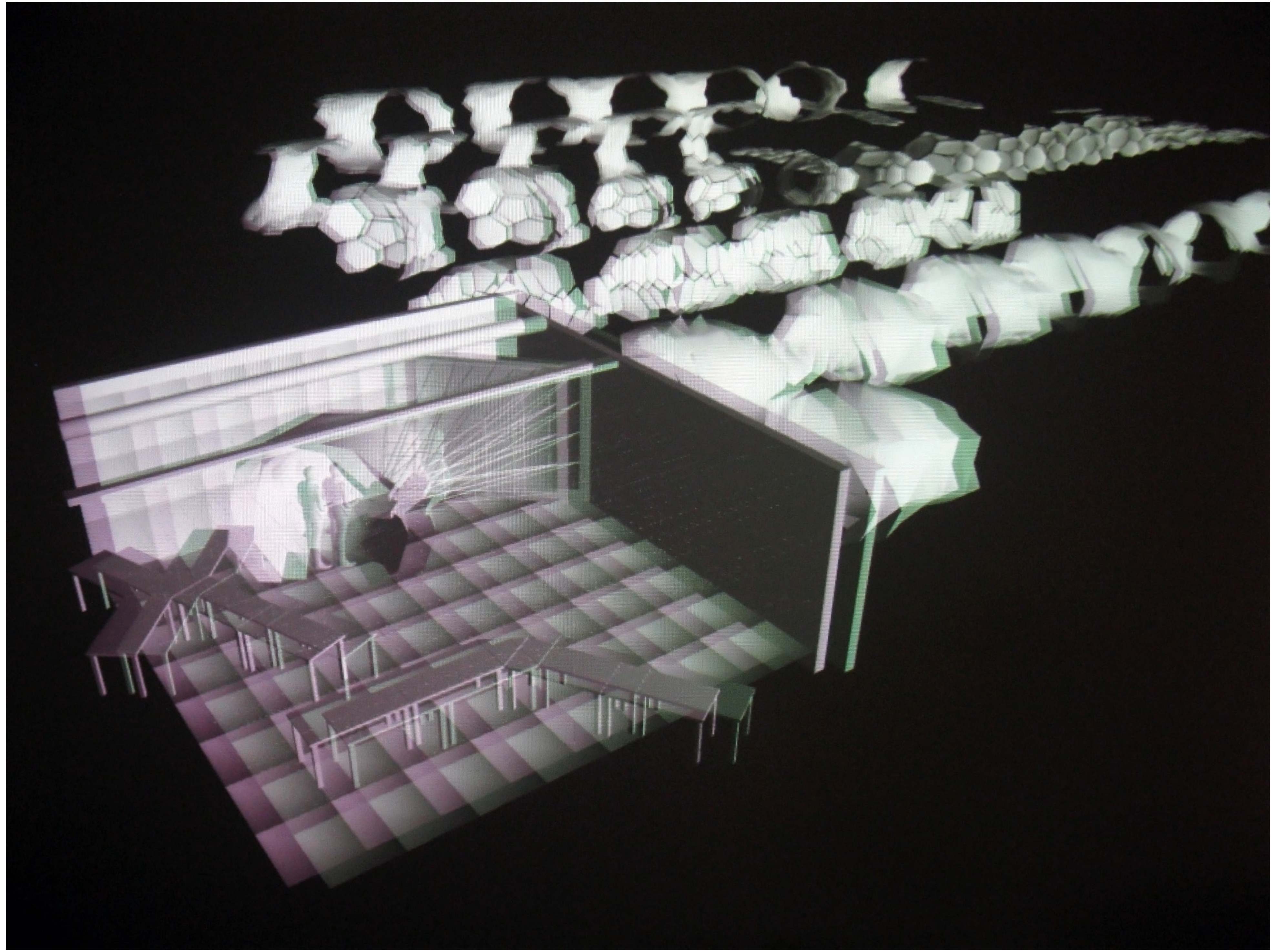
Space Experiment 11.

In this experiment the form of the design was developed to enclose a person. A series of surface warps were used to modify a single strip of components into a tube, as illustrated in the 'graveyard' on the following page. This tube was then twisted and one end was rescaled. The components were then placed to face outward on the inside of the cone in order to emphasise the importance of stepping within the space, rather that observing it from the outside.

The next step in the design process (shown in the two images on the right of this page) illustrates the importance of fine tuning the form in order to remove all of the intersecting surfaces. The top image indicates how the inside and outside surfaces would intersect if the form were not modified. This is shown through the use of a lighter interior wall and a darker exterior wall. The bottom image illustrates the addition of wires connecting each of the central points. This was a method in which to modify the interior wall to avoid intersection with the exterior wall.

The method of using a twin wall surface was the same as the final experiment developed in the Digital Manipulations stage. The central point of the cone on each component was triangulated with each of the other closest points. It is this triangulation that provides structure for the components and effectively locks each shape into place. The points were then manually tuned by either scaling all of the points together or each individually.



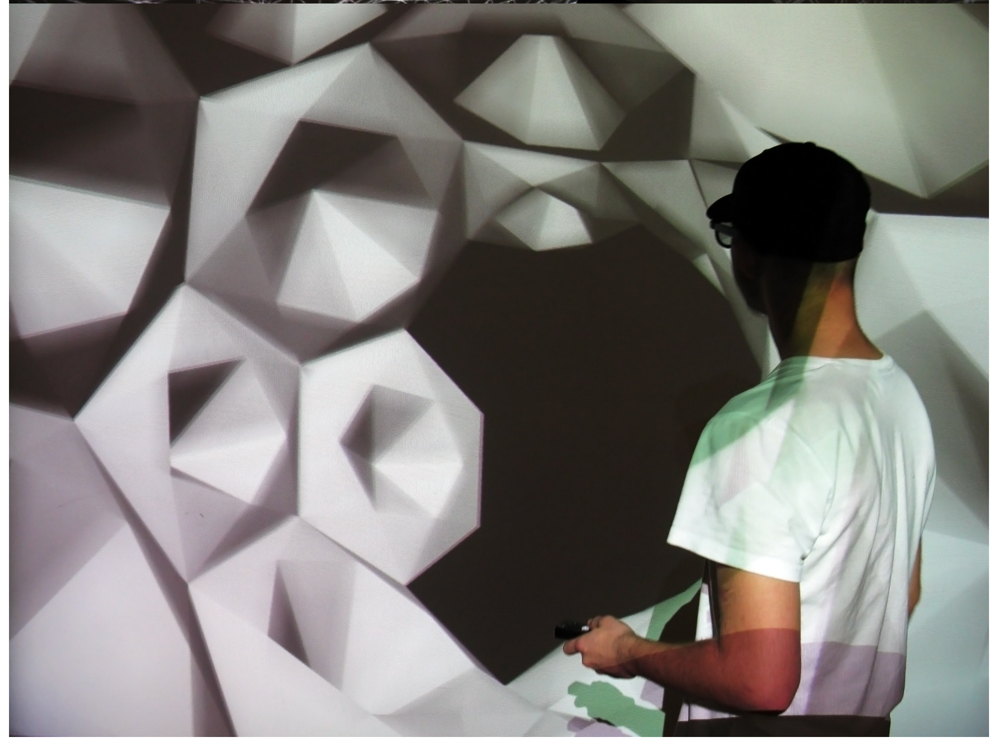


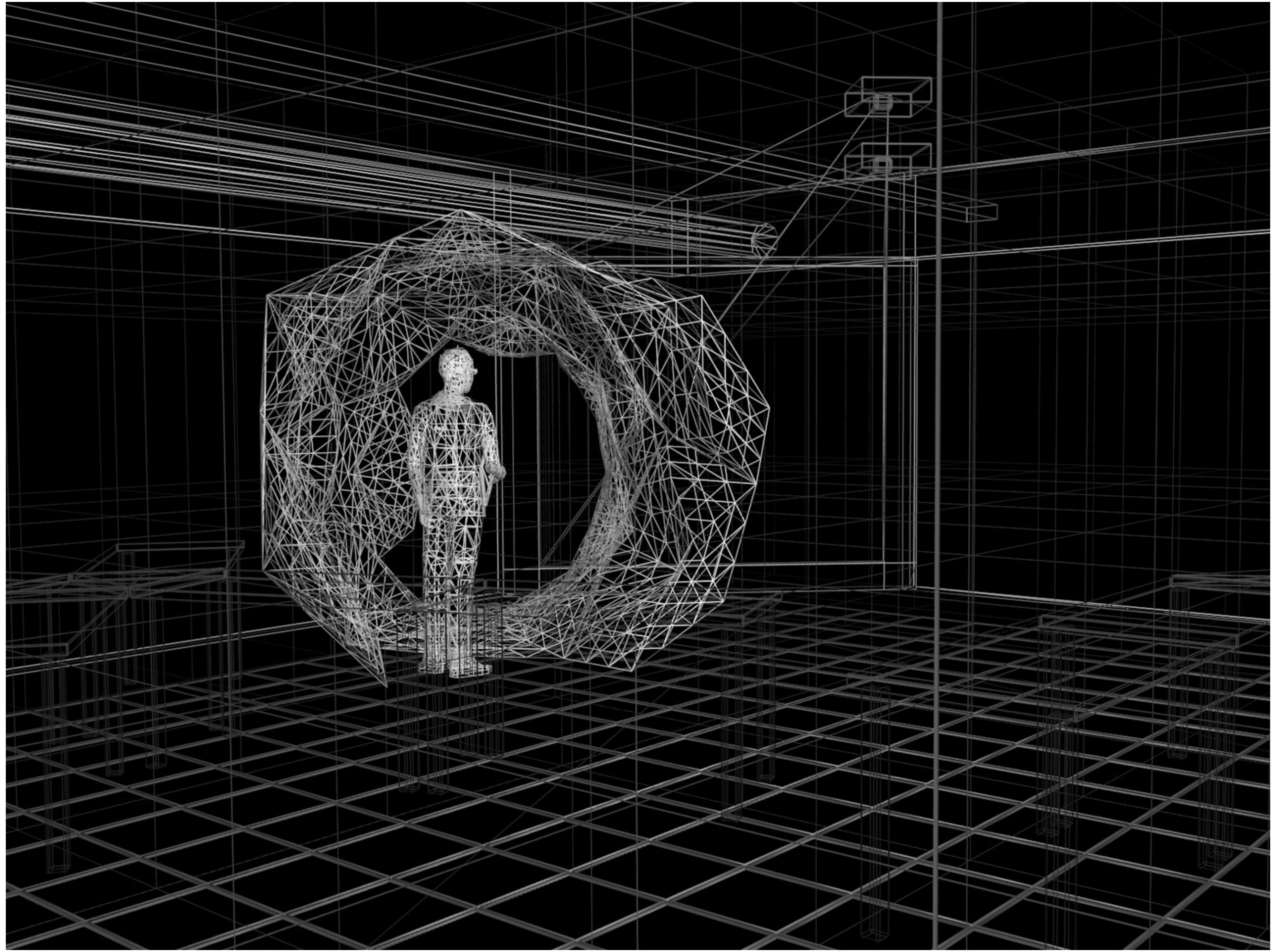
Spatial Inhabitation

Space Experiment 12.

In this experiment the model developed in the previous experiment was further explored by subdividing the surface into a more dense wire mesh. In this way, when viewing the model in a wireframe mode, it was easier to distinguish the structure within the stereoscopic environment. This technique of subdividing surfaces highlights the form of the surface but also allows the user to look through the surface and gain a greater understanding of the thickness of the form and the relationship between its inner and outer walls.

The purpose of this experiment was to situate the design next to the stereo projection so that both the virtual and the physical could sit side by side and present a direct comparison between the two representations of the model. This was explored further in the next experiment by selecting a portion of the model for physical fabrication.





A Physical Comparison

Space Experiment 13.

In this experiment the model developed in the previous experiment was further explored by subdividing the surface into a more dense wire mesh. In this way, when viewing the model in a wireframe mode, it was easier to distinguish the structure within the stereoscopic environment. This technique of subdividing surfaces highlights the form of the surface but also allows the user to look through the surface and gain a greater understanding of the thickness of the form and the relationship between its inner and outer walls.

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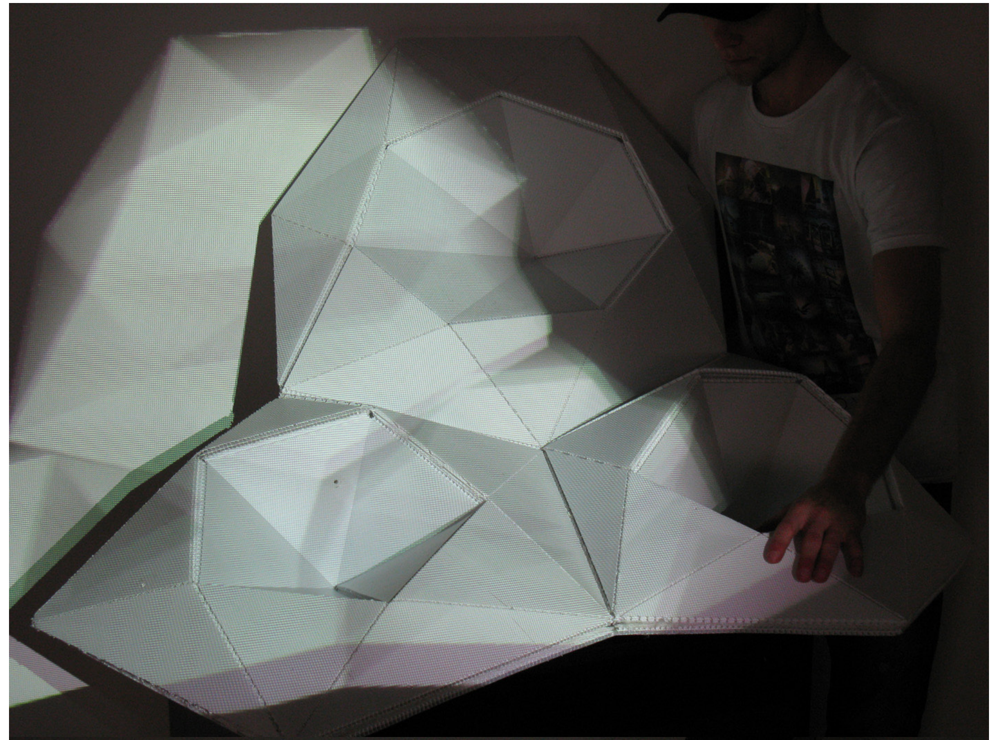
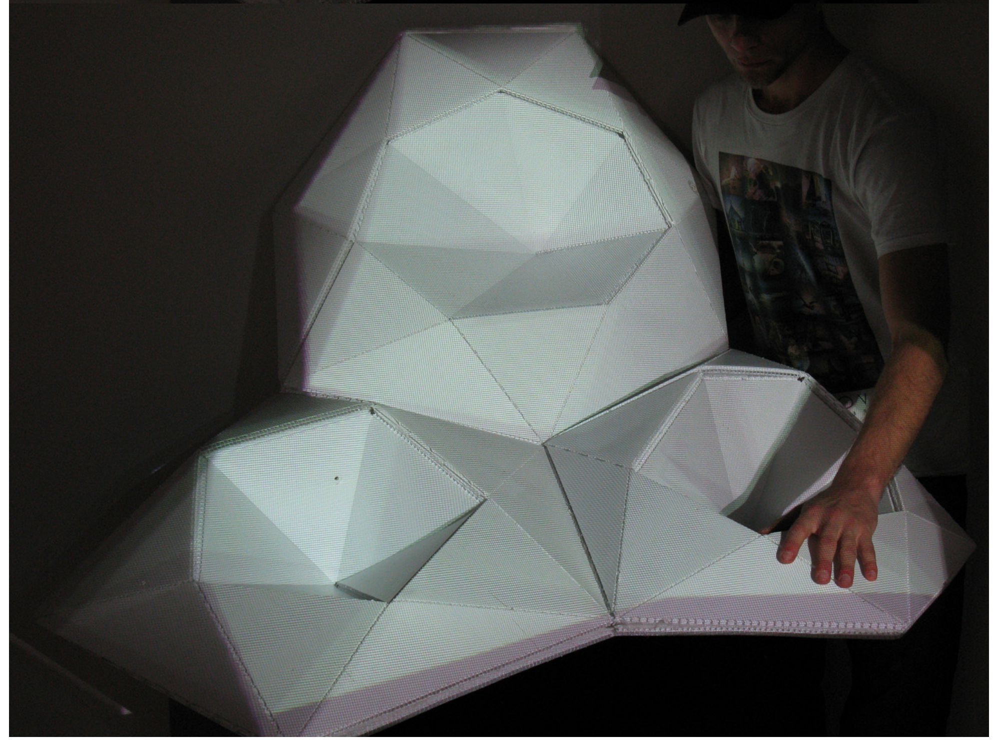
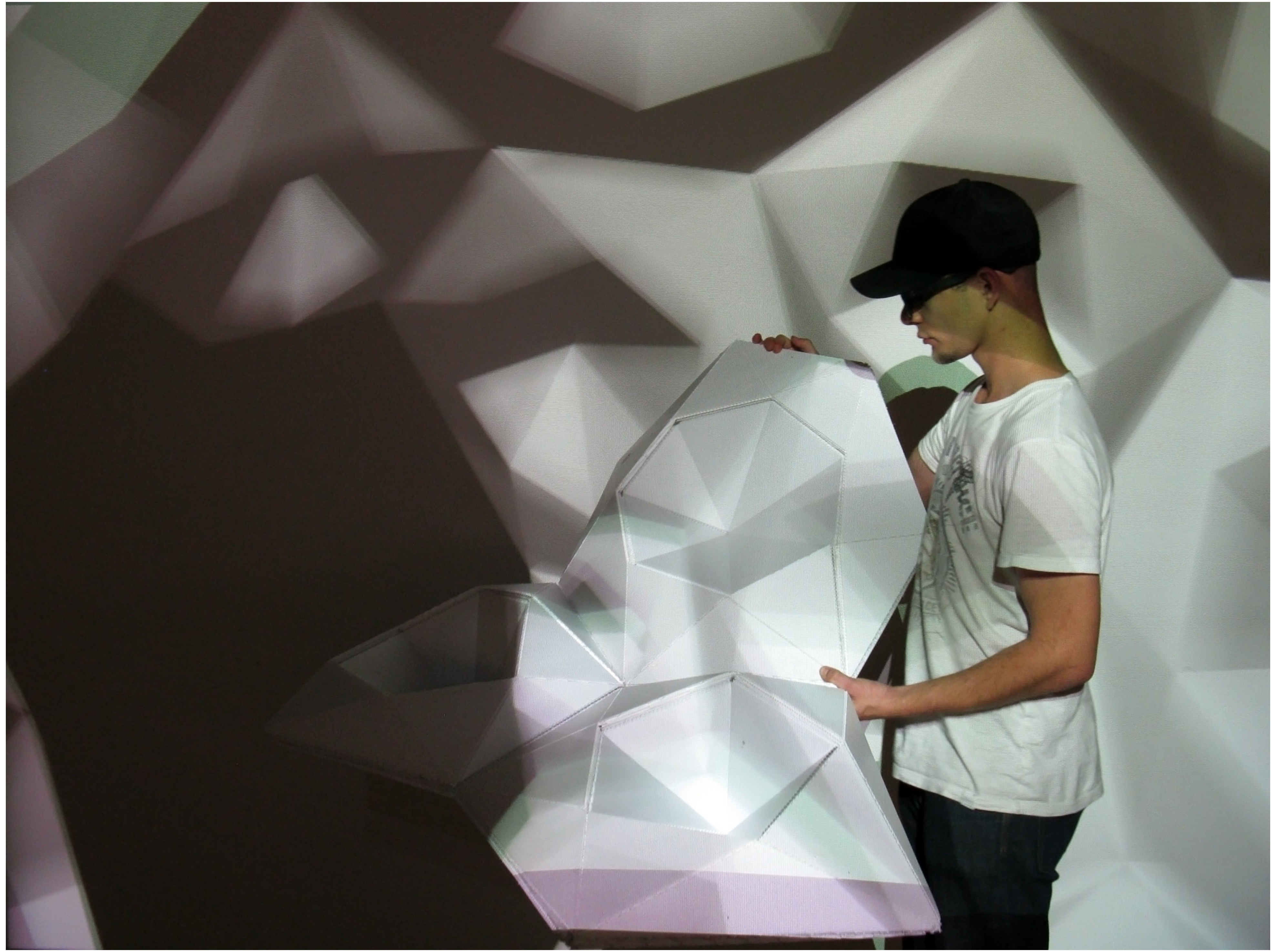






Summary of Findings

In the experiments described in this Chapter, a series of 3D visualisations were explored covering a broad range of concepts and strategies that could be developed as part of the Final Design stage in this project. While this Chapter investigated the making of virtual models, these needed to be able to be translated into physicality.

Entry into 3D stereoscopic projection systems first involved an investigation of the hardware and software required to view a model from Blender in 3D. This resulted in the development of a Max MSP/ Jitter patch called the Stereoscopic Model Viewer. This investigation included the development of a wireless remote control (Wii remote) that could be combined with the patch to provide a navigational interface in which to interact with the models. Observation from many different angles, including the ability to observe and experience structures from within, assists in satisfying a designer's curiosity in form and space.

3D stereoscopic environments provide a fresh insight into the form of an object within space, and offer greater clarity and understanding during the decision making process. The aim of these experiments was to embrace the use of this technology by creating virtual spaces that would be more easily understood with an immersive experience than with a 2D computer monitor.

The experiments began with investigations to derive the optimal visualisation qualities to view folded objects and their faceted surfaces in 3D. A great deal of experimentation was undertaken to determine the suitability of a model for viewing in 3D. Suitability was determined by how close to reality the 3D visualisation represented the qualities of a physical model.

A selection of models concepts developed in the Digital Manipulations stage was expanded upon for visualisation in 3D. What were previously viewed as small parts of a surface were expanded into large arrays. These could be warped and twisted to envelope a person and create forms in which to experience spatial qualities that would only be achievable with 3D immersive environments.

The notion of scale was explored in these experiments as means through which to situate a person both inside and outside a space. The designs eventually needed to be situated within a site and the space in which the projection environment was 'housed' was identified as a key location for making. It provided the opportunity to build a structure that would directly engage with the 3D projection.

Outputs within this section of the project were aimed at refining the visualisation qualities of the design and the effective representation of a physical prototype. From the strategies for investigation raised in the introduction of this Chapter, the following concepts were identified as key elements for success.

Capability to interactively engage to gain understandings

Methods of visualisation that express design construction in a 3D immersive environment expand the designer's understanding of form and structure. This is achieved through a greater sensory understanding of space, in which a 'sense' is an intuitive or an acquired ability to estimate the perspective of a 3D environment. With 3D glasses you add an extra layer of tangibility, turning non-sensical 2D information (lines and solid faces) into readable 3D spaces. In this way, for example, the intangibility of wireframe structure represented in 2D can be viewed as a tangible 3D space. Spatial immersion, as well as the ability to look from outside and within, achieved an alteration of one's perception of form and space. It meant that these could be analysed for new interpretations without old preconceptions, and provided a holistic understanding of the design.

In these experiments the design of the mesh was used as a tool for triangulating points in space. It was found that after the orientation of the user and the object was established, a more in-depth perspective of form was possible. The use of a faceted surface, and the use of lighting as a way in which to create spaces that were compelling to enter, enhanced the visualisation of surface, form and space. Such methods could assist in representing the form as it might be, rather than simply as it actually is.

Situating a virtual object in physical space

A model without orientation and floating and rotating in a boundless hypothetical environment is more open to reinterpretation than it would be if it were contextualised within a set placement. This allows the viewer the opportunity to perceive the object as both form and space without the biased presumptions of a physical or virtual location. However the stereoscopic environment can also be used as a tool in which to contextualise an object. This allows a designer to have a greater understanding of the space within a real site and gain a better understanding of the orientation of the design. Within this project, spaces were explored as both an object without context as well as the context for situating an object in physical space.

The use of the ground plane was integral to the notion of establishing the orientation of an object. This was aided through the use of the navigation controller which restricted the movement of the model and ensured it would never rotate abnormally. Simultaneously, the situation of the model within a physical setting heightened the sense of realism. Situating the design within physical space would also enable a comparison of the physical and the virtual to take place.

Biomimcry and developing organic structures

One of the findings of the earlier stages of research, and extended into these experiments, was the notion of representing the visual aesthetics of biomimicry and organics. An organic form is typically composed of a number of heterogeneous or diverse parts, which emphasises the natural qualities of the ability to grow, adapt or evolve, where change is steady or gradual. Biomimicry draws from the patterns and complex geometries found in nature and applies the concepts of functionality and form. In these experiments, this was represented through modular construction systems and through digital manipulations as mutations.

The capabilities to explore surface geometries were more pronounced in this stage of the research. It was found that the modifiers in Blender could shape the surface organically. This was possible through the use of shape modifications such as curves, twists, warps, and repetitions to make the forms appear organic through complex asymmetrical geometries.

The immersion achieved with a 3D stereoscopic system was also developed as a means through which to visualise these complex geometries. This was done so that the designer could better comprehend the spaces in which they were operating and allow them to freely and confidently design ever more complex forms. They could do this with the assurance that they would be able to more easily explain it to their audience than through only the use of a 2D presentation.

Creating realistic representations to facilitate designing

In these experiments it was found that visualising in 3D was an important phase of the iterative design process. An immersive experience provided the ability for the user to minimise waste, not only of the time taken for tedious or laborious tasks, but also of materials. 3D stereoscopic immersion creates understandings that can reduce the time for actual construction. Errors incurred during large scale prototyping can be costly and result in large losses of time and money. Instead of using physical prototyping to test the qualities of a model, 3D stereoscopic visualisations can be used to reduce the cost of making multiple prototypes.

With larger scale constructions, the ability to inhabit space allows the user, designer, maker or builder to gain a full interpretation of the forthcoming construction effort. This is most important when the design of forms and spaces are beyond the scope of traditional fabrication. For example, a complex organic design may incorporate a great number of individually unique parts, interior spaces, or curvaceous faceted geometries. The opportunity to create 3D visualisations allows for rapid iterations to adjust and improve the design. It can also assist in the sharing of knowledge through visualisations, considering that many large scale fabrication projects are team based.

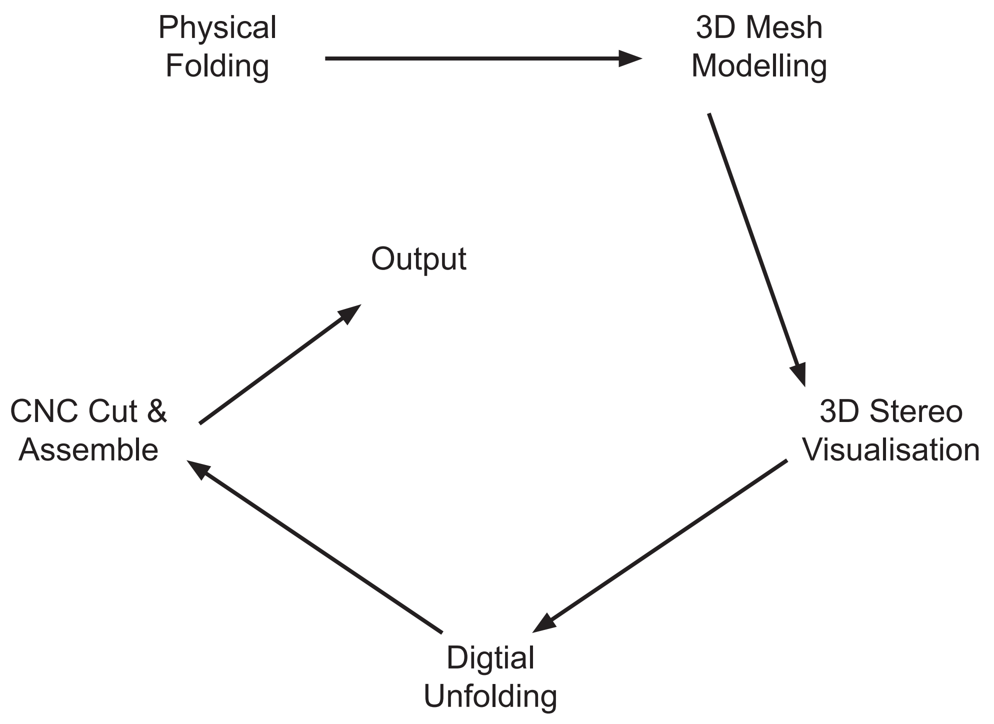
Final Design

This was the final stage of the project and a demonstration of the integration of each of the mediums identified in this research. The methodology of crossing between one medium and another created the unified strategy for visualising and making in 3D.

The full cycle between each of the mediums is demonstrated in this final stage. The 5, 6 and 7 pattern geometries were developed in the physical folding stage. These were digitally manipulated in 3D modelling software to make a final form/space/structure that could be experienced in a 3D immersive environment. This design was then unfolded and exported for digital fabrication through the use of CNC cutting. The cut patterns were then assembled to create the output.

The culmination of this approach was a final composition designed as a physical space in which to stand within, as well as a visualisation of the design which could be watched. This was intended to be a play on the interrelationship between the virtual representation of a form and the physical manifestation of that form.

This unified strategy illustrated in the diagram on the right crosses from the 3D modelling stage into the 3D environment, through the digital unfolding phase, CNC fabrication and assemble for reconstruction and finally reaching the design output.



Introduction

The purpose of this research was to take the key elements discovered throughout the Physical Folding, Digital Manipulation and Immersive Environments Chapters and apply them as an integrated process. Once an approach for developing form and space was identified, it was possible to create a final composition that demonstrated the culmination of the findings of this research and indicated a unified strategy for making and visualising in 3D.

Key findings from the three Chapters highlight the importance of creating structures that are flexible and have strength and integrity, and yet can be assembled with ease. The un/folded forms needed to work towards a seamless transition between the physical and virtual. Digital manipulations could increase structural integrity and allowed printing and assembly in order to minimise material wastage. Situating a virtual object in physical space provided more realistic representations and a more interactive experience between the virtual and the physical. These enhanced understanding of the design process for the development of organic structure.

The virtual world is a space that is not bound by the rules that govern the physical world. As such there are opportunities to explore form and space in a manner that could not be achieved physically.
The entry into the virtual world began by tunnelling inwards with a surface of 5, 6 and 7 sided components. The form of the surface was then expanded to create spaces that would engulf or envelop a person within. The idea was to not create fully enclosed spaces but to create forms that had spaces within which to stand and openings through which to walk. Some components were then removed to create windows through which the person could look back into the physical world. The further the person was from the entrance, the more unreal the surfaces became.

The constraints of the unfolding methodology meant that surfaces could not exist physically without structure or support and therefore the closer to the entrance, the more realistic the forms became. The tunnel was then projected outwards into the physical world as a fragment of the virtual space. The point was that it had to encapsulate the notion of a free and boundless environment and yet still be situated within physical reality. The key elements addressed in the earlier Chapters concerning the making of a physical form were utilised to assist in the transition from the virtual into the physical.

The final composition of this research was created as a metaphor to describe the interrelationship of a un/folding strategy that encompasses physical folding and construction as well as virtual modelling and 3D visualisation. This was an opportunity to use 3D modelling to create a virtual world in which we can step into and step out of. It is a play on the interlinking of virtual space, physical space and folded form.
The strategies for transitioning between the making and visualising of folded forms in 3D are demonstrated on the right.

Strategies for Demonstration:

• Demonstrate the design of physical form, space and structure that can be interlinked with a virtual experience.

• Demonstrate the blurring between the boundaries between virtual and physical spaces.

• Demonstrate and define a virtual and physical making strategy that allows for the fabrication and assembly of large scale prototypes.

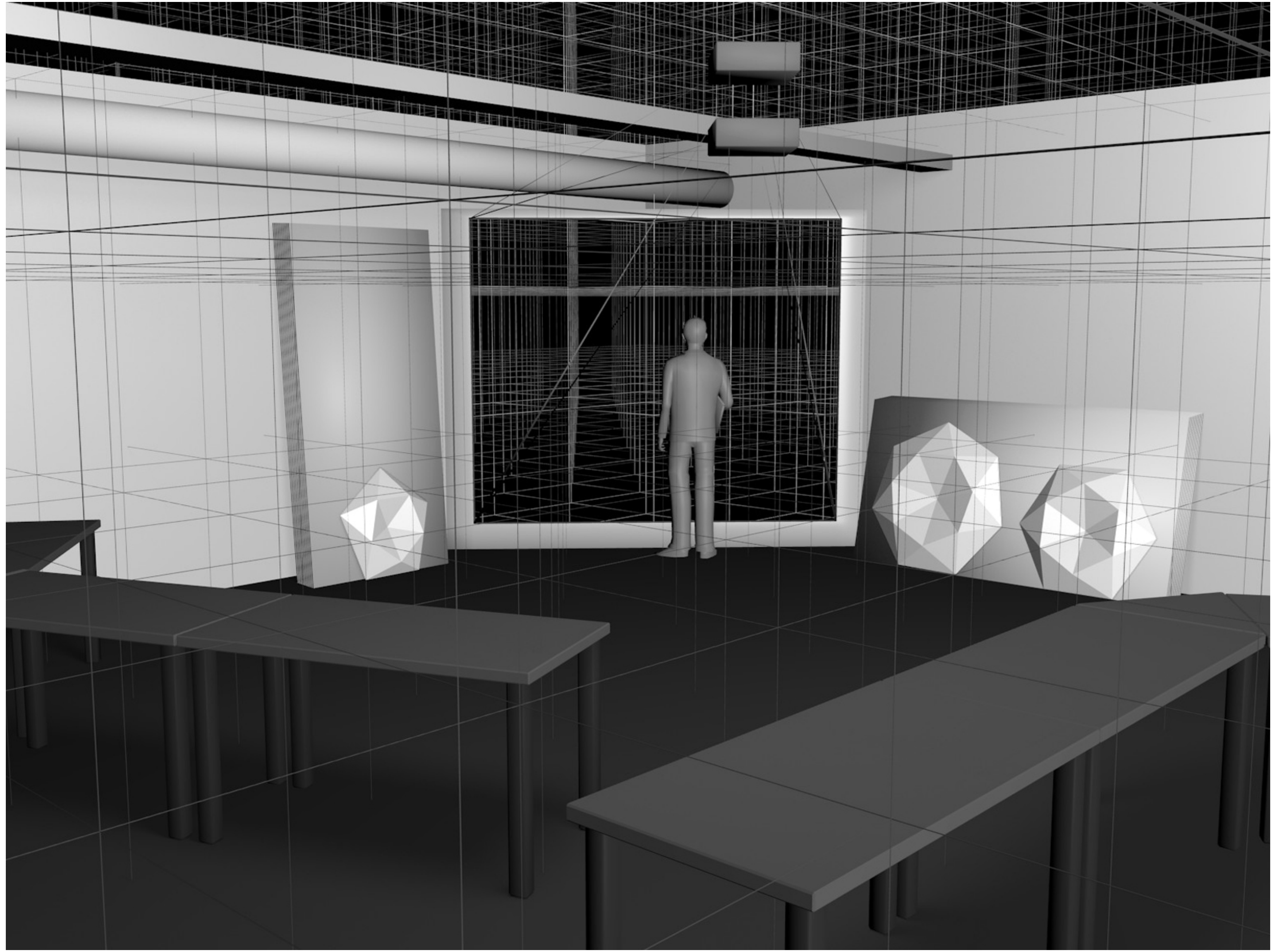
• Demonstrate the unfolding of folded forms to create the final pattern lay-out for CNC machining and the requirements for such fabrication.

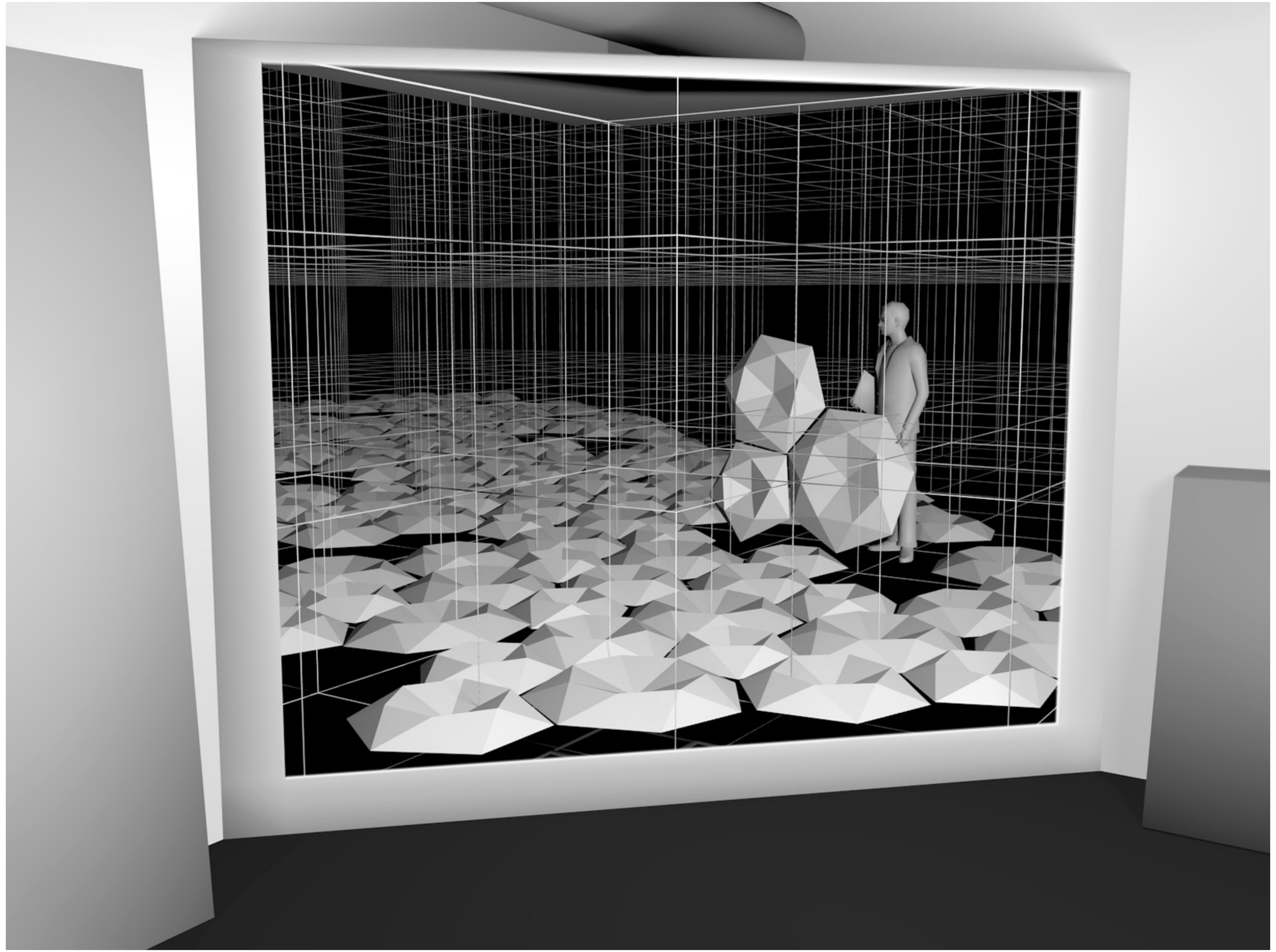
• Demonstrate the assembly methods and the experience of making.

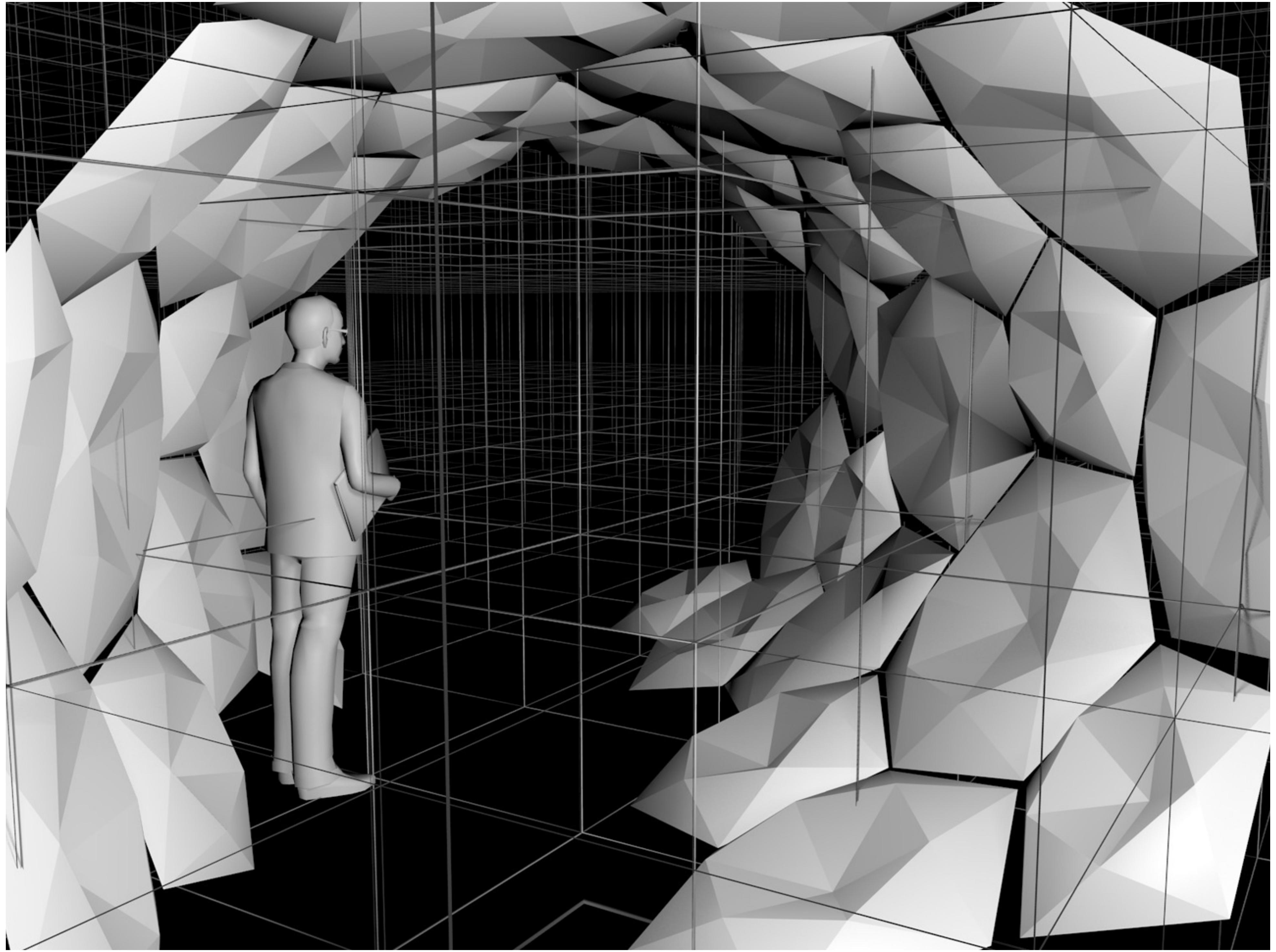
• Demonstrate the capability to analyse the relationship between physical form and digital space.

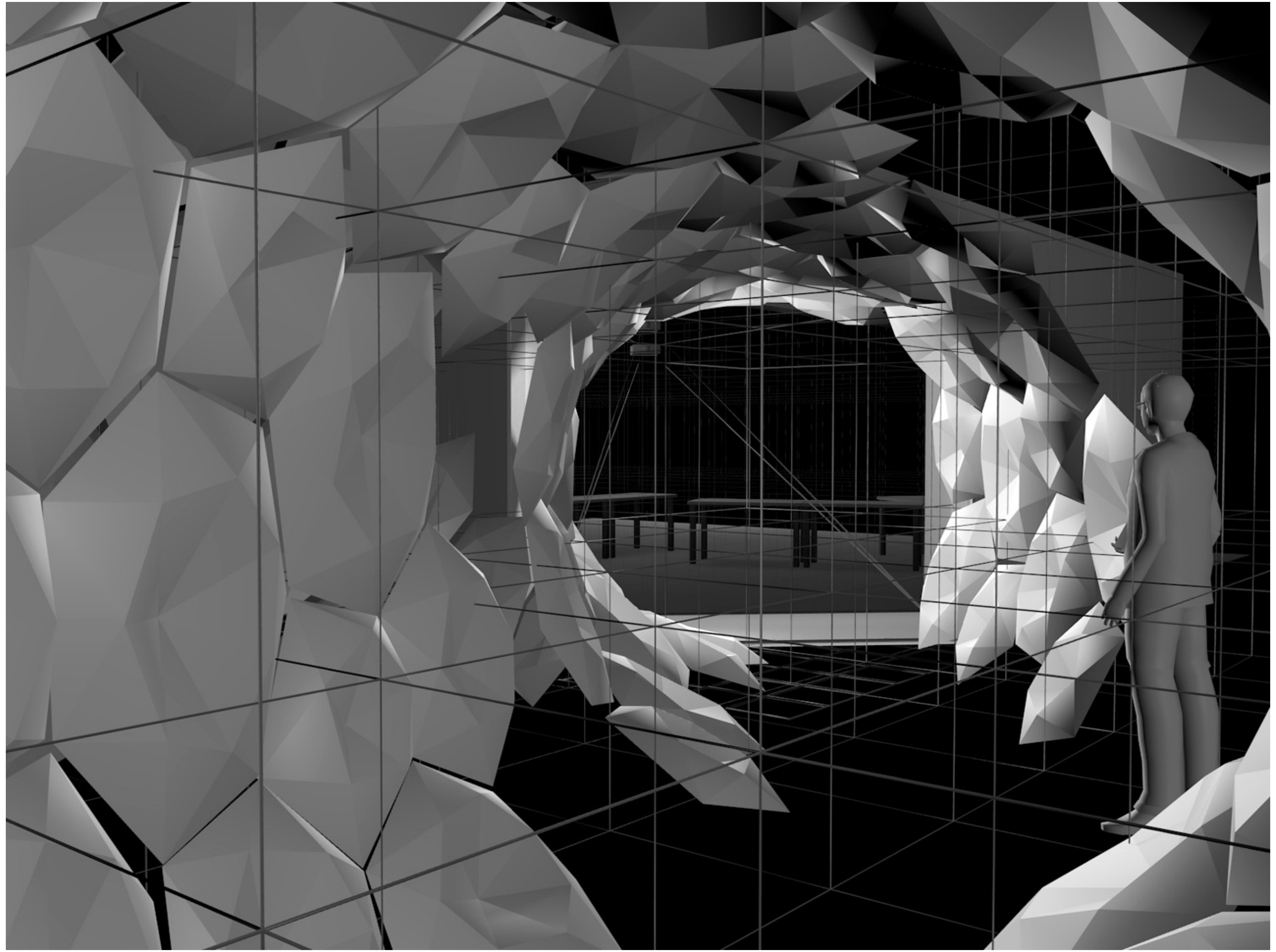
• Demonstrate an engaging and interactive experience which can be communicated by the designer to their audience.

• Demonstrate new interpretations of form and space as an abstract arena for creative thought.









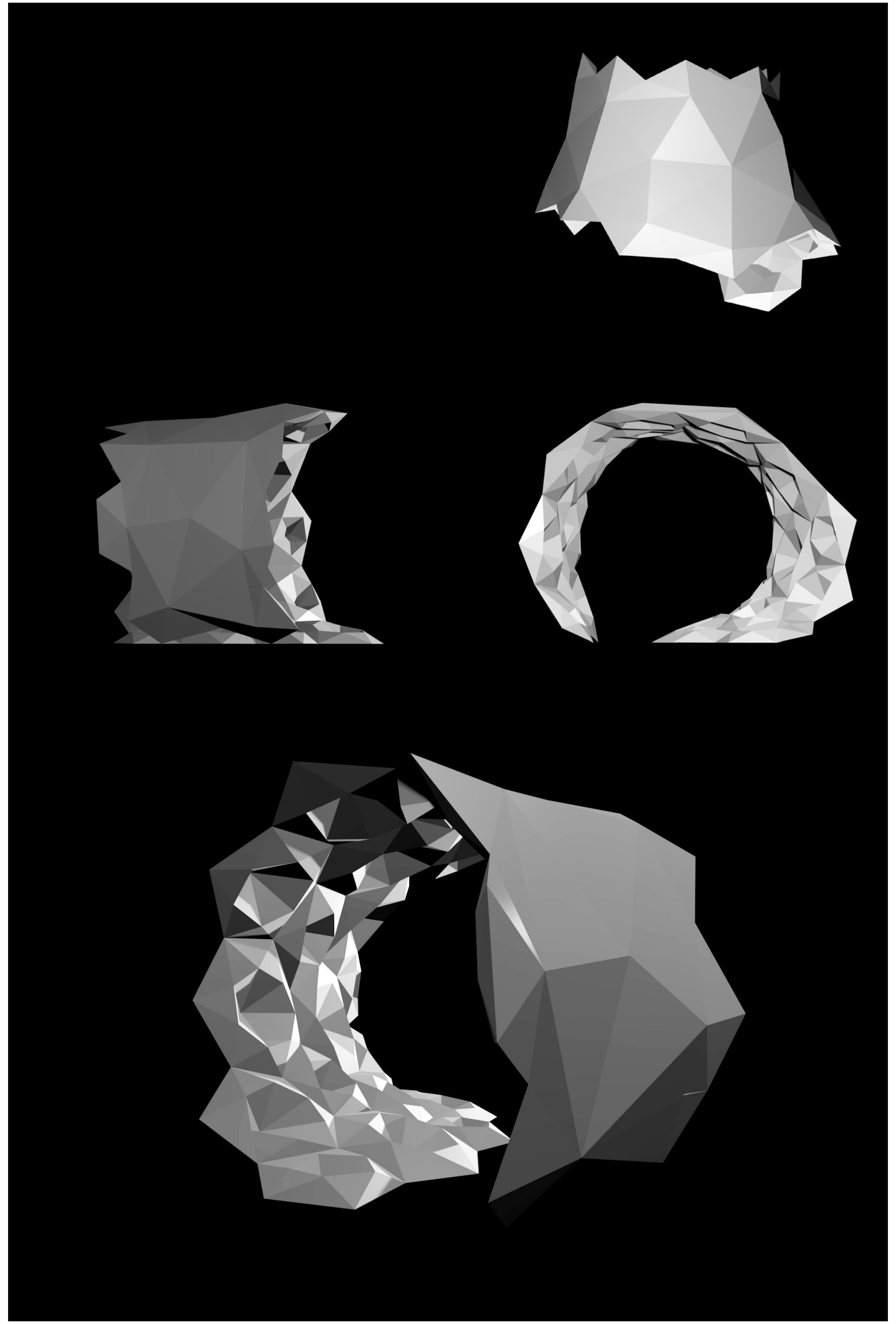
The Final Design

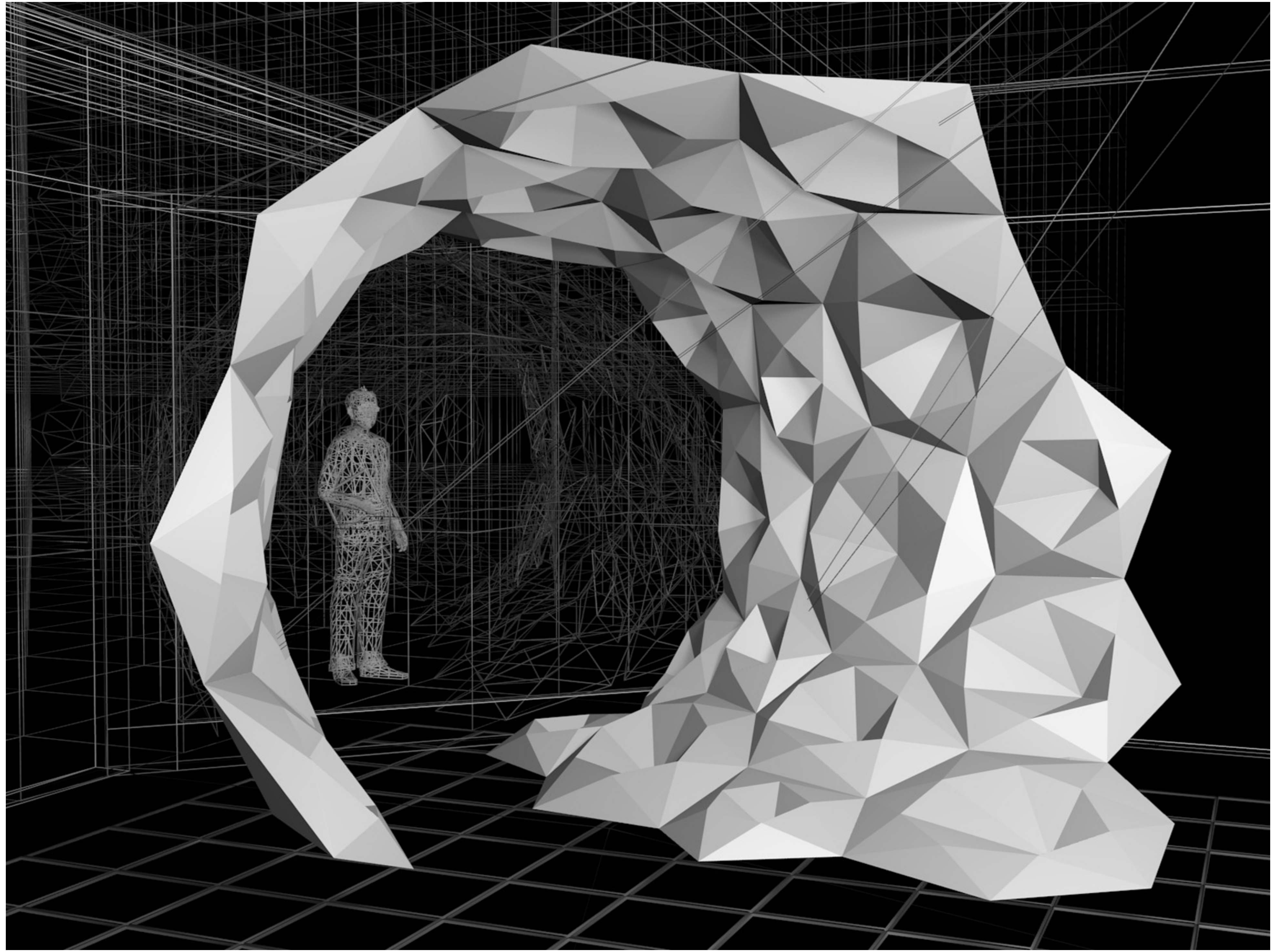
The Physical Space.

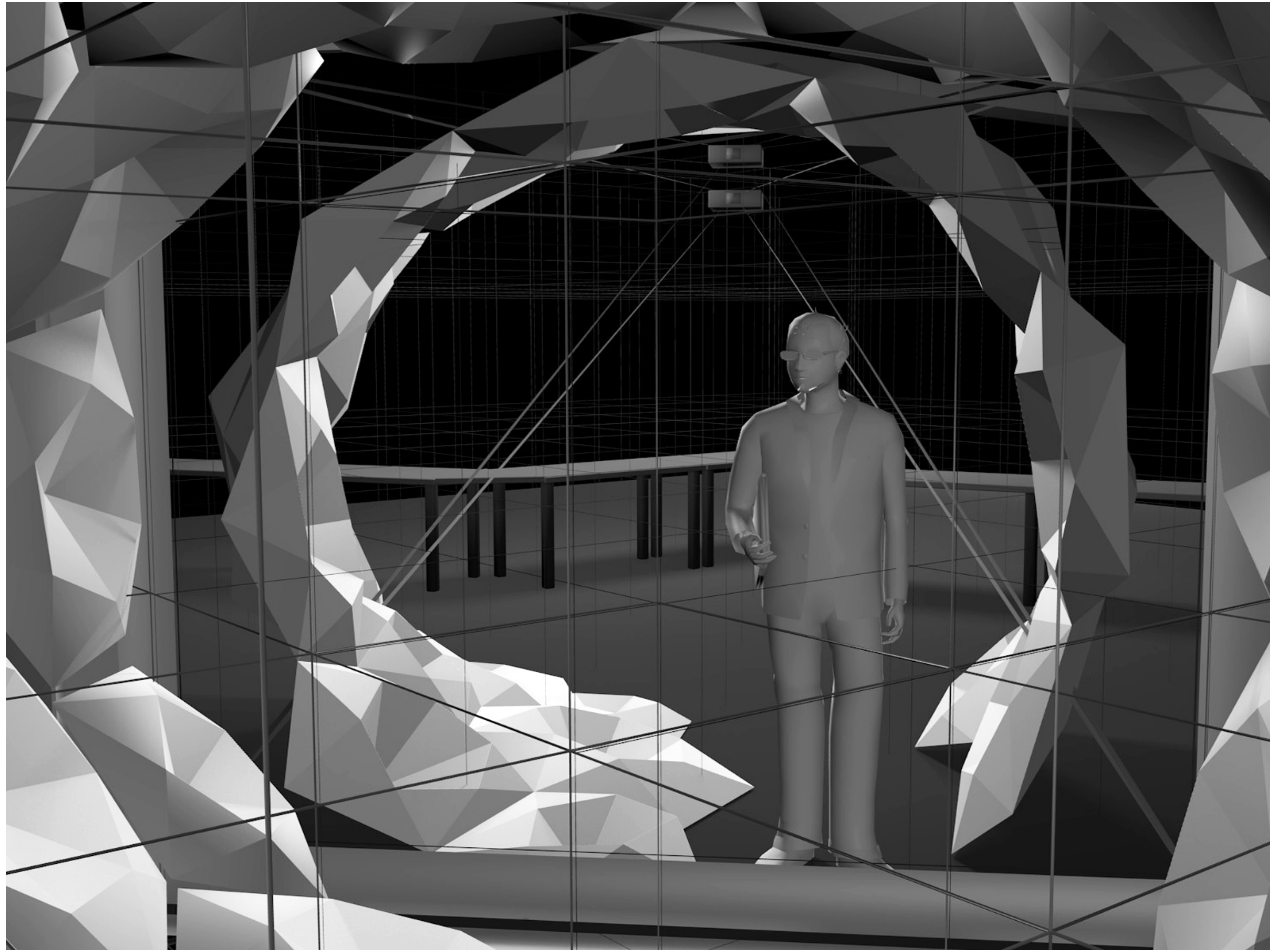
The images on the right depict the final design: a fragment of the virtual space extended into the physical world. If the 3D projection is the window or a gateway into the virtual world, the final design frames the space in which one can both look through, and enter into, this world. For this reason the Final Design was named 'The 3D Portal'; an entrance to a digital space that is beyond the limitations that are imposed on physical reality.

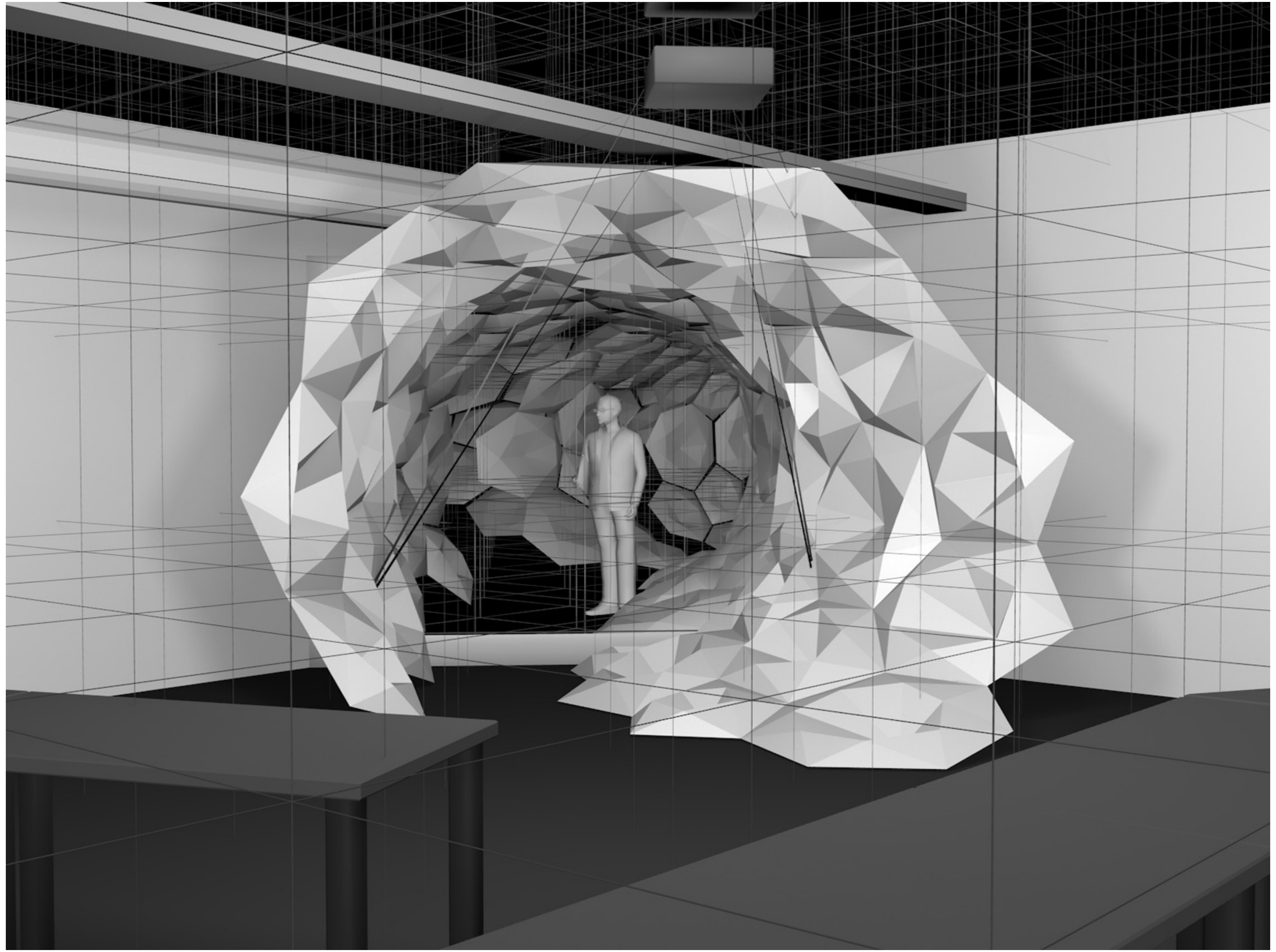
The 3D Portal was designed to be unfolded and separated into component pieces, and then cut and reassembled. This meant the components needed to be appropriately scaled in order to fit on the 1.2 x 2.4 meter sheets as indicated on the previous pages. There were a total of 26 components that made up the interior surface and 31 faces that triangulated each of the components.

The aim was to make a model that would enclose both the person within the space as well as the projection screen. A key component of the design was to allow for a large enough opening to enable the projection to shine through the Portal. Simultaneously the model was also designed to obstruct the outer edges of the projection. The light shining onto both the projection screen and the inner surface of the model would achieve the effect of blurring the boundaries between the virtual space and the physical structure.









Final Pattern Layout

The Design on 35 Sheets of Coroflute.

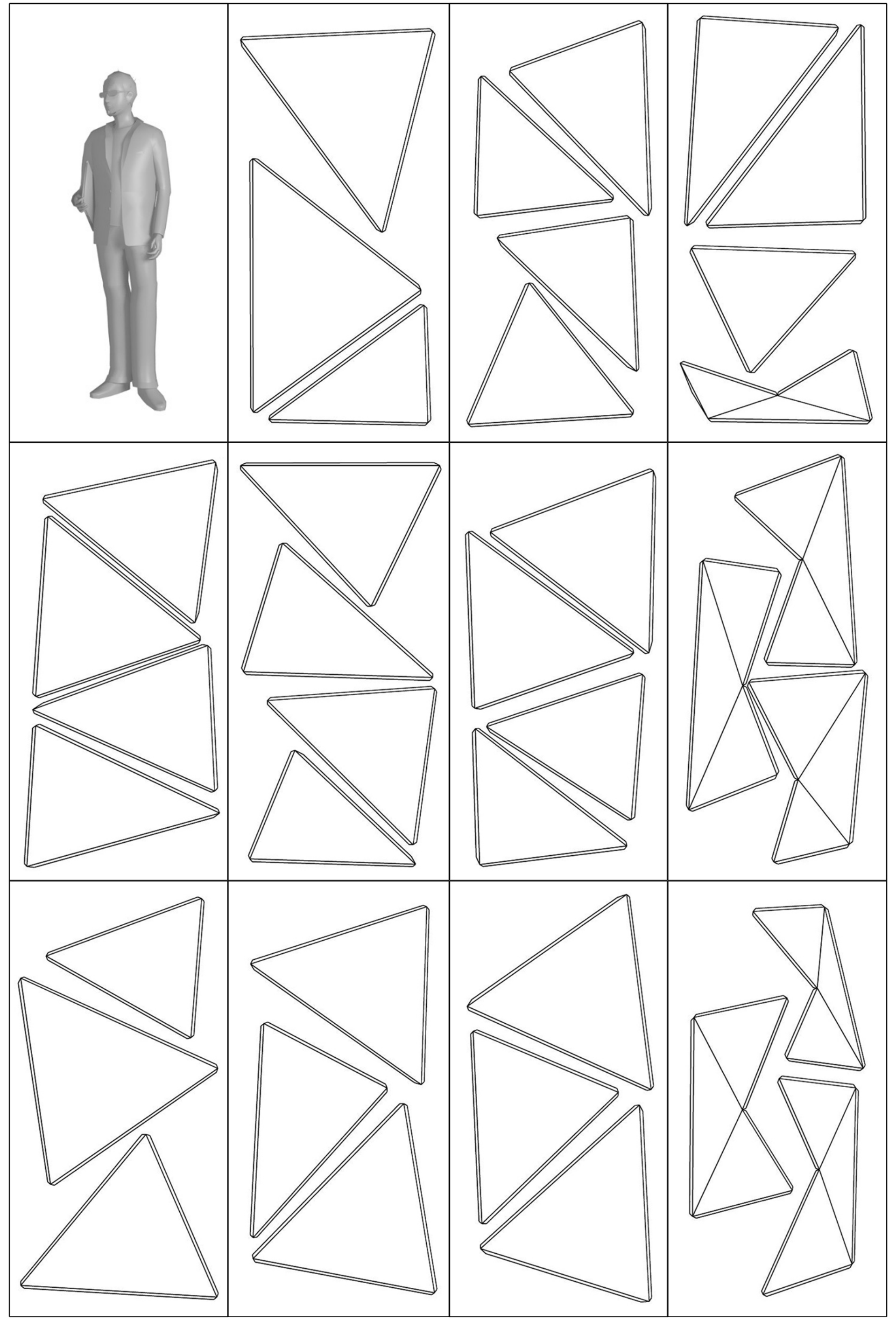
The final model was exported from Blender and imported into Pepakura for unfolding. The entire model was manually separated into its component parts and laid onto sheets 1.2m x 2.4m in size. Emphasis was placed on using as few sheets of material as possible and reducing the amount of wastage that would result if the parts were not tightly nested together. After a significant amount of experimentation, 35 sheets were needed to fabricate every single piece of the final design.

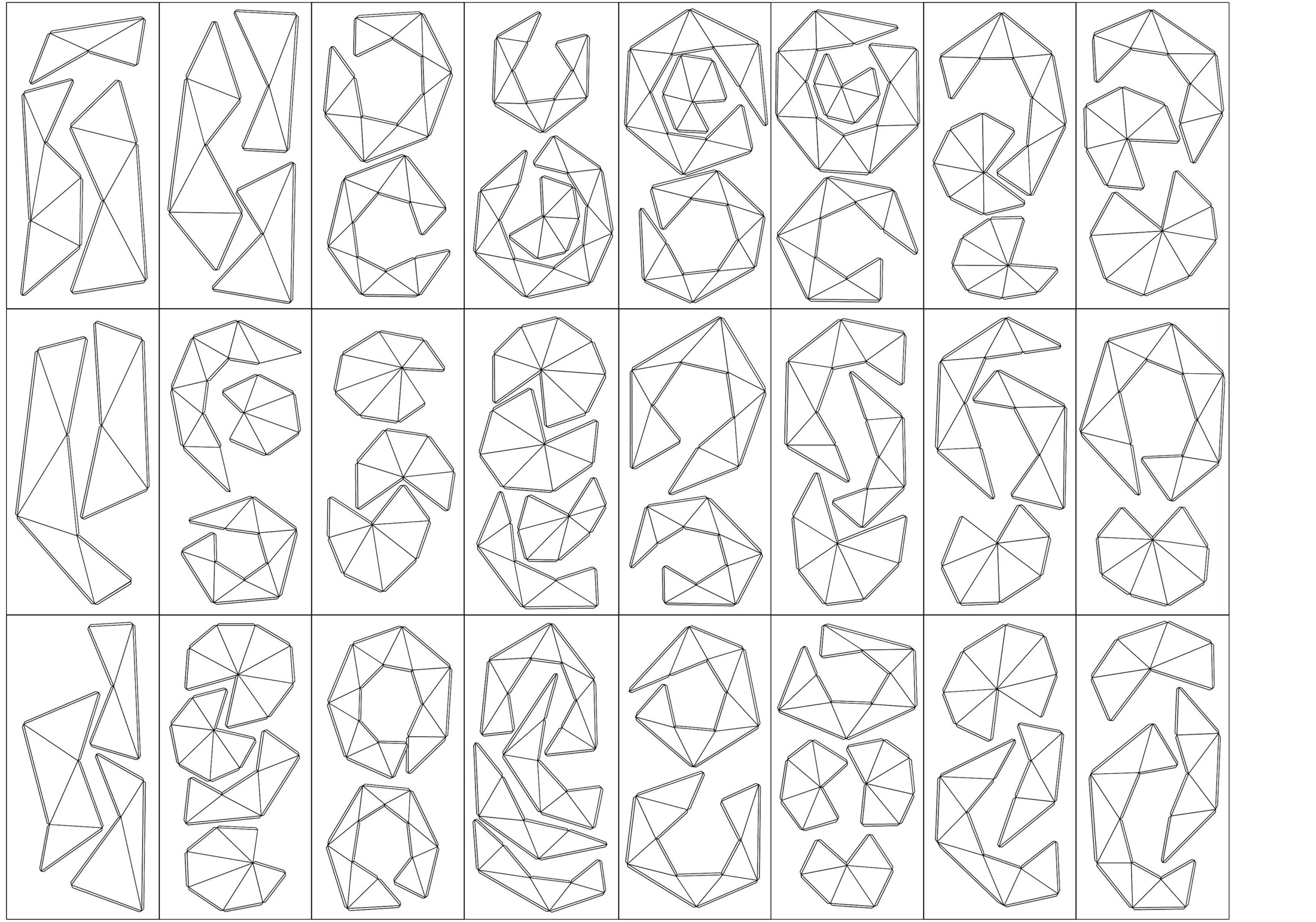
The outer surface and the inner surface of the 3D Portal were separated onto different sheets. This was because the patterns were to be cut from different thicknesses of material.

Pepakura comes equipped with an edge numbering system that tags every edge and its corresponding edge with a number that can be identified. This makes the reconnection of parts significantly easier and is of great importance when dealing with a large number of components.

In total there were 764 open edges. This meant that 382 edges needed to be fastened together. The model was broken into 4 different sets that could initially be cut and connected separately so that it would be faster to determine which part went where.

These files were then exported as a vector format and imported into Visual Mill 6.0 which the software used to create the G code which the CNC machine requires to router the paths.





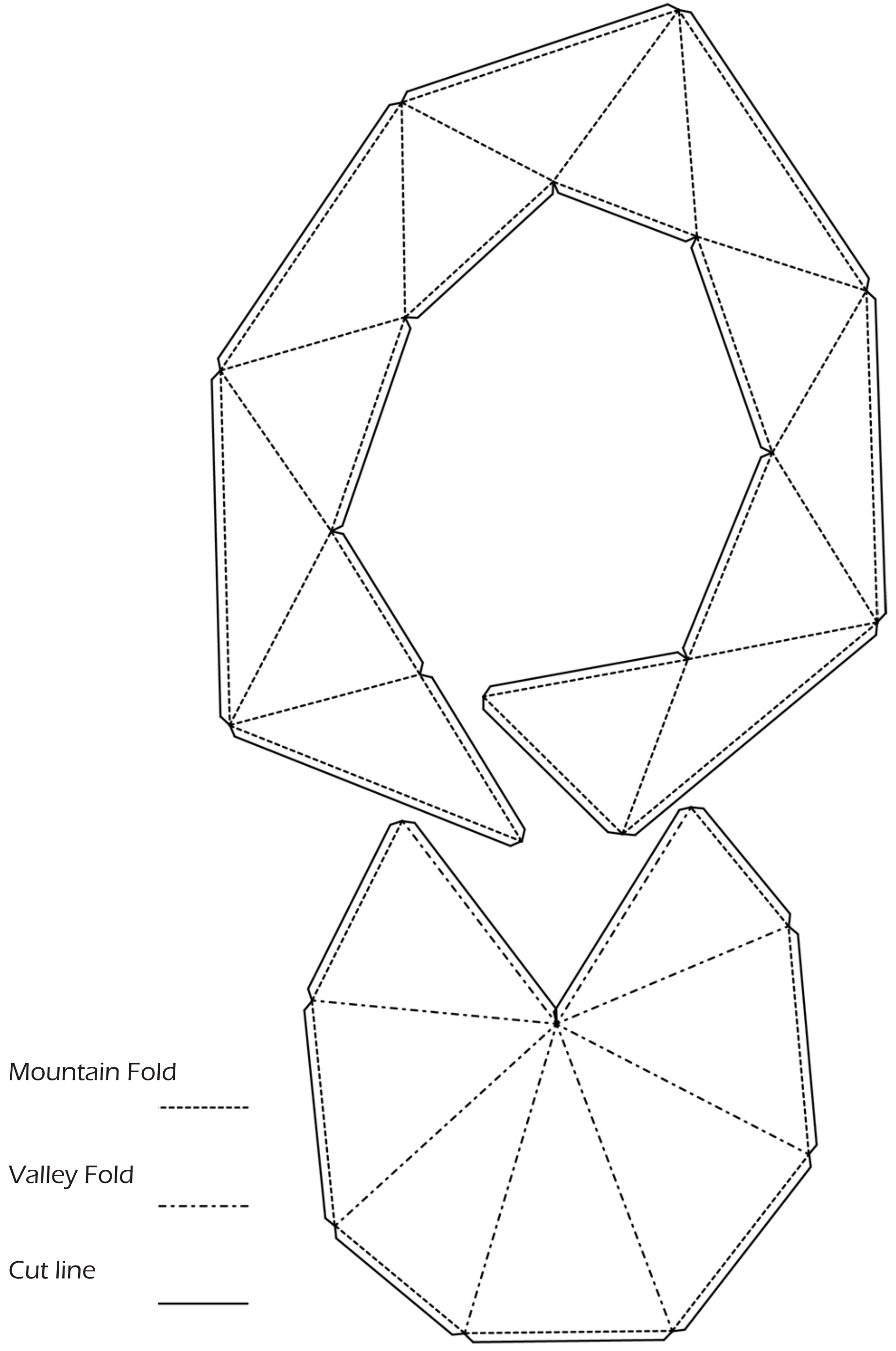
CNC Machining

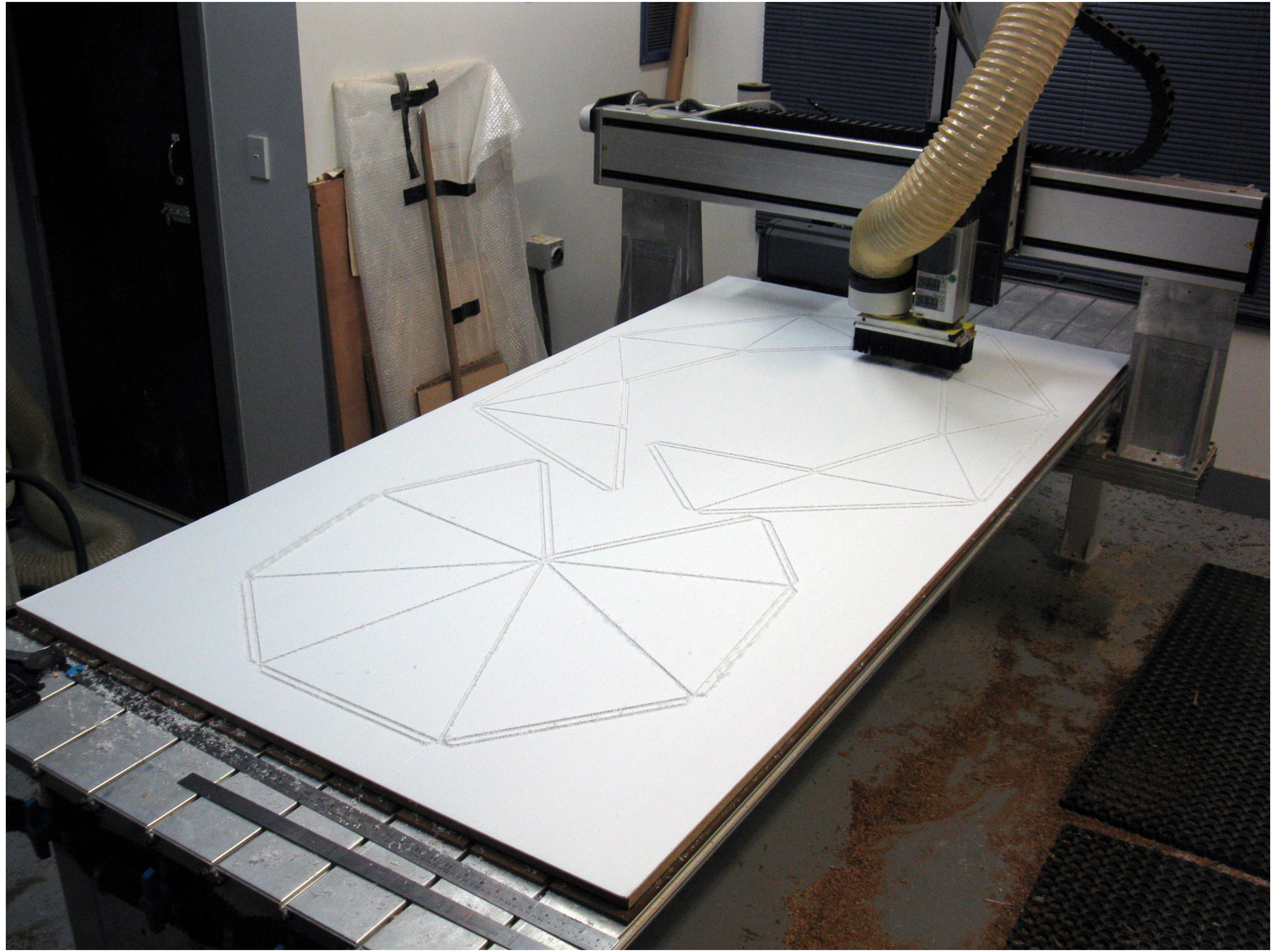
Digital Fabrication of the Component Parts.

The CNC has a maximum bed size of 1.2 x 2.4 meters which is the same size as the material to be cut. As previously identified in Living Hinges in the Physical Folding stage, it was decided that corflute would be used. A 3.3 mm thickness was used for the interior surface and 5mm for the exterior surface. These sizes were chosen based on both the ease of folding and the strength to weight ratio. The 5mm sheet was thicker and heavier and would therefore be used as the exterior material to triangulate each of the interior components.

After some initial experimentation, it was determined that the most effective manner in which to cut the patterns would be to cut on one side only. This would mean that the cut line would function simultaneously as both a mountain and a valley fold. The material would otherwise need to be cut on both sides, meaning the sheet would have to be flipped over and aligned perfectly. Cutting on one side would mean that the cut line would be hidden on the inside of the model.

Experiments were conducted in order to determine the most effective cutting tool to achieve folding hinges that could function as tabs for reconnection. An 8mm flat tipped cutter was used as it allowed each tab to fold to a 90 degree angle, and account for the tolerance needed for the thickness of the corflute. Given the softness of the material and the speed of the machine, each sheet took approximately 6 minutes to cut.





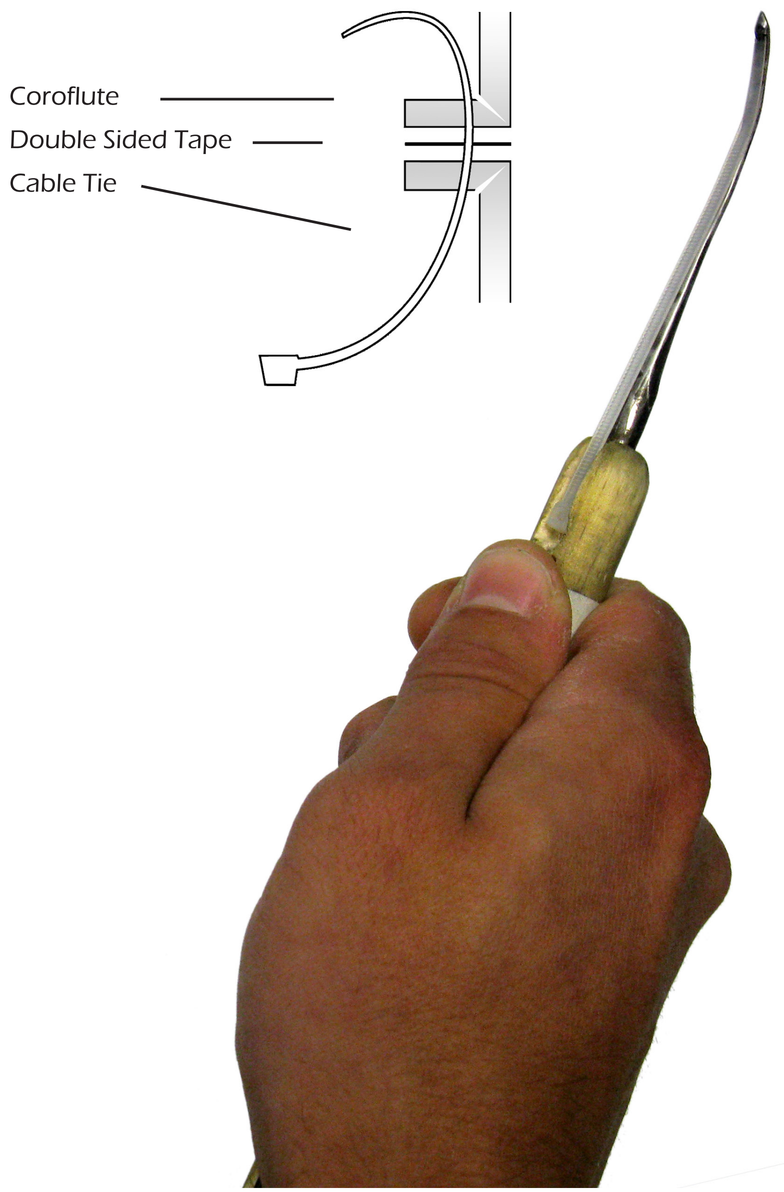
The Assembly

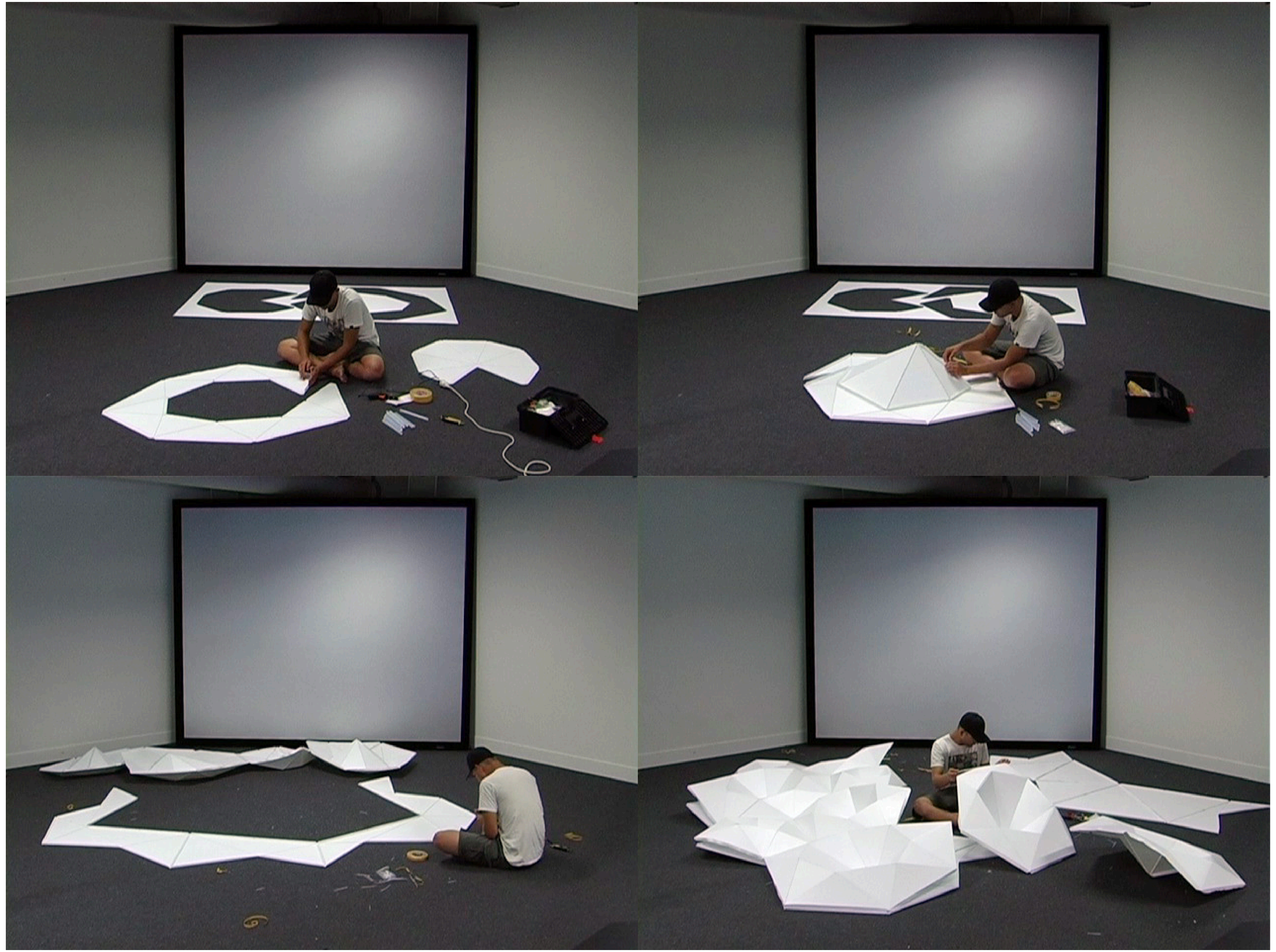
Joining Edges.

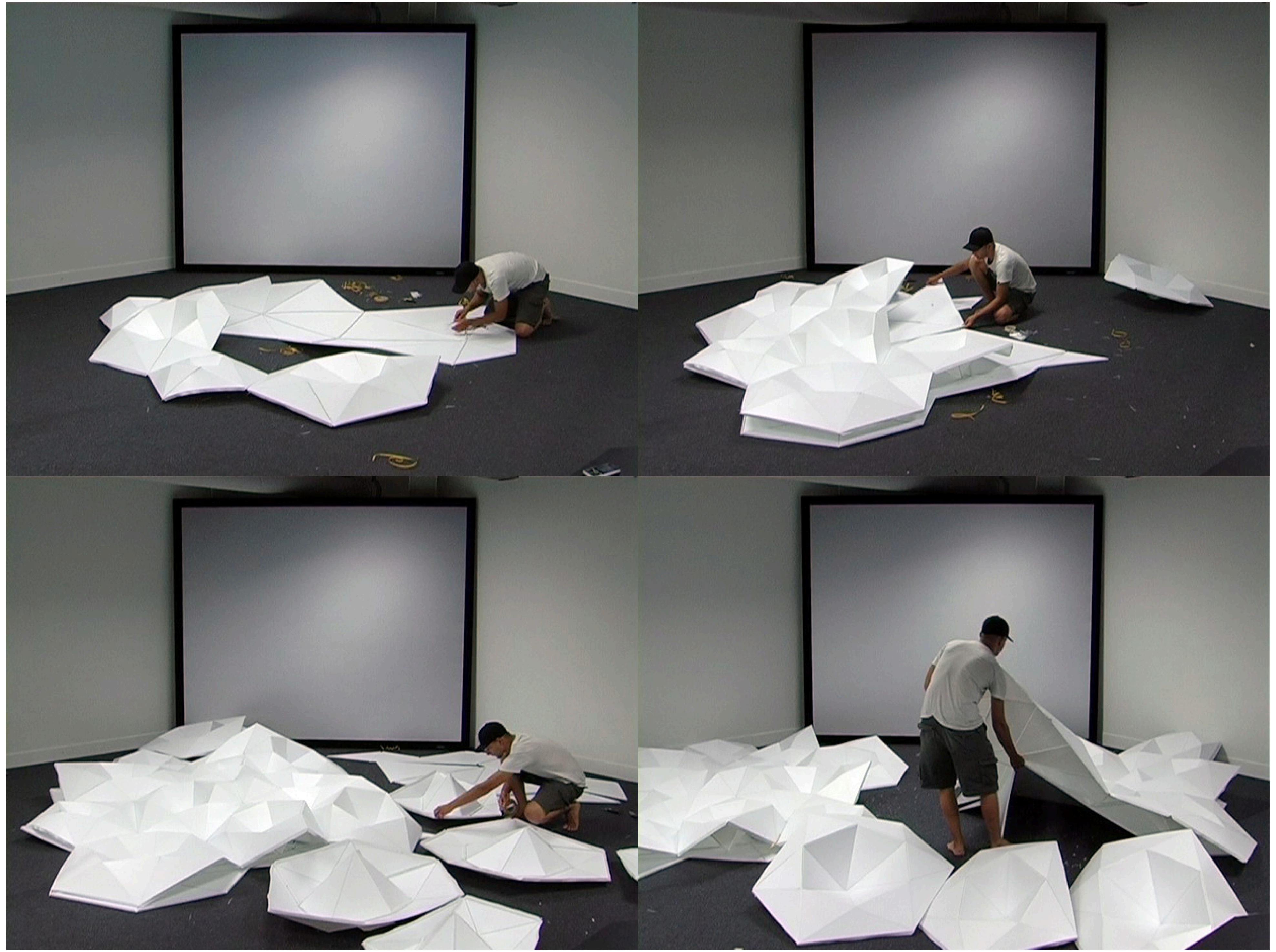
Before construction could begin, each of the 764 open edges needed to be hot glued to a 90 degree angle. This was so that the tab's edges would be facing each other and would connect together more easily. After this stage was complete, each of the 26 components and triangular faces could then be assembled together. The edges were fastened with an industrial strength double sided tape and cable ties. Double sided tape was first used to position each of the edges so that they were in the right place for tying together. Cable ties were then used to join them together semi-permanently. The cable ties provided the strength for each edge connection, and prevented the edges from ripping apart. The use of cable ties was advantageous because they can be easily cut and removed for disassembly.

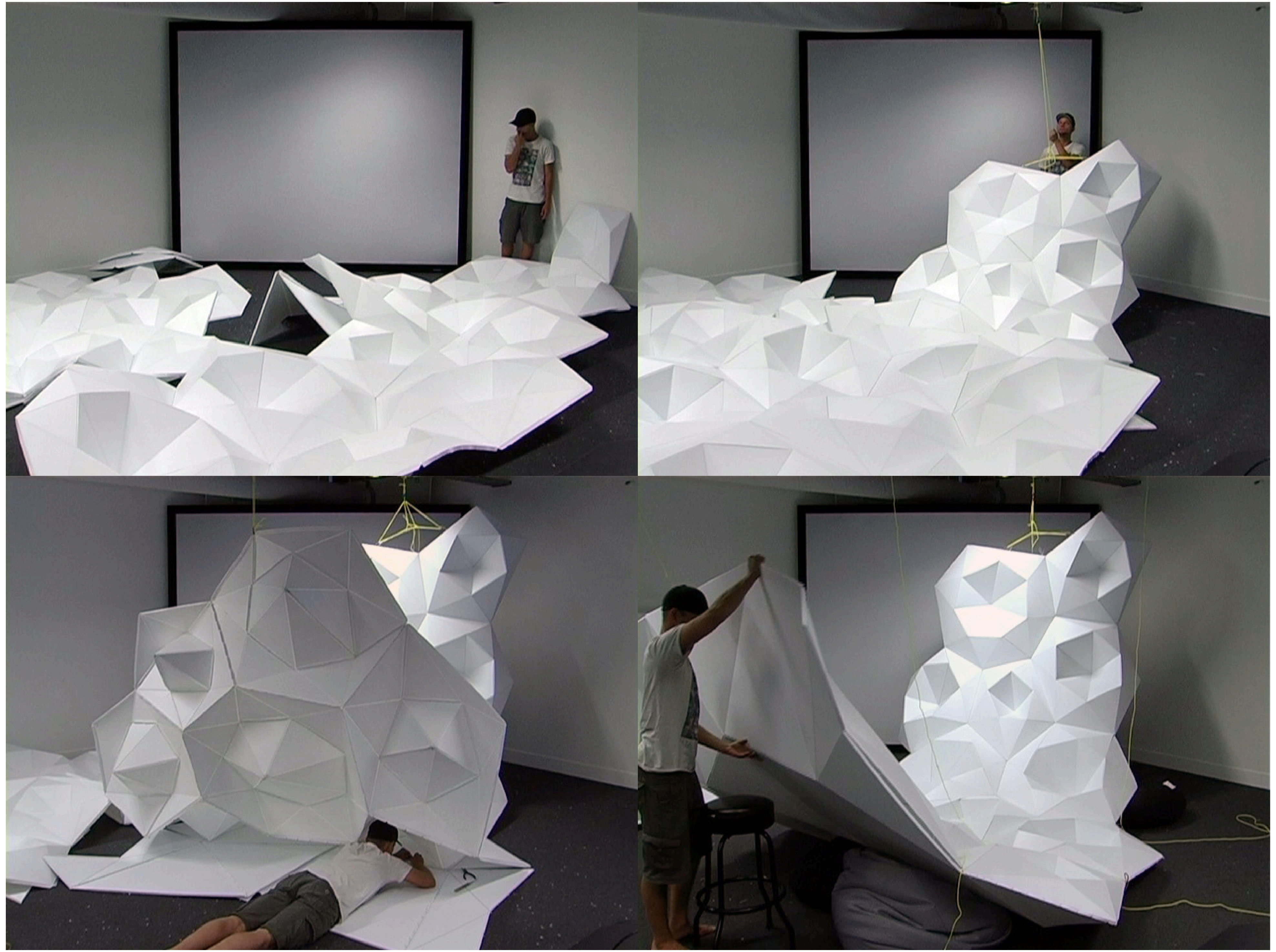
A custom-made piercing and tying tool was made to simplify the process of piercing through the corflute tabs and connecting the two edges of the cable tie as indicated on the right of this page. This tool saved countless hours of fiddling with the end of a tie and having to squeeze it through a small hole. The key feature of this tool was it ability to create a small slot at the end of the piercing tip in which to hold the end of the cable tie tightly in place. This meant that the tie could pierce through the plastic and be looped around in one single action.

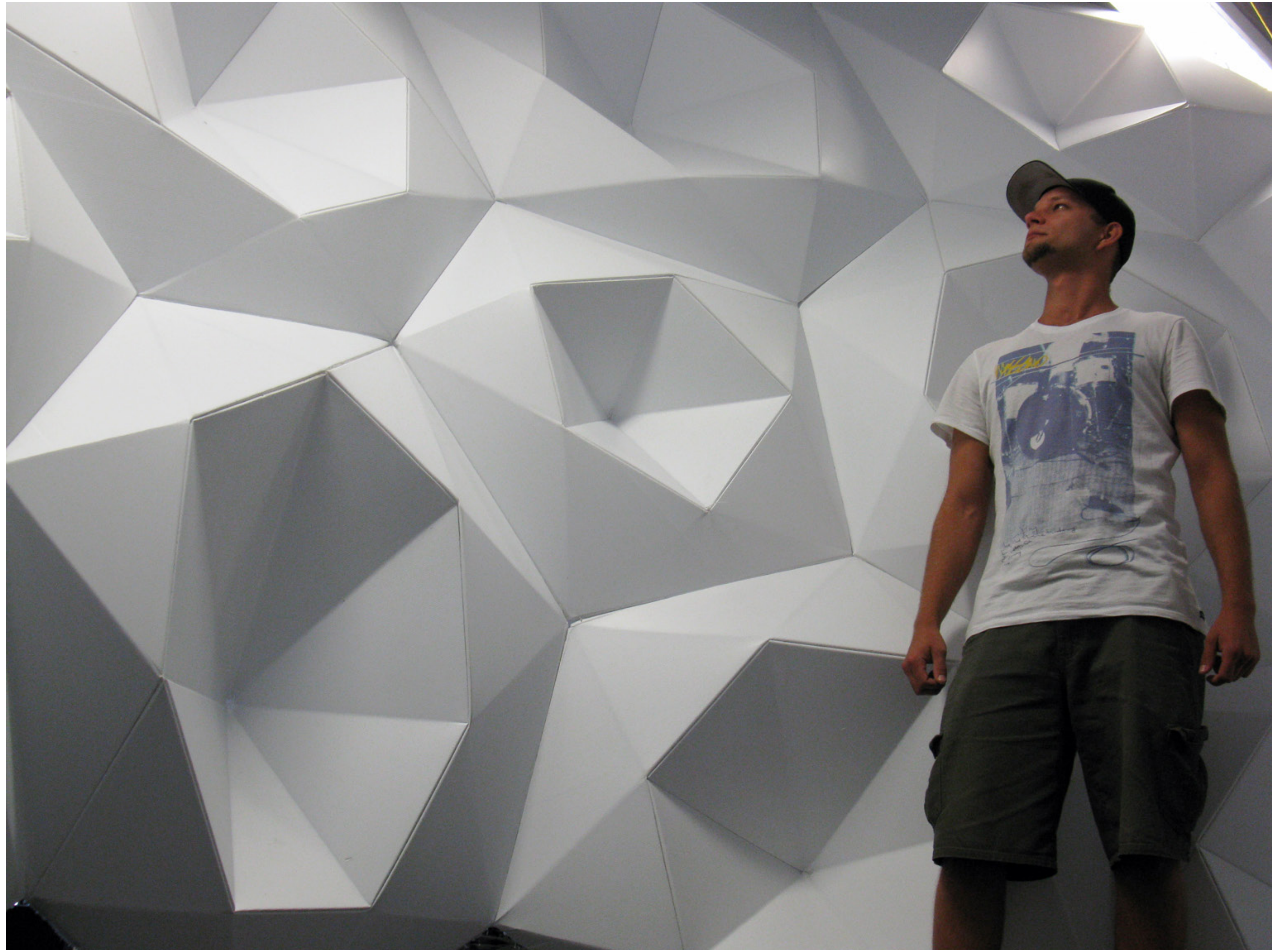
The set of images on the following illustrate the assembly of the final design.











The Finished Assembly

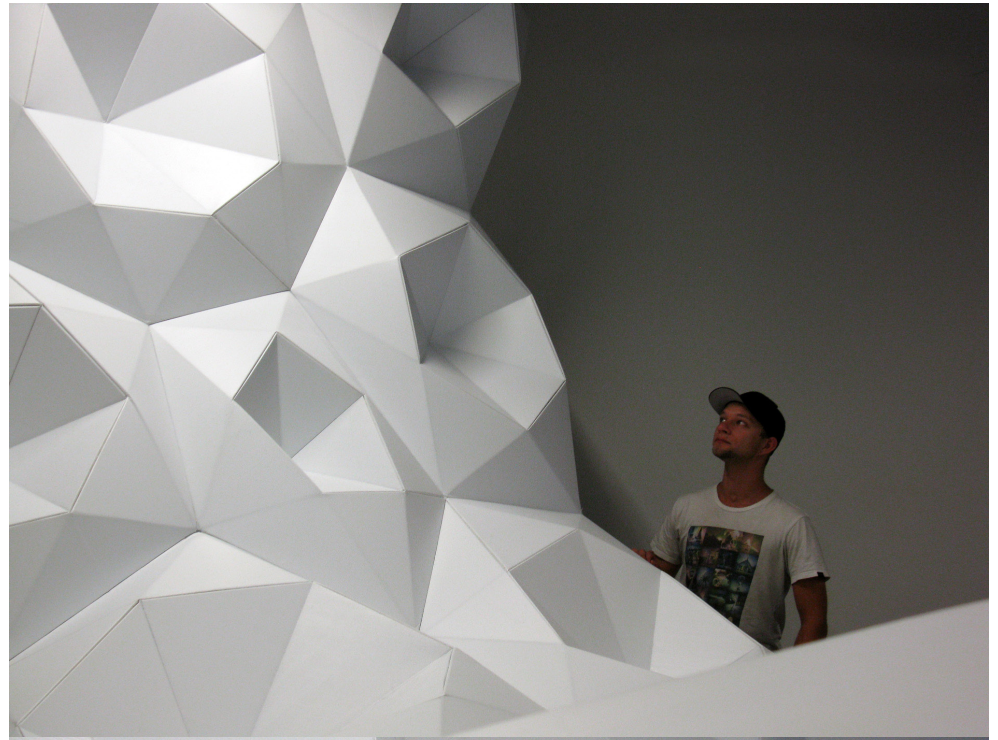
An Experience in Physical Making.

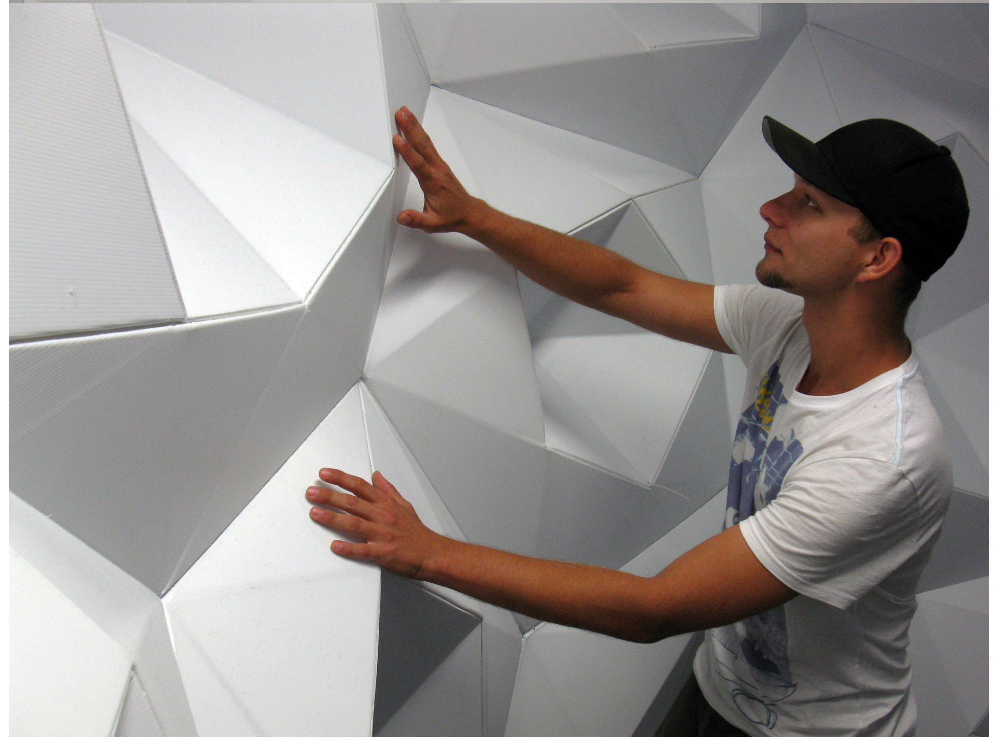
The assembly of the model was definitely an experience in making. The structure was assembled with each of the interior 5, 6 and 7 sided components and exterior triangular faces joined together one by one. Both the outer and inner surfaces needed to be assembled and connected simultaneously, because they were both too large to be connected as separate sheets. Once the model became too large to assemble as a flat surface, it needed to be flipped over onto its side where it could take its intended curved form and flipped again into its final resting place.

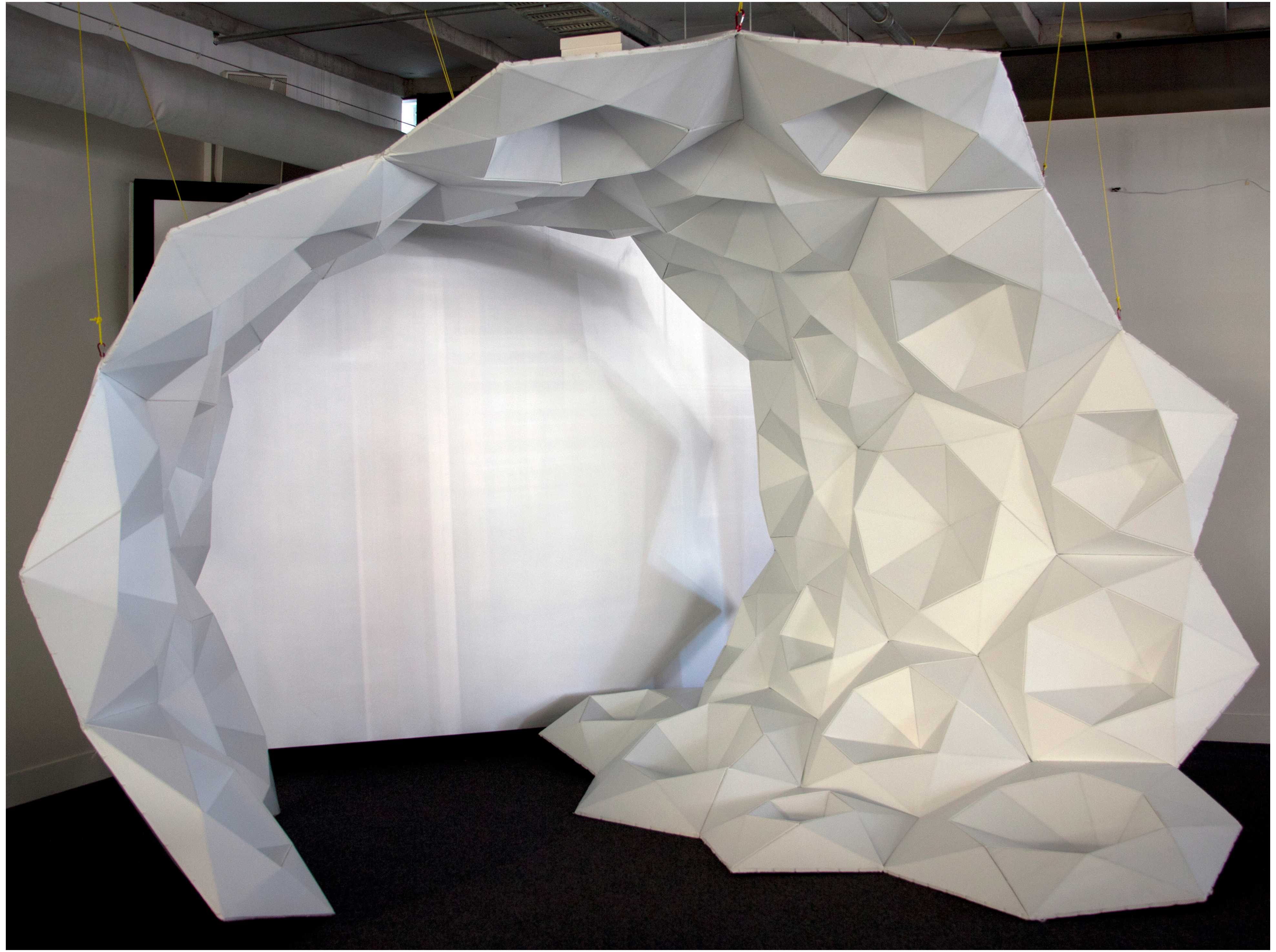
It was useful for the assembly process that both the material and the fold geometries of the components were flexible enough so that the edges could be twisted, bent and pushed out of shape to allow for easier joining. Throughout the assembly ropes were used to ensure that the structure would not deform out of its intended shape and damage the components.

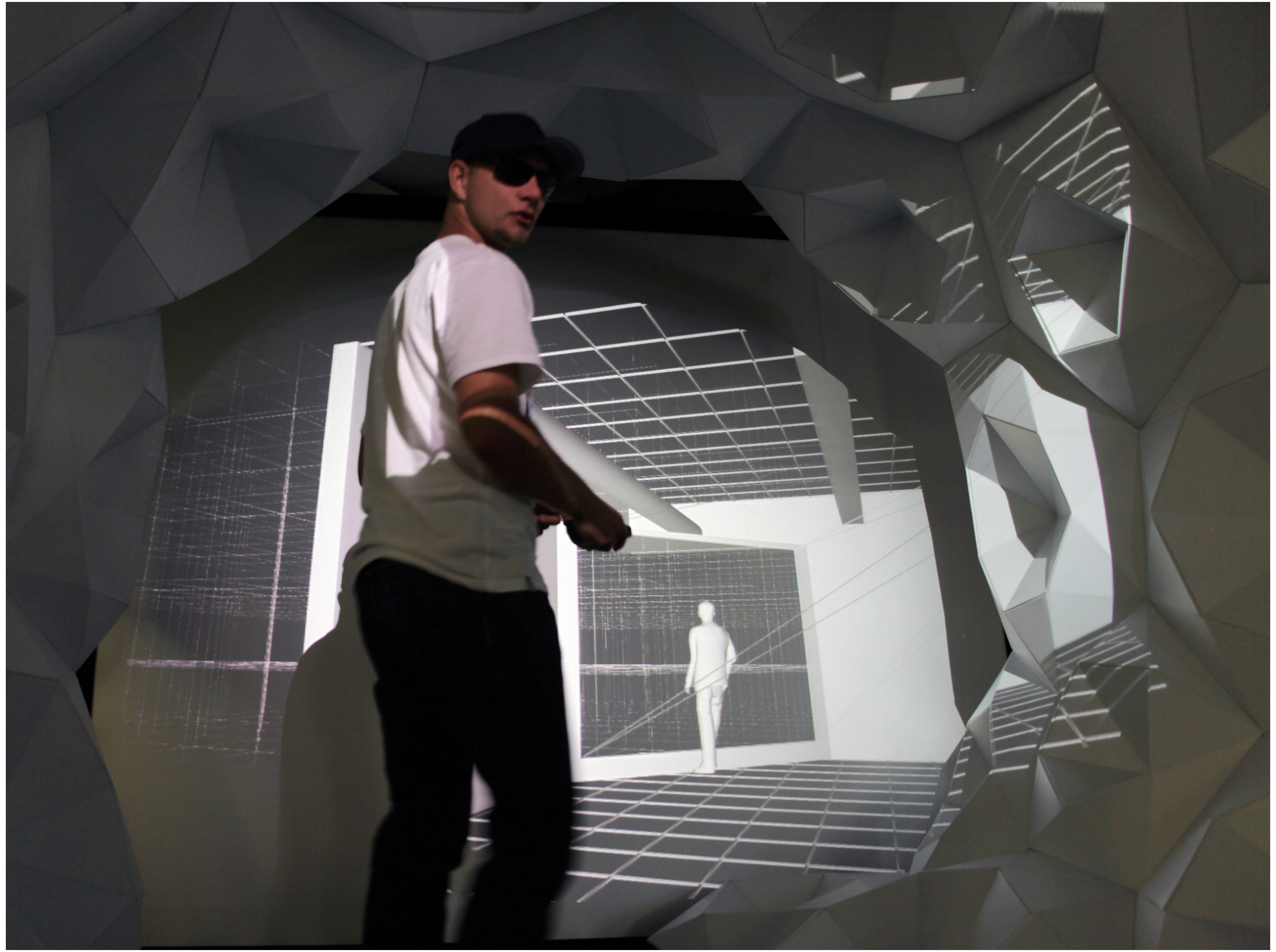
From a construction perspective, the single handed physical assembly of the model was labour intensive, requiring the joining of every single edge and seam. The connection of each edge required anywhere between 3 and 10 cable ties (totalling close to 2000 ties).

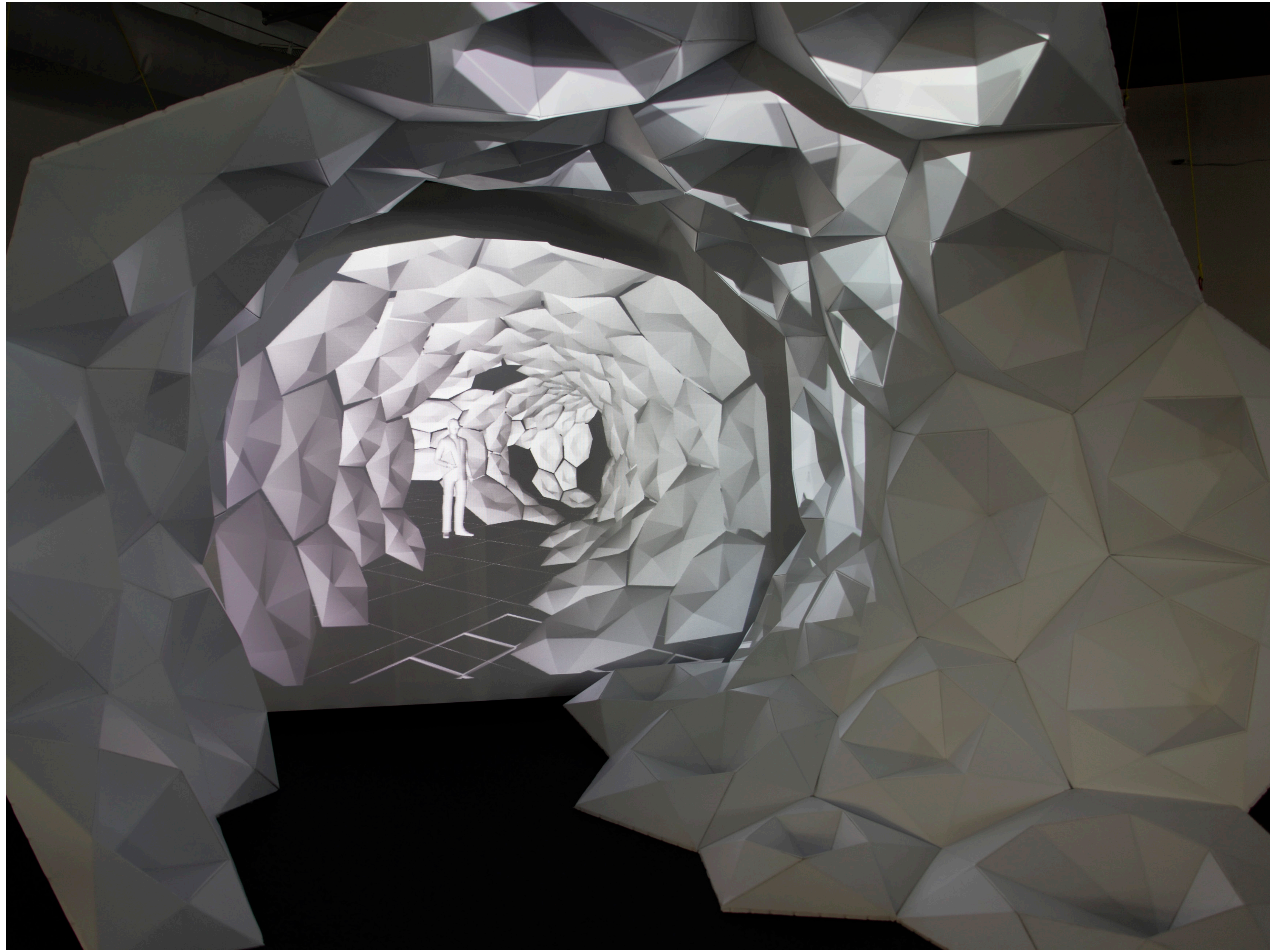
For the scale of the design, the assembly process pushed the limits of the methodology for making. This suggests that the model would have been more suitable for smaller designs or for more machine aided assemblies.

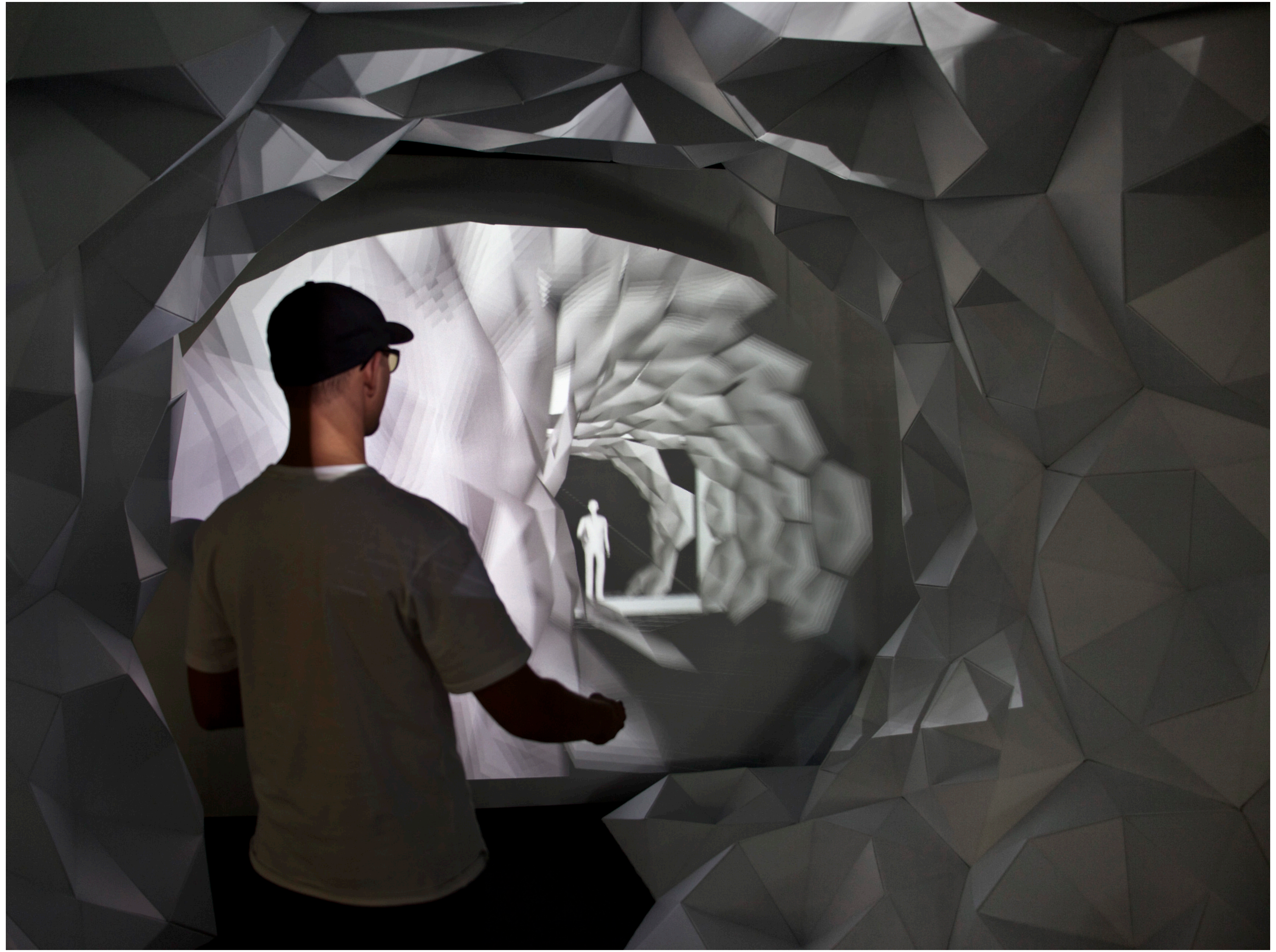


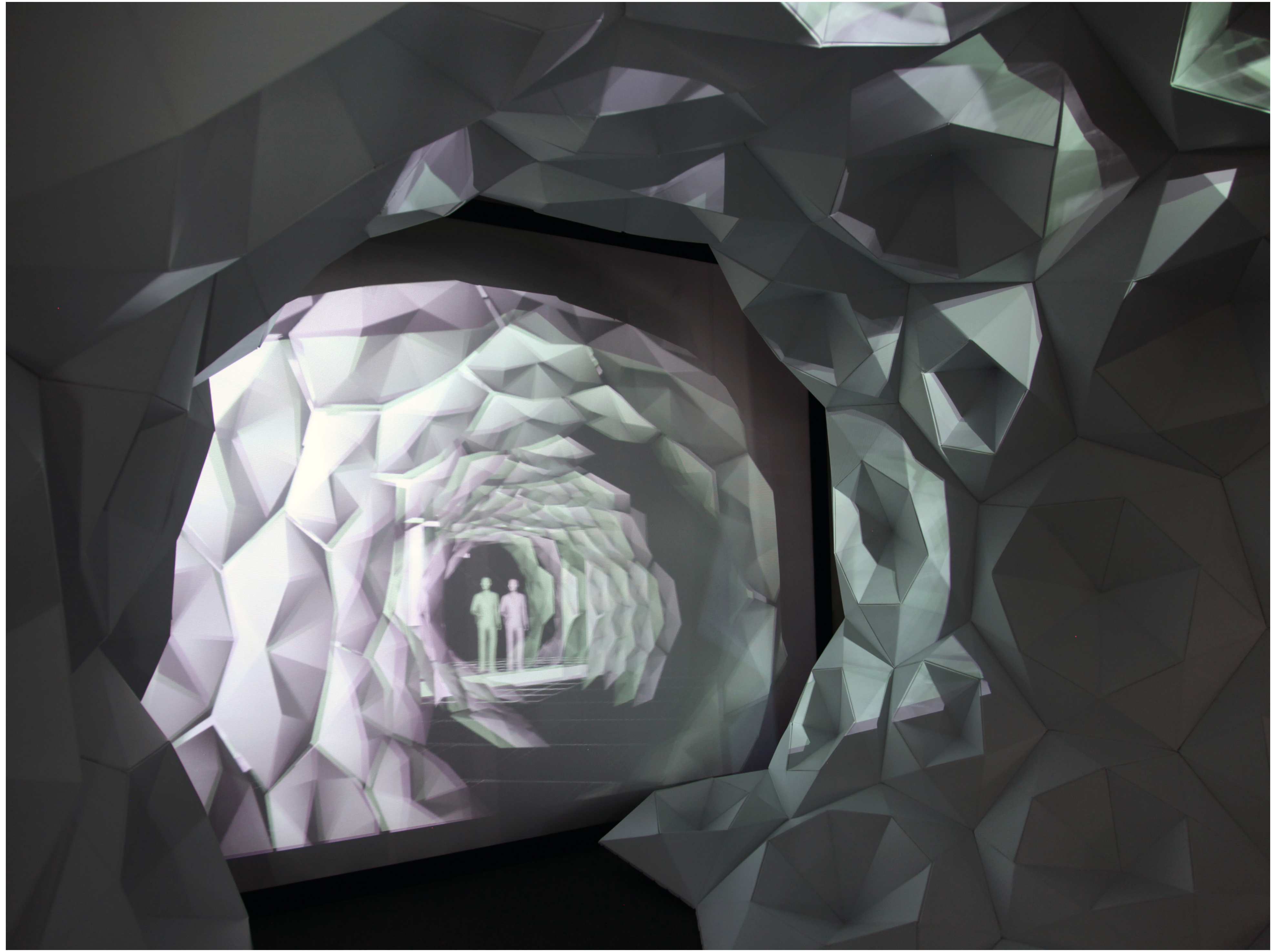










Physical Form and Virtual Space

A Summary of the Experience From Within.

Once the assembly of the 3D Portal was complete and was lined up perfectly in front of the screen, the projectors were turned on. Turning the projectors on was the first step in validating all of the findings that were advocated throughout the research. The 3D scene, from which the model had been made from, was loaded into the Stereoscopic Model Viewer. Then the virtual model was aligned with the physical model so that the virtual and physical were overlapped into a unified composition.

This was the first chance to compare the interrelationship between the model and the physical structure. Initially there was an opportunity to play around with the Wii remote and experience the sensation of standing in a physical space and looking through into the virtual world.

After this initial exploration, there was then the opportunity to step back and create a presentation that would allow the designer to communicate to an audience the development of the design within the design itself. This involved creating an animation through a series of exported models that could be scrolled through with the Wii remote.

The presentation showed the step by step process involved with digital manipulation of forms in Blender, and the manner through which space could be created to inhabit in the virtual world. This was achieved through the making of a tunnel to frame the entrance into the virtual, which could be explored by the user, who could exit back into the physical space.

This process is similar to a stop motion animation, except that it was possible to navigate through the model at the same time as the animation was happening. This occurred because the functionality of navigating the object was separated from the loading of the object. The user could scroll through the different model iterations while simultaneously navigating the virtual 3D space. This meant that it was not a conventional cinematic presentation as the moving space could be interactively explored and at any point the presentation could be stopped or moved forward.

The most important thing was to develop system that allowed for a rapid transition between models and therefore allowed an experience that conveyed information that could not be expressed with a static model. It allowed for rapid exploration between revisions of design and presented a more defined alternative to developing surfaces in real-time.

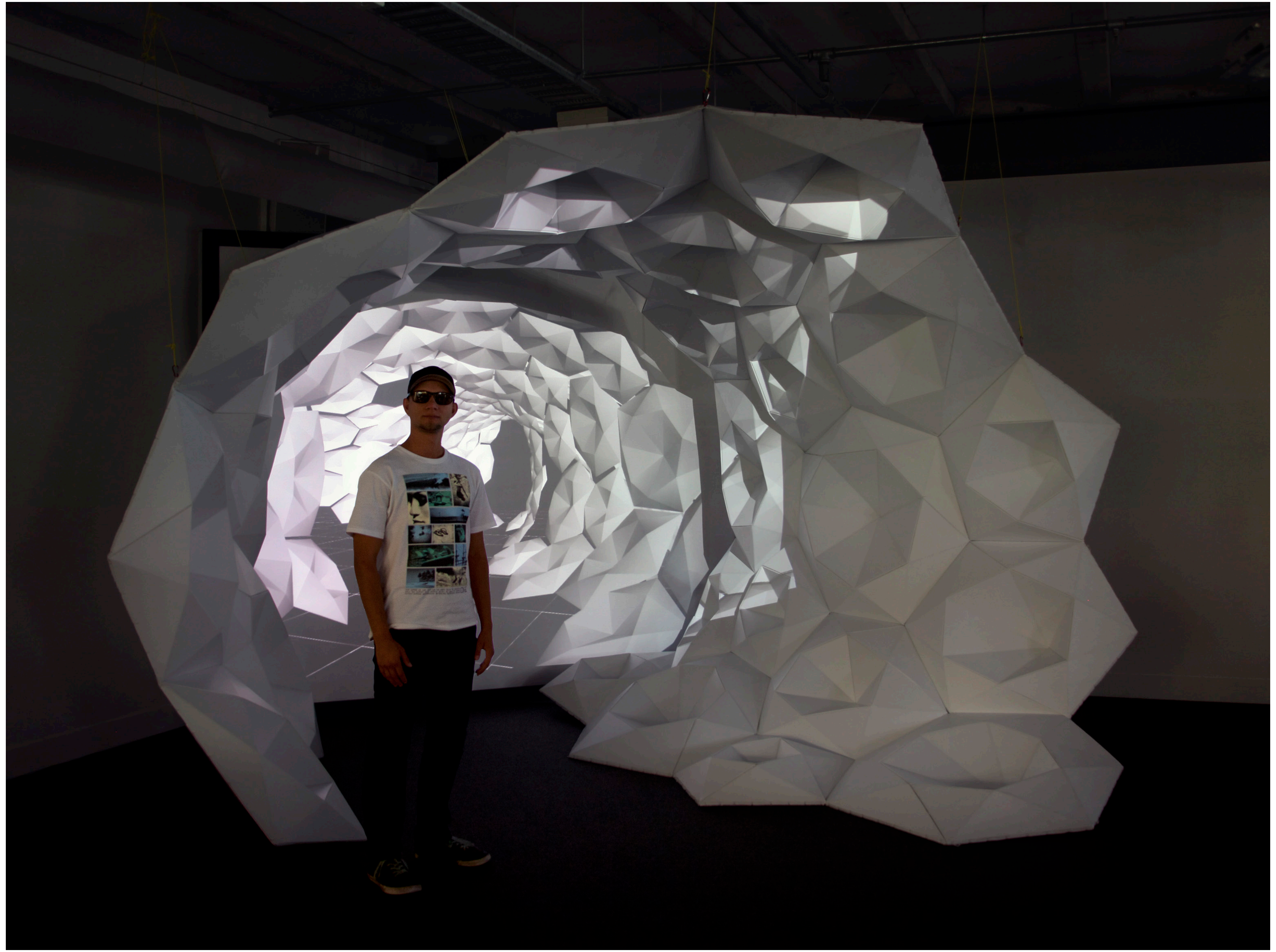
The experience was more interactive for the person in control of the Wii remote. Just as a driver does not feel the sway of a car as much as its passenger, the experience of watching the presentation left the viewer feeling out of control. It was up to the driver to create an experience that would engage the audience in a fluid ride.

The purpose of the composition was to immerse the user physically in order to better comprehend the feeling of being immersed virtually. From the physical space, the designer had the chance to step their audience into and out of virtual space, exploring the blurring of the boundaries between these two worlds. The 3D Portal in combination within the virtual projection was welded together in interplay of form and light. This allowed the designer to help situate the scale of the virtual space with physical components. Comparisons could then be made about the seamlessness between the virtual and physical forms. Even though the physical space is only a fragment of the virtual world, because it was built, we can better understand the nature of the virtual environment and how that might exist physically.

This overlapping of the physical and virtual worlds produced an effect of disembodiment or sensory dislocation where the observer experiences the physical environment and simultaneously observes themselves from the virtual environment. The result of experiencing a fragment of the virtual environment, as a physical experience, enhances the effect of the experience overall.

In essence, the 3D Portal is a fragment of the infinite possibilities that exist in the virtual and yet it must be grounded as a form, structure and space that can exist physically. It was used to assess the seams between the virtual and physical, and demonstrated the validity of the unified strategy for making and visualising in 3D developed in this thesis.

A video CD documenting construction of the final composition and the experience from within is attached as an Appendix to this thesis.



Conclusions

This thesis project Un/Folding Form explored the transition between the virtual representation and the physical fabrication of folded forms. The aim was to create an understanding of the process and evolution of design using folding as a technique and to develop a unified strategy for designing a work using this technique. The diagram on the following page depicts the unified strategy that was used in this design investigation to develop a methodology to transition between the virtual representation and physical fabrication of folded forms.

The methodology involved crossing between different mediums of both physical and virtual making. It used the strategies identified through the experimentation of folding geometries and the interlinking of these processes with 3D immersive environments and digital fabrication techniques. The methodology was an iterative process that integrated the strategies in each stage of experimentation to refine and assist in the design process.

The final composition, the 3D Portal, used this methodology as a unified strategy to integrate the construction of a prototype with a virtual space. It sought to combine two different realities (the physical and the virtual) within a single concept and through this, demonstrated the idea of working towards a seamless digital process of making. A unified strategy assists in closing the gaps between virtual representation and digital fabrication.

This thesis took as its starting point the notion that folding surfaces would transition between virtual representation and the physical reality. The first stage of the design investigation was to explore the manual or physical making of form. Experiments investigating the physical folding of paper were done to assess the properties of physically folded forms. Geometry and pattern, biomimicry and organics were key concepts which guided the development of the folded forms. The resulting forms were tested for their fabrication and assemblage potential using CNC cut and assembly techniques to ensure the practicality of the output.

The second stage took the physical forms created through paper folding experiments and explored these through digital fabrication. Various digital techniques or mediums were used in this process. 3D mesh modelling using the computer software Blender created virtual objects from the physical forms. Digital fabrication and in particular the unfolding of the digital form was developed through the use of the Pepakura software. Again the practicality of these was tested through the application of CNC cut and assembly.

The third stage involved a further exploration of the interrelationship between the virtual and the physical through visually representing physically folded structures within 3D environments. The transition between making and visualisation was developed through the use of computer software and the Stereoscopic Model Viewer. This provided the interface for a dual 3D projection system enabling a greater understanding of virtual representation of the physical form.

The output of this development process was a large scale prototype constructed to frame the entrance into the virtual world. The 3D Portal is a projection through a physical space onto a 2D screen. A 3D projection is displayed and the designer and their audience can immerse themselves within the 3D environment. The 3DPortal is a visualisation, presentation and integrated mode for design development. The aim was to engross the users within a visually immersive physical space and engage them with a virtual experience. This experience increases the designer's understanding of their own creation and provides a platform in which they can communicate to their audience.

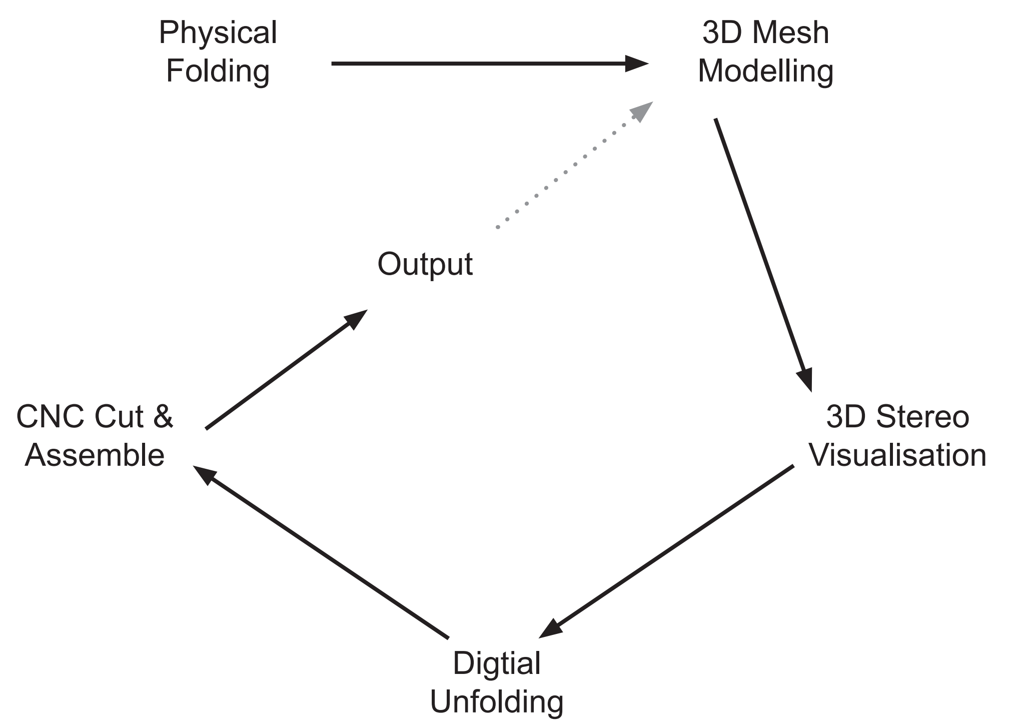
The 3D Portal, a gateway to the virtual world, was a play on the inter-relationship of the 3D visualisation and its corresponding physical form. The transition between the virtual and the physical would not have been possible without mediating between the different methods of making. The 3D Portal could be used to assess the seams between the virtual and the physical. Its construction and the final presentation validated the methodology developed in this research for making and visualising in 3D.

One of the most important findings of this thesis was that designing using a unified un/folding strategy could accurately convey a physical design as it was developed virtually. This was evident in the design of the final composition, the 3D Portal.

This research concludes that a unified strategy of un/folding can assist a designer throughout the design process and improves the designer's understanding of the methods of making. This ultimately results in more creative and resolved outcomes. It takes the abstract qualities of organic form and distils these within a mode of design that encompasses folding and unfolding and allows for the exploration of a range of digital manipulations and virtual representations.

The use of a unified strategy for making and visualising in 3D has potential design applications in areas beyond this thesis. The application of a surface skin to contain or encapsulate something lends itself to the design of structures such as pavilions, which can showcase or shelter. It has a versatility that may depend simply on the application, site and context for the desired effect. Whether it is a pavilion, canopy, car port, exhibition enclosure, tent, greenhouse, building facade, architectural product, or sculpture, the strategy can help to provide structural integrity, functionality, and versatility and can be used to draw on the concepts of biomimicry and organics.

Through a unified strategy of making and visualising in 3D, this thesis has developed a pattern configuration that is versatile and adaptable enough to create a range of virtual and physical surfaces that will transition from 3D space into virtual 3D space and then back again. The unified strategy assists the design process as the designer can conceptualise in 3D the eventual physical construction of a design. This allows errors to be removed prior to actual construction. This can also help to minimise wastage of time and human and financial resources. It supports the proposition that if people are going to make things physically they need methods in which to be able to prototype and visualise designs that give a designer a greater insight into the things they make before they make them.



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