Re:Form

Growing Architecture

A 120-point thesis submitted to the
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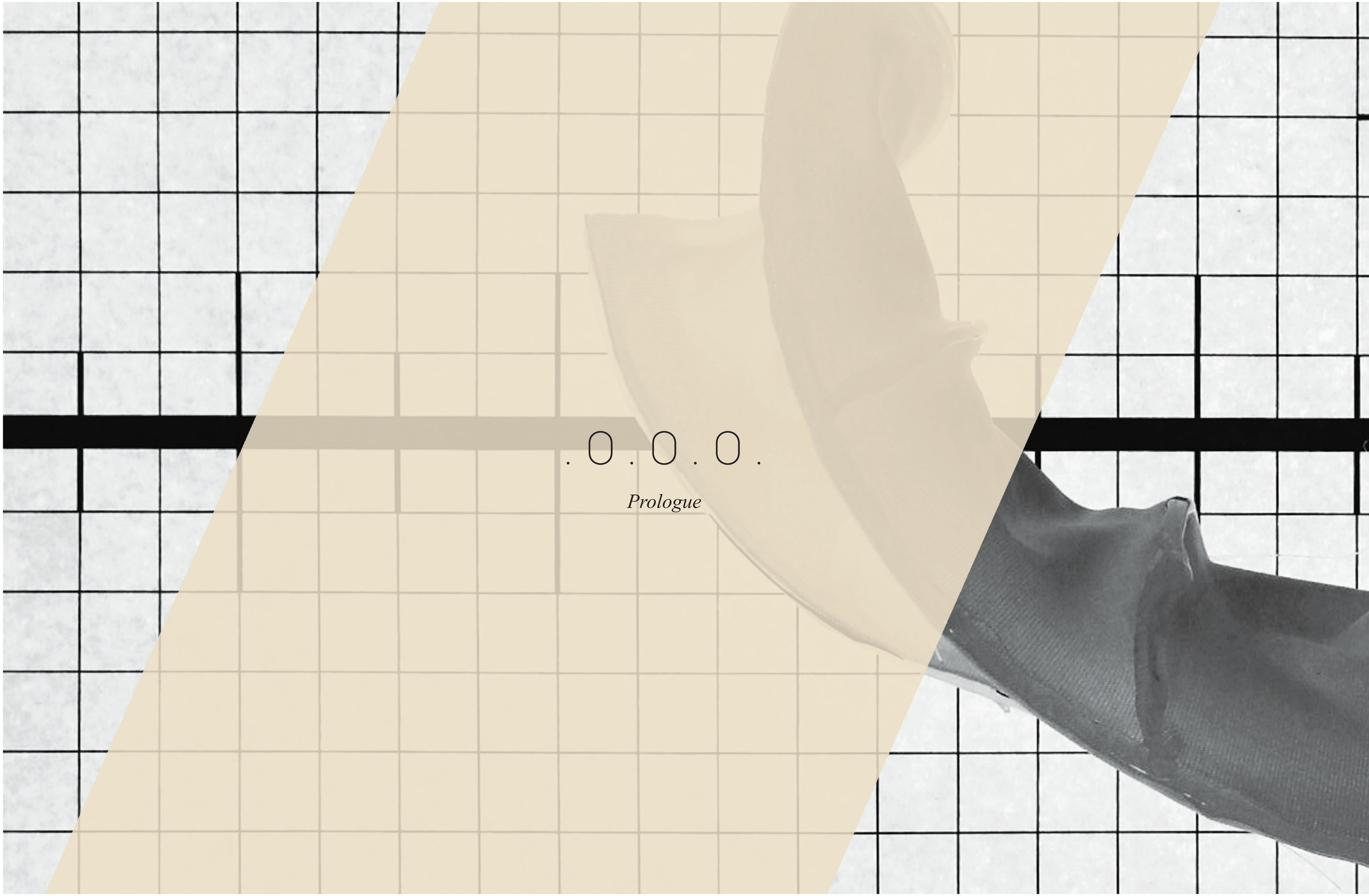

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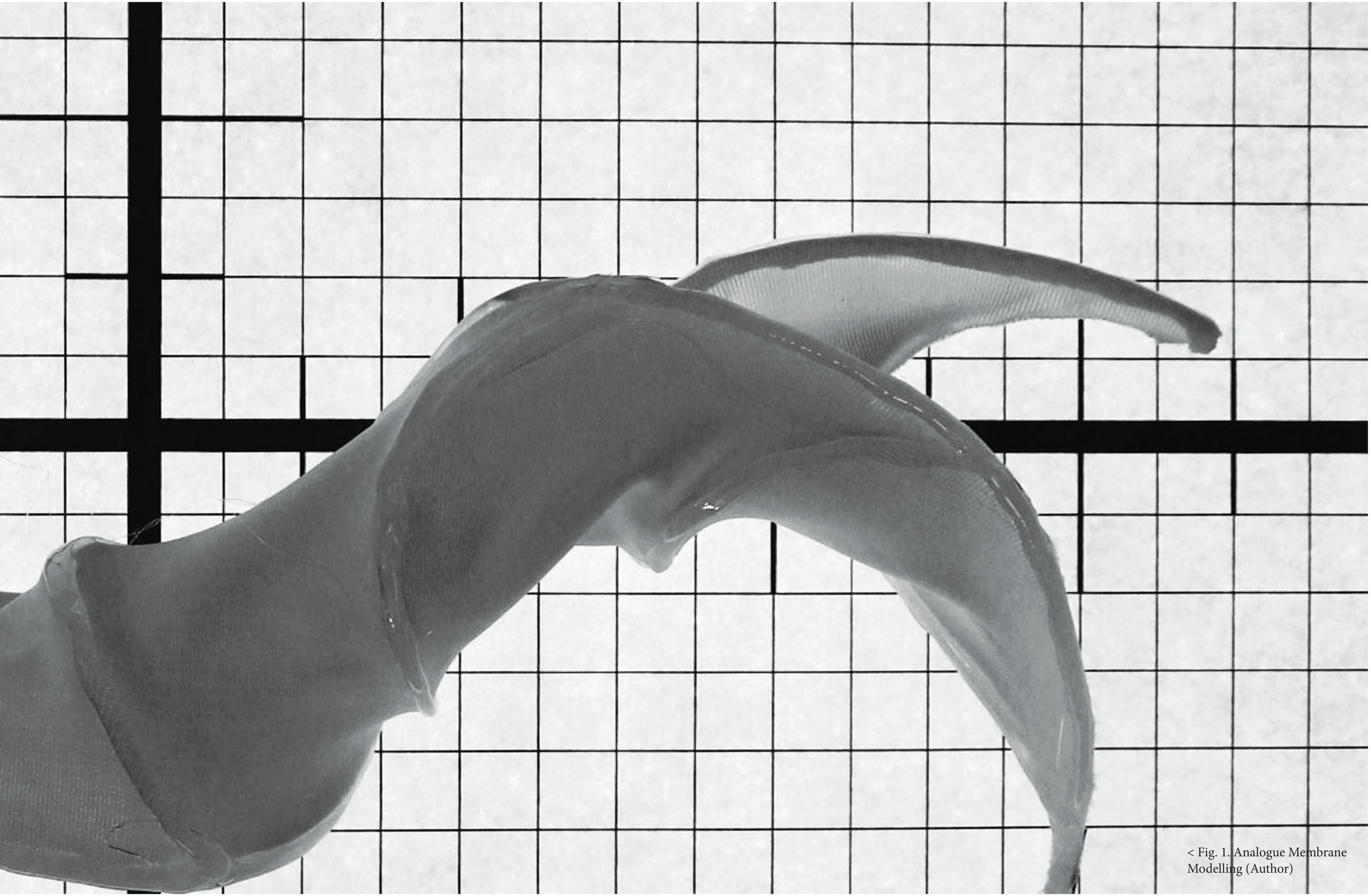
Prologue



< Fig. 1. Analogue Membrane Modelling (Author)

.0.0.1. Abstract

Over the past decade robotic fabrication in architecture has succeeded where early digital architecture has fallen short: in the synthesis of the immaterial logic of computers and the material reality of architecture.

In light of this new/profound shift architectural theorist and historian of the 'Digital Turn' - Mario Carpo argues: 'We no longer are witnessing the delayed modernization of an industry, but rather an historic departure: the modern division between intellectual work and manual production, between design and realization and manual production. Through this we see traditional modes of design becoming obsolete'.

The increasing power of digital design software, the widespread availability of digital fabrication tools, and the growing complexity of our built environment, are in stark contrast to the inefficient techniques that currently hinder today's construction industry.

Furthermore, the utilisation of concepts from nature including biomemesis, biophilia, swarm tectonics, as well as cross-disciplinary influences - from the film industry to social sciences and artificial intelligence - has contributed significantly to the depth of change in the tools, and their subsequent delivery of, architecture.

Using nature and biological paradigms as a key influence for the work (specifically biological systems as defined by Menges, Wienstock and others) the thesis asks the question: How can biological theories on growth disrupt inert material perception within the discourse of 3D-printing architecture?

It seeks to consider a design and fabrication process that allows the dynamic potential found in natural systems (patterns, forms, behaviours, organisation) to design and build with far more complexity and sophistication. Such work could fore front notions of growth, evolution and natural forms of optimization compared to the current post industrialised notions of beauty. New computing capacity and assembly efficiencies should over time produce more advanced structures than are possible with current technologies.

The researcher is 'aware' of the range of fabrication methods available to the industry, firstly the invention of Computer Numerical Control (CNC) known primarily as a 'subtractive method' of machining and additive manufacturing machines (3D printers) by Charles Hull (1984) which revolutionized rapid prototyping throughout the automotive, aeronautic, and design industries.

The application of additive manufacturing workflows - in particular to the architectural field - holds significant potential to provide a fabrication method for the complex geometrical forms that substantiate the parametric design paradigm. However, contemporary attempts in mass fabrication of computer generated componentry are still costly in terms of practice, investment, and time... They are also complex in terms of assembly and co-ordination.

Using customized CAD/CAM workflow the author speculates a self-assembling '4-D' architecture. As a piece of explorative design research, the thesis focuses primarily

on the underlying philosophy and design methods, and looks to offer up a series of tectonic iterations that integrate form, surface and structure. These iterations have been designed and developed through complex surface pattern projection, a speculative technique developed by the author. It allows a use of direct additive 3d print to surface and enables a prototype fabrication system. This prototype system results in the production of self-assembling tension based membrane surface structures. These structures could, for example, be used for rapid deployment construction scenarios. (see final Design Research).

Resin-impregnation patterns are applied to 2-D pre-stretched form-active tension systems to induce 3-D curvature upon release. Form-finding is enabled through this method based on materials' properties, organization and behavior. A digital tool is developed in the CAD environment that demonstrates the simulation of material behavior and its prediction under specific environmental conditions.

The methodology follows a systematic design-led research approach, in which physical form finding techniques, developed throughout the 19th and 20th centuries, are digitized via parametric 3D modelling software. Extensive physical modelling and analysis is conducted into a biomimetic approach to the design of fabric tensegrity surface structures, and their CNC fabrication potential explored. This research demonstrates the association between geometry and material behavior, specifically the elastic properties of resin impregnated Lycra membranes, by means of homogenizing protocols which translate physical properties into geometrical functions.

The work challenges the shifting role of the architect from that of an assembler of inert (discrete) material parts towards that of 'an orchestrator of material effects'. This shift in role is enabled through the affordances of computational design tools, and emerging fabrication methods. Conclusions are drawn from the physical and digital explorations which redefine generative material-based design computation, supporting a synergetic approach to design integrating form, structure, material and environment.

How can biological theories on growth disrupt inert material perception within the discourse of 3D-printing architecture?

For Mum and Dad.

.0.0.2. Acknowledgments

There are so many people who I would like to extend my deepest thanks to…

First and foremost, to Mum and Dad (and Buddy). You have given me every opportunity to chase down any idea, no matter how irrational, and you were always there for me with immeasurable support when times got tough. I will always look back on these years at Uni with massive gratitude and a big smile, but nothing ever beat coming home to you guys. Thank you.

I must thank my supervisor Derek for what has been an eye-opening year and some more. You have broadened my horizons and introduced to me a whole realm of design methods, tools, and a culture that I otherwise would remain oblivious to. Without your support this thesis would never have been completed. Thank you.

To Rob, with what started as a summer job in Gizzy turned into one of the coolest experiences and a an amazing friendship with the chilliest of ANZACs. It's been too fun and I look forward to seeing what comes next for you. Lilli, thanks for sharing him with me.

To Tama, Dylan, Ariana, and the rest of the SITUA crew, thank you. I couldn't think of a funnier, more relaxed group to have been bunched with. Congratulations on your hard work and coming out the other end! We must finish recording our road trip techno album asap (worldwide).

To the Masters class of 2016 and all those who joined the real world along the way, thank you. You guys are the most fun, intelligent, and supportive group of nerds to have to spend 5 years with. I can't wait to see what great things you all achieve in the paths you have taken.

.0.0.3. Contents

.0.0.4. Introduction

Background

Louis Kahn proposed through his philosophical explorations that buildings were not inert "configurations of form", but "living entities". (McCarter) Kahn hypothesized a universal ordering system, whereby function must accommodate itself to form, insofar as form was the result of an understanding of the task it had to support – a 'form follows function' perception. Through applying Kahn's theories away from the study of the brick towards the notion "material", and replacing the idea of 'task' to that of 'performance', this research speculates 'how does material perform'? Is there a way in which we can 'predict' material behavior and organization within a given context? Moreover, how do we 'find' material form?

Frei Otto is largely attributed to extending this strand of logic in his form-finding design methodology. He followed on from Kahn's opinion of a predetermined search for material form, and produced a refined paradigm regarding to the synergetic relationship between performance and material integrity. (A. Menges)note Otto proposed new types of structures in which form was systematically the result of load applications. His membrane structures exemplified this, as results of material studies of minimal surfaces that utilize pneumatics and soap-film as natural computation tools. Note This research seeks to build from material based form-finding approaches, and explore how this research tradition may be extended through translation from the physical into the digital design realm.

Problem Definition

Architecture continues to evolve as contemporary designers attempt to redefine the built environment. Rapid advances in digital technology, building materials, and construction logics continue to eradicate the inert rectilinear limits synonymous with modern architecture. Current CAD (Computer Aided Design) applications, and parametric modelling software packages, promote more generative approaches to design.

Although CAD tools have become widely democratized, there is still an evident gap between the ability to design on screen, and to physically manifest the output. Generative design approaches often result in geometrically complex forms that fail to reach physical realization due to imposed fabrication and assembly limits. This in turn has reserved the ability to implement information rich digital design and fabrication processes almost exclusively to projects that are not constrained by limited budget, time, and accessibility.

This is largely enabled by CAD tools' failure to recognize materials' inherent capacity and tendencies under specific conditions. Materiality is largely ignored, and applied as an afterthought within the design process as the inert reciprocals of form. (Oxman, Performative Morphologis: The Vertical Helix)

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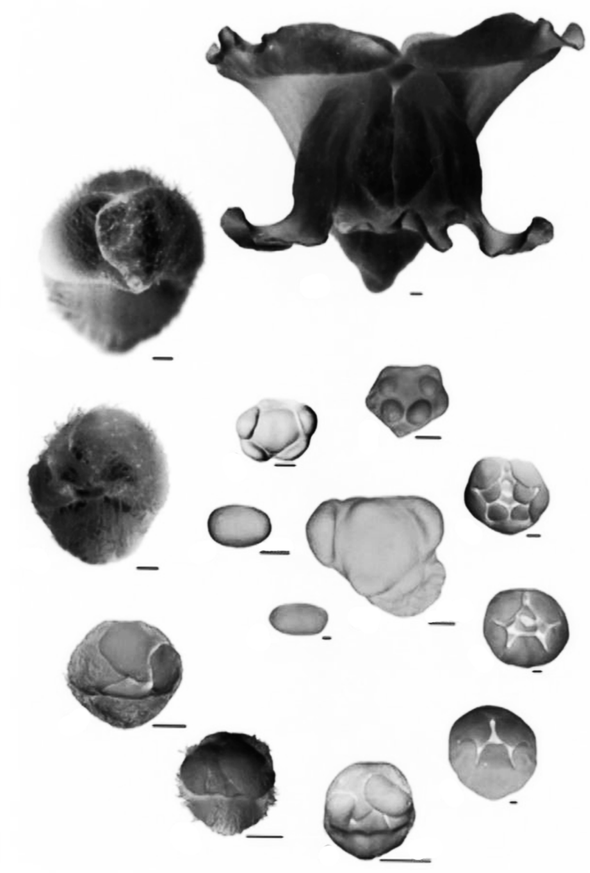


^ Fig. 2. Heydar Aliyev Center in Baku, Azerbaijan (Ivan Baan)

> Fig. 3. Enrico Coen presentation, John Innes Centre (Cohen, Cells to Civilizations)

as an afterthought within the design process as the inert reciprocals of form. (Oxman, Performative Morphologis: The Vertical Helix)

Aims and Objectives

This research takes aim at existing fabrication methods of CAD-generated, geometrically complex architecture through a biomimetic lens. It examines how nature achieves incredibly complex geometries (that are materialistically optimized to external environmental and performative criteria), and studies how current CAD/CAM workflows could be reinterpreted through these findings.

It seeks to develop a synergetic approach to design, whereby material organization and behavior, as they may appear in the physical world, are integrated into digital tools for design exploration. This approach is based on the premise that 'material, structure, and form can become inseparable entities of the design process which relate to matter, performance and geometry respectfully'. (Oxman, Programming Matter)

The key output of this research is to develop a fabrication system that systematically reflects morphogenetic processes found in nature; one that optimizes material efficiencies and energy to externally influencing factors. To achieve this, the design process conducts methodical and recursive physical and digital modelling in parallel, to effectively simulate natural form finding systems accurately. This involves an understanding of the micro-mechanisms within material systems and their influence on the macro scale. In attempting to achieve this, the research develops a digital simulation tool which is targeted towards material-based design generation.

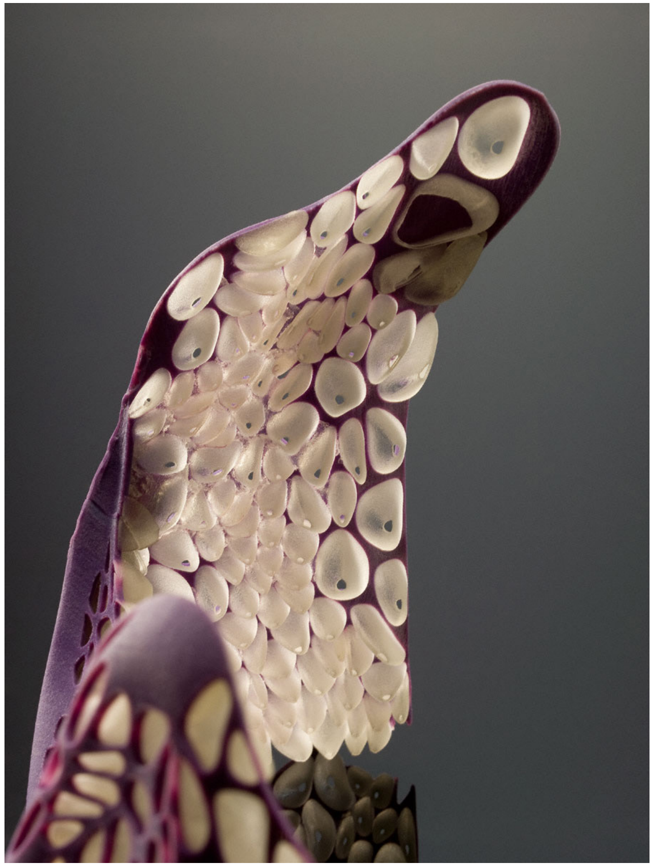
Organisation

This investigation is conducted in four parts, reflecting the design research approach.

The first part reviews the theoretical framework in which this research lies through a literature review. This chapter examines the field of biomimetic design in and how it deviates from similar biology-focused schools of thought. This leads to a review of the notion of 'material intelligence', and its history within the fields of architecture and design. This section highlights significant practitioners within the field who developed generative material-based research methods and applied them to the architectural/ engineering disciplines.

'New Materialism,' an emerging computational thought that proposes a significant challenge to both the current digital design approaches and the 'truth to materials' perception, is introduced here. Sanford Kwinter's essay Landscapes of Change: Boccioni's 'Stati de animo' as General Theory of Models is discussed in its application of New Materialism thought to a trilogy of futurist paintings by Umberto Boccioni. The section concludes with a short reflection on how a New Materialism perception could be applied to CAD/CAM workflows, and how the role of the designer might shift to accommodate this.

This research systematically concerns itself with the morphogenesis of natural forms. Leading plant biologist Enrico



^ Fig. 4. Neri Oxman, Multi Material Print
(Luong)

> Fig. 5. Material Computation
(Otto)

Coen's theories surrounding the growth of natural systems is discussed – in particular, his theory on growth through conflict, a proposal that suggests a genetically encoded 'hidden colour' patchwork of cells of various growth rates. This theory is related to earlier theories regarding the 'deformable grid' as a simple mathematical translation method explaining the geometric variations found in nature. Coen's theory is illustrated in referral to art of the Byzantine period, and the lithographs of M.C. Escher. Application of the conflicting growth theory within digital design is discussed, outlining the potential architectural implementations.

The literature review concludes with a summary of current digital fabrication technology, and the emerging field of '4D-printing'. This section examines traditional CAD/CAM workflow, and the inherent drawbacks of 3D-printing within the architectural realm. MIT researcher Skylar Tibbits is one of the leading protagonists of the 4D-printing paradigm. His merging of machine, material and genetic programing is discussed in its application to the production of 'smart materials'.

Part Two of this research frameworks a preliminary design exercise, in which physical form-finding methods are translated to the digital realm. This exercise focuses on material surface structure form-finding methods, in particular: ruled surfaces, minimal surfaces and funicular shells. Each material study is broken down to its micro-mechanisms for translation to the parametric design modelling plugin 'Grasshopper', a plugin for CAD modelling software 'Rhino3D'. These experiments are then explored through rapid iterative simulations, to discover their theoretical application beyond what would be practical/ possible to conduct within the physical realm. The output of this preliminary design research is a series of 'sculptural' explorations that utilize the fundamental principles behind the physical material system.

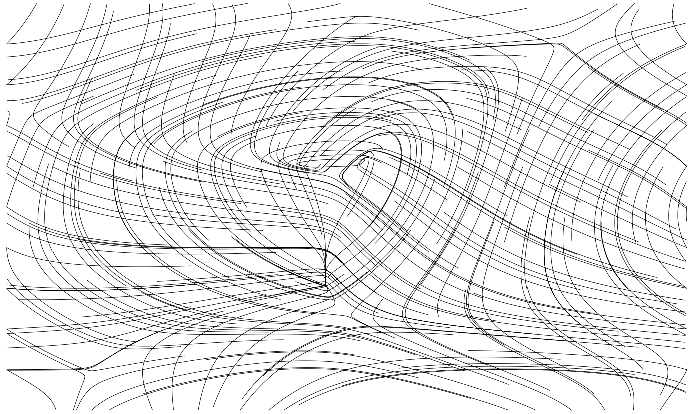
Part Three of this research sees the development of a novel fabrication method for geometrically complex surface structures. Beginning with an open ended initial material study, the effect of plastic deposition onto pre-stretched surfaces is explored. This study sees multiple extrudable materials of varying properties extruded onto inflated balloons. Once dry, the balloons are popped and their emergent 3D forms examined. This relatively uncontrolled exercise serves as an experimental 'sketching' approach to physical design, in which new design avenues emerge. This study confirmed that by creating material composites, operating as on united organizational entity (as opposed to material assemblies operating individually), flexible fabrics may be globally manipulated to induce curvature. The results of this initial balloon study lead to a second more thorough, and methodical physical surface study. This controlled surface deposition study examines the effect 'pattern' has on the emergent 3D curved surfaces.

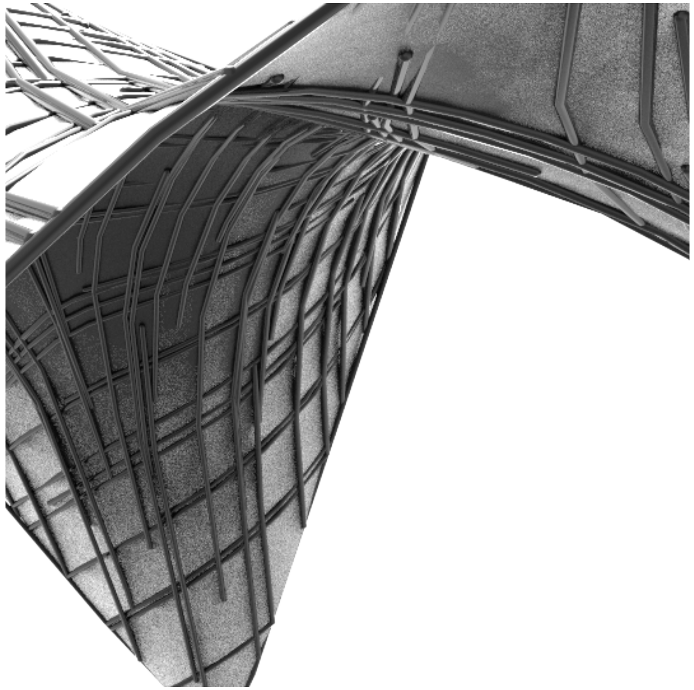
A compendium of patterns (of generatively increasing complexity) is established to then be manually printed onto Lycra fabric under uniform tension using thermoplastics. This study develops an understanding of how the local plastic impregnation pattern, acting as “lines of constraint or hardness”, force the membrane to remain at its initial (pre-stretched) length when released. The induced global curvature of the released model is examined in relation to the specific pattern to understand the micromechanics of the system.

This system is then algorithmically translated for further experimentation within the digital design environment. An understanding of pattern to form is tested and reverse engineered, to output 2D patterns that when printed, emerge to a goal global surface form. A series of rapidly deployable, self-assembling 4D printed architectural surface pavilions is here proposed for implementation in non-conventional construction environment.

Part Three of this research concludes with the design and build of a prototype low-cost, portable 4D-printer. This printer system is designed to fit within a larger ‘file to factory’ paradigm in which the digital pattern file of a given structure can be sent via the internet to the onsite location, saving on material transportation cost and reducing time of construction. The resultant shelters’ fabrication method requires no previous construction knowledge, and the shelters are rapidly self-assembling, making them ideal for deployment in disaster relief scenario.

Part Four comprises a conclusion and critical reflection. Here the design research is critiqued, reviewing effectiveness of applying a biomimetic scope to the production of geometrically complex architecture, and the future prospects of the developed 4D printing approach is speculated upon.





> Fig. 6. 2D Pattern Print (Above) (Author)
> Fig. 7. Emergent 3D Shell Structure (Below) (Author)

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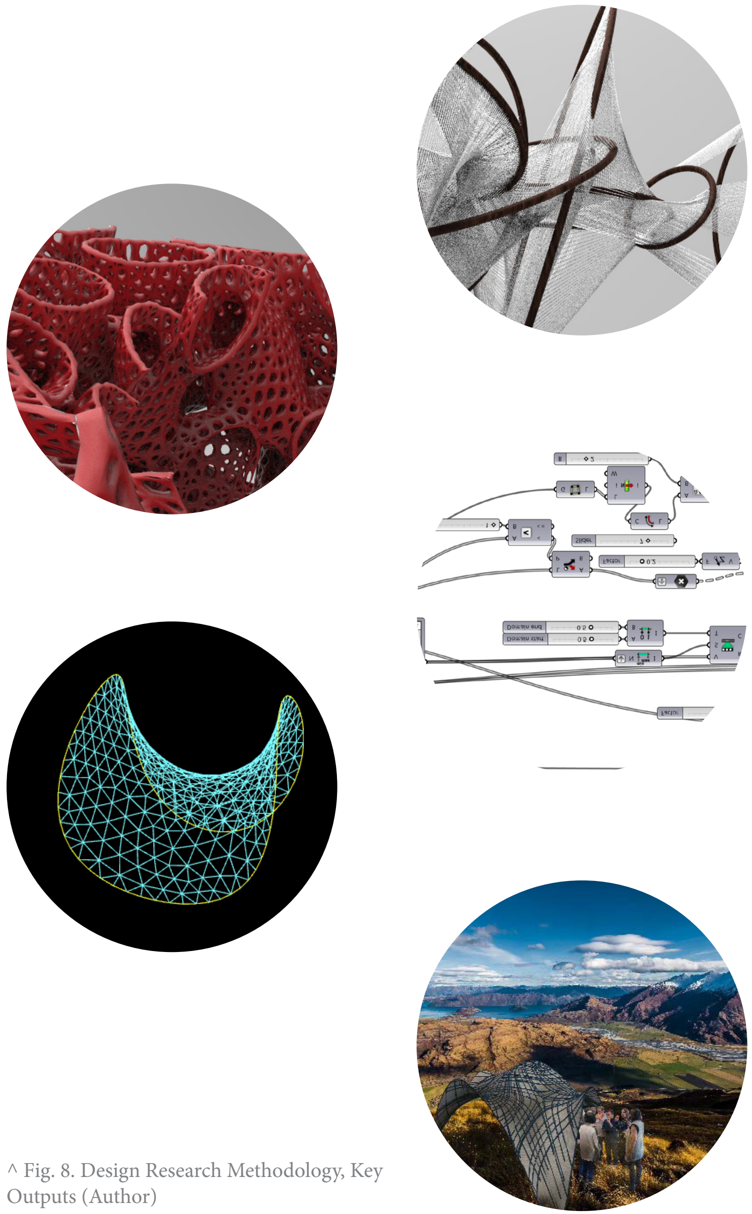
Methodology: Design-Led Research

This thesis employs a design-led research approach. Through a journey of iteration and constant feedback, each aspect of the research is developed. Flaws become apparent, leading to re-angling of focus and refinement. This methodology can be described as an 'action – reflection' model. Through the process of designing, the aim is not a final resolved outcome, but rather a process of '(re-) construction for the purpose of appropriate (re-)action'. (Jonas)

This chosen methodology reflects that of early material practitioners, allowing for open ended exploration and the opportunity to work both in the physical and digital environments in parallel. This method is iterative in nature and provides the potential to disrupt conventional avenues of architectural production through exposing possibilities along the design continuum.



^ Fig. 8. Design Research Methodology, Key Outputs (Author)

.0.0.6. Project Scope

The scope of this research sets out to achieve an architectural solution that showcases how a biomimetic, 'New Materialism' approach can disrupt conventional CAD/CAM design workflows. In doing so, it contributes to the wider investigation of greater democratization of 3D printing within the architectural discourse. Three key objectives are here established to substantiate the design research scope:

First, this research seeks to understand the historical implementation of material-based, form-finding design research, and the potential to expand these methods within the digital design environment. It aims to do so through examining the microstructures of traditional form-finding experiments, conducted by the pioneers of the field. This preliminary exercise looks to develop digital modelling skills, and exploit the affordances of computation in testing otherwise time and material costly physical experiments. It also establishes a physical-digital design feedback loop, in which the digital modeling can be tested and checked against its physical counterpart. This work aims to establish a synergetic approach to design, where by material organization and behavior, as they appear in the physical world, may be integrated into digital tools for further design exploration.

Second, this research seeks to understand an underlying relationship between pattern to emergent form. Through extensive physical and digital testing, methods to exploit this relationship are exploited through the introduction of time to the design process. This study fits within theories of complexity and emergence schools of thought transposed from the computational realm.

Finally, this research aims to develop a system in which geometrically complex architecture can be fabricated at low-cost, with minimal construction experience. This objective fits into a wider 'file to factory' design paradigm, in which files are sent directly to site for automatic production via CAM tools. This emerging paradigm has created debate around the meaning of 'authorship' and 'creditability' in the age of mass-produced architecture. This research does not attempt to engage in this discussion as it falls outside the underlying theoretical scope.

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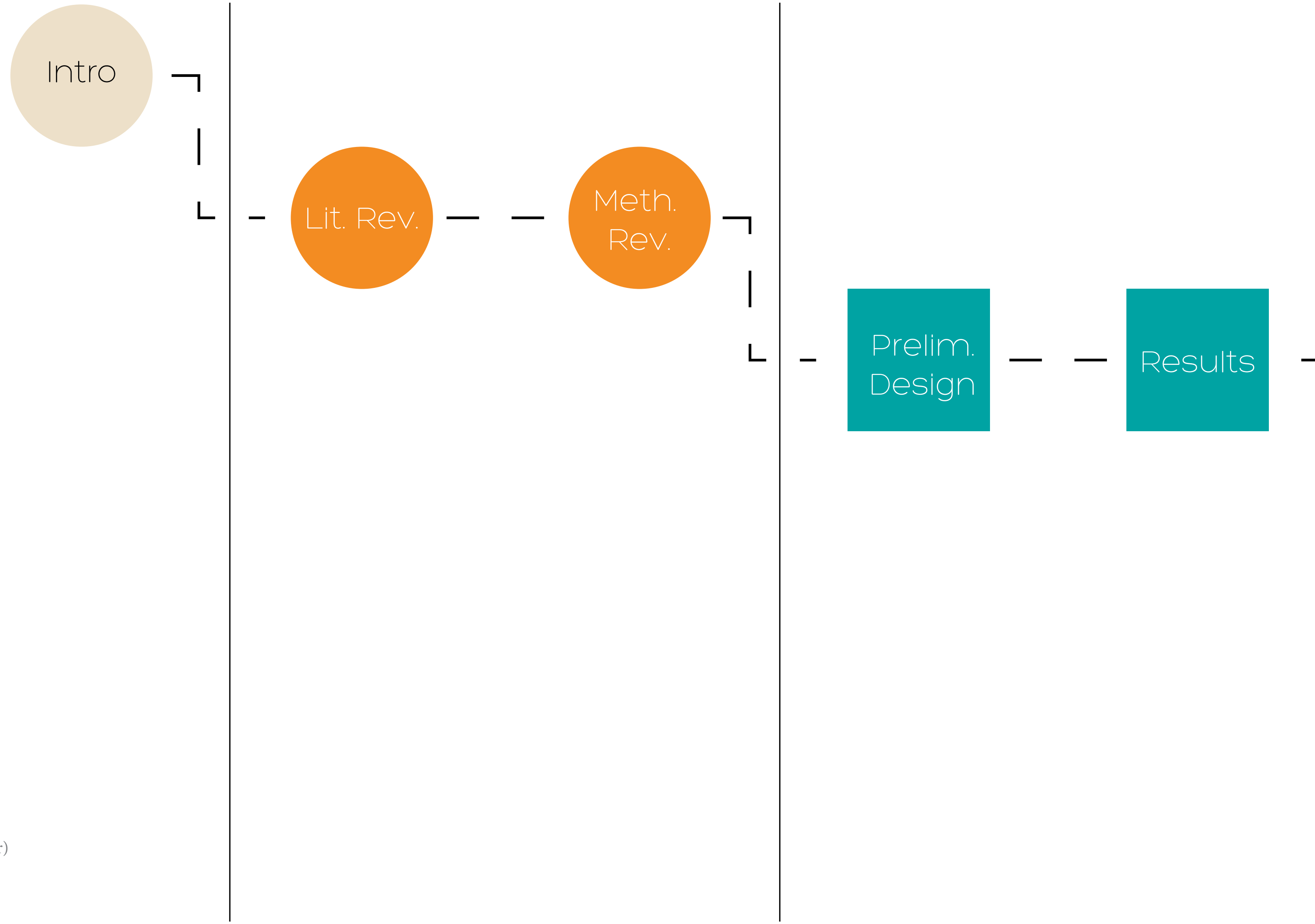
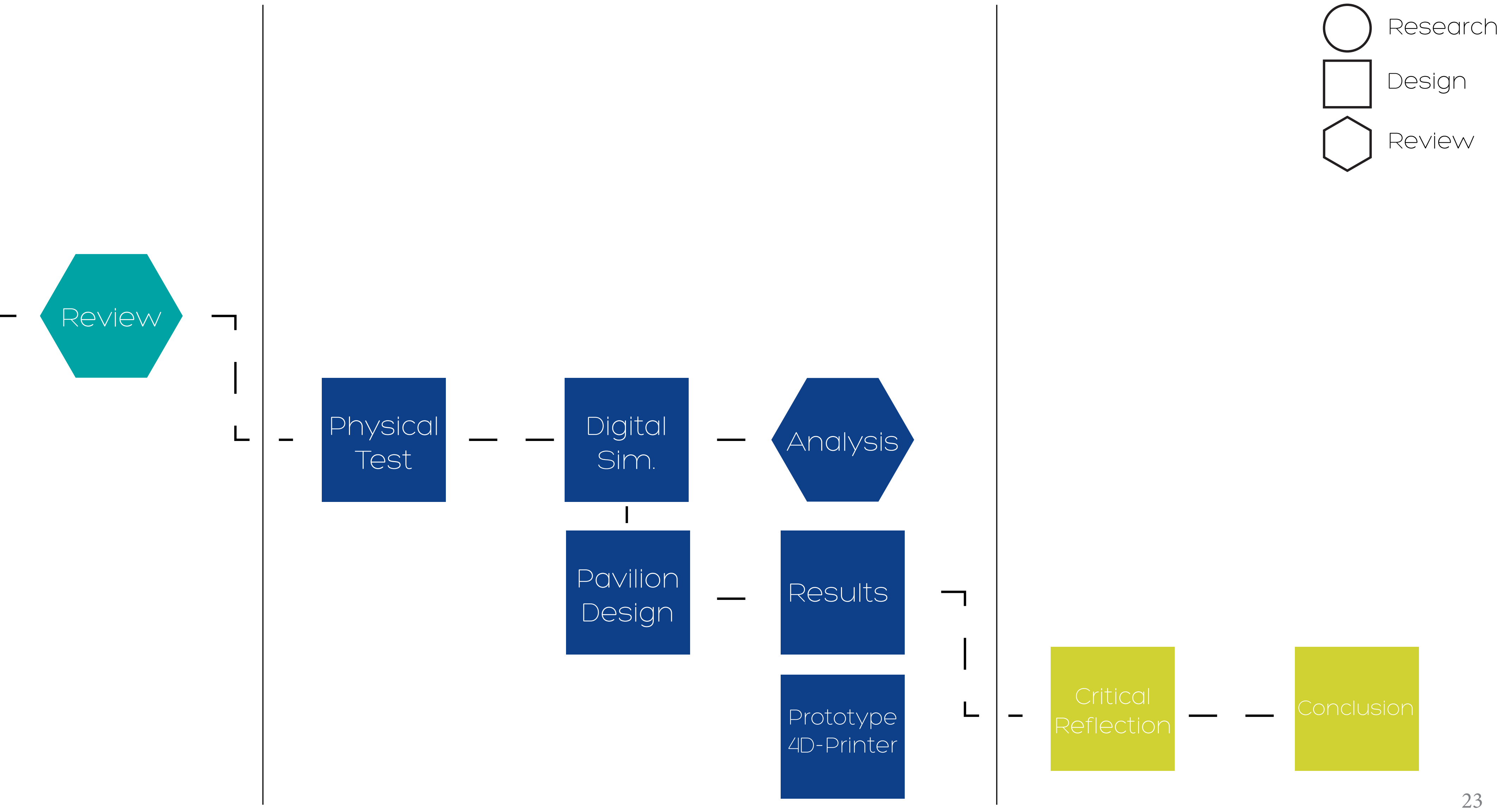
Research Road Map



> Fig. 9. Design Research Road Map (Author)


Research
Design
Review
Review
Physical Test
Digital Sim.
Analysis
Pavilion Design
Results
Prototype 4D-Printer
Critical Reflection
Conclusion

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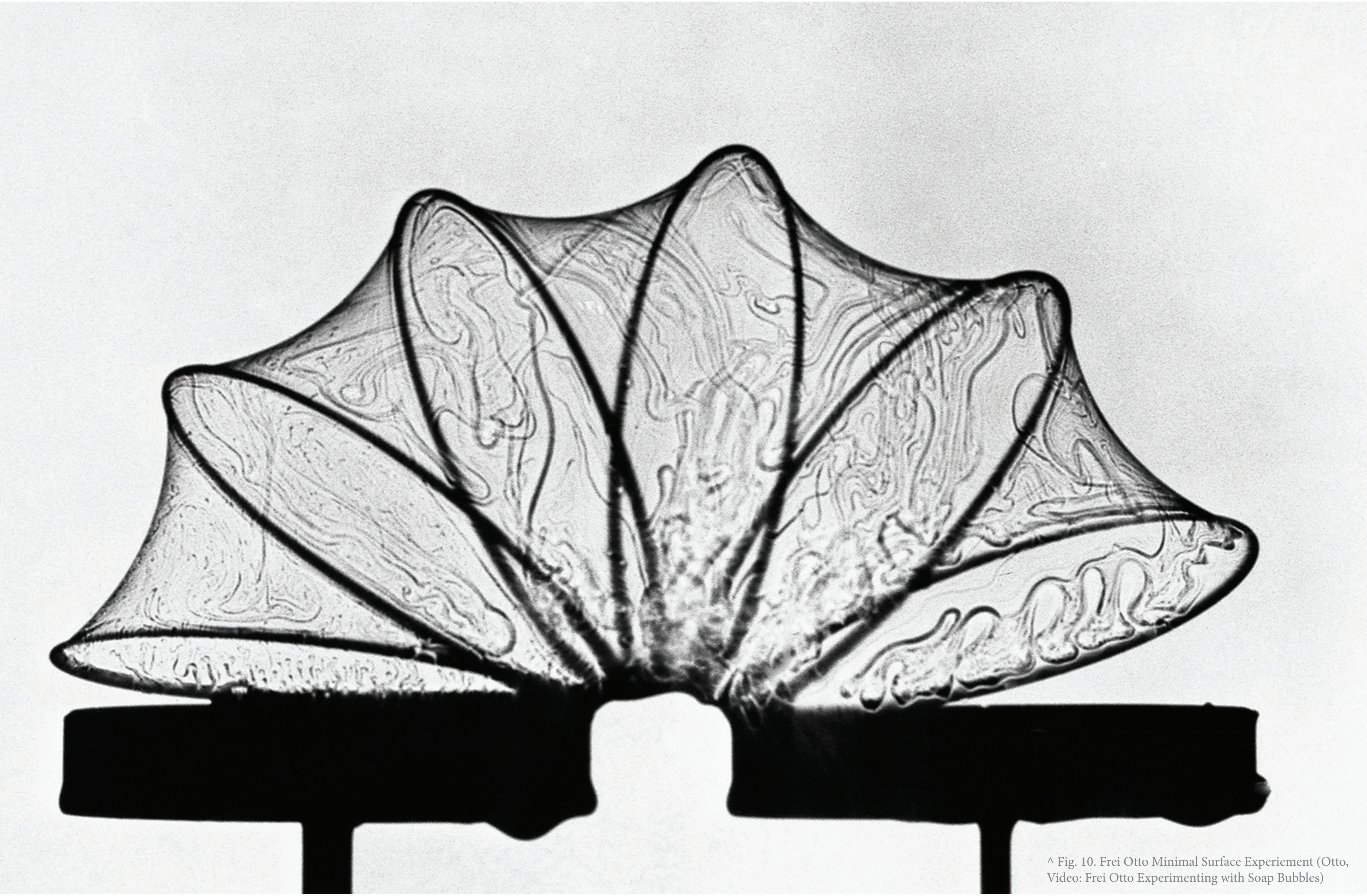
Literature & Methodology Review



^ Fig. 10. Frei Otto Minimal Surface Experiement (Otto, Video: Frei Otto Experimenting with Soap Bubbles)

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Biomimetic Design

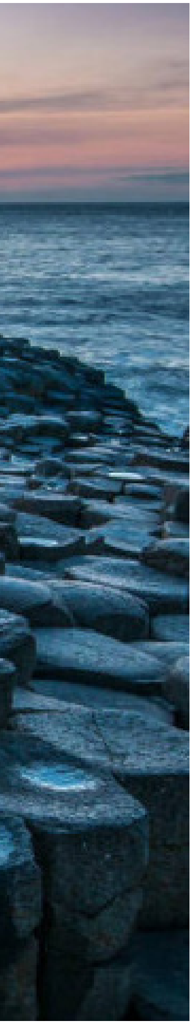
Introduction

Biomimetics as a scientific discipline concerns itself systematically with the technical implementation and application of structural systems, processes, and developmental principles of biological systems'. (Pohl and Nachtigall) The biomimetic field can be divided into two areas, 'structural biomimetics' and 'process biomimetics'. This research concerns itself with the latter.

Process biomimetics seeks to understand the fundamental mathematical principles that govern the development and behavior of a natural system. This approach does not seek to imitate the organism, but to decode the underlying rules the system is governed by. Goran Pohl writes: 'Through understanding a fundamental idea from nature… these inspirations can contribute to bolder technological-biological adaptations'. (Pohl and Nachtigall)

As nature presents no instruction manual for its designs, it is the biological, morphogenetic processes that must be fundamentally understood to design biomimetically. Historically, the biomimetic process developed from the comparison of results from functional morphological research with the requirements of technical constructions.

^ Fig. 11. Brain Coral (Oceana)
> Fig. 12. Hexagonal Rock Formations (UNESCO)



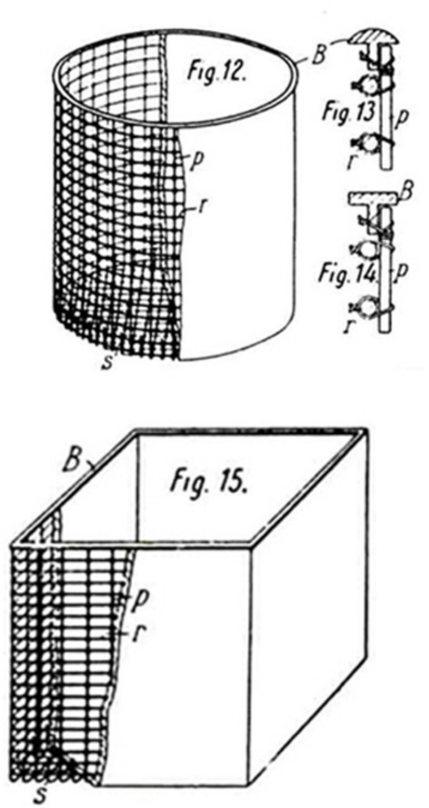
Early Biomimetics

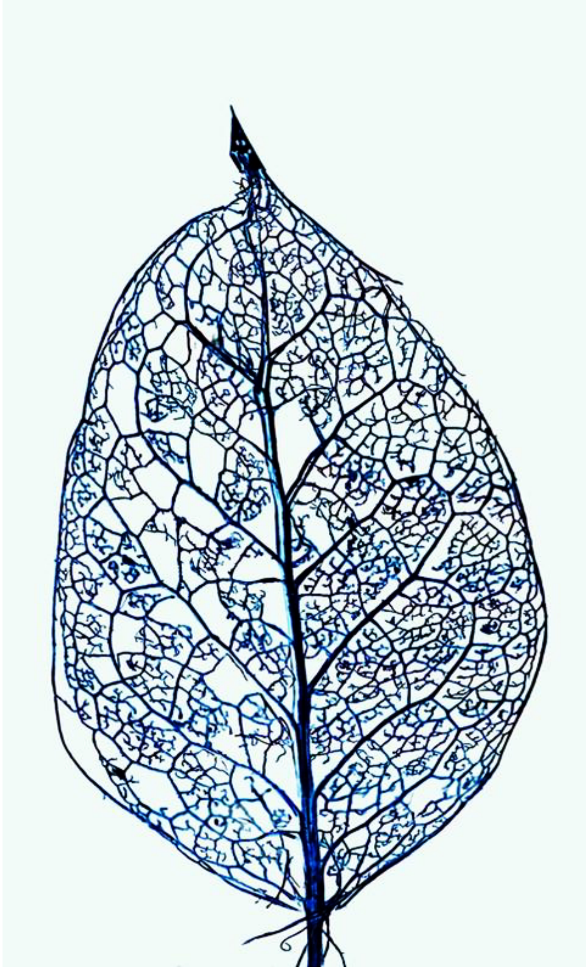
TThe most influential early biomimetic engagement within the built environment (although naively), can be found in the planting pots designed by Parisian horticulturalist and landscape gardener Joseph Monier. (Pawlyn)

His frustration at the expense and fragility of large stone or clay planting pots led him to take direct inspiration from the branching sclerenchyma (vein) network of Opuntia plants. He examined their ability to provide rigidity to the leaf masses via a network of structural members. In 1880 his observation led to the invention of pots with a multicomponent structure. A wire basket, corresponding to the sclerenchyma (vein) network in plants, gave tensile strength to the pot whilst simultaneously holding the pressure-resistant cement mass, corresponding to the parenchyma (tissue) of plants, in shape. At the same time the cement stabilized the wire basket form.

Little did Monier know, but his multi-composite system would have a profound historical consequence on the course of architecture and engineering. The system he had invented later evolved into reinforced concrete structure. Incidentally the creative gardener lives on in the expression 'Monier iron'. (Morsch)

Monier's approach can be considered typically biomimetic, as a principle of nature was abstracted; however, no 'natural' forms were slavishly copied.





^ Fig. 13. Leaf Sclerenchyma (The Editors of Encyclopedia Britannica)
< Fig. 14. Monier's Planterbox (Sack and Scoffoni)

.2.0.2. Biomimetic / Biomimic / Bionic

It is important here to distinguish the differences between 'biomimetic' design and 'bionic' or 'biomimicry' in design.

Bionics

Bionics is an artificial word, combined from BIOlogy and techNICS. The term bionics has existed since the 1950s in early research into echolocation systems used by bats for use in radar technology. (Pohl and Nachtigall)

Biomimicry

Biomimicry is a more recent term which literally refers to the direct imitation of life. Early examples of biomimicry can be found in Leonardo da Vinci's sketches for flying machines, or the invention of 'Velcro' by Swiss engineer George de Mestral, whose dog returned from the bushes covered in burrs. (Pawlyn)

Biomimetics

Biomimetic goes beyond merely imitating nature in material, functional, or creative regard. It concerns itself with 'the grasping of natural principles to aid in the comprehension of analogous, technological questions, which could then be solved by the application of optimized technologies.' (Mazzoleni and Price)

A functional analogy demonstrating the difference between biomimicry and biomimetics can be found in comparing Sony's robot dog, AIBO, and Frei Otto's tree columns at Stuttgart Airport. Although the Sony robot dog looks cute, wags its tail, and can pee, it is in no way a biomimetic conception, it is simply a complex assembly of inert material parts that resembles a technical copy of a natural form.

The AIBO dog is therefore an example of a bionic/ biomimic construction. Alternatively, Otto's tree columns in Stuttgart Airport represent true application of biomimetic understanding. They do not 'look' like trees – they do not have bark, leaves, or roots – yet they align analogously with a "structural tree" concept. They were developed as a solution to an optimization problem; studies were performed on branching angles, thickness,

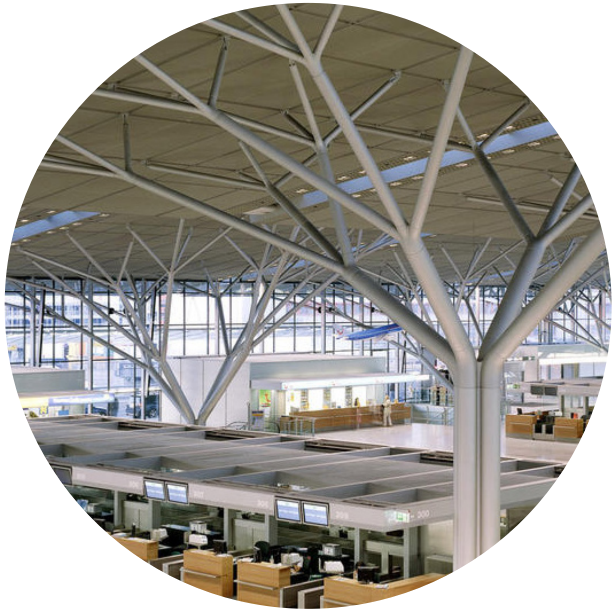
and proportion in trees to derive a solution to support a load over a given area while having least possible mass. (Ahmeti)

To reiterate, through researching the natural system (the tree), Otto's approach grasped the natural principles of optimising structural material in relation to load, and applied it to the design problem.

Biomimetics in the age of Modernism

The functional analogies of natural precedent that inspired the invention of reinforced concrete were ironically later lost to the essentialist 'brick whispering' ideals of the modernist, 'truth to materials' approach of the 1930's. This belief remains prevalent in today's design thinking that 'assumes essence of an apparently inert material to a set of given- supposedly appropriate- structural and spatial typologies'. (A. Menges, Fusing the Computational and the Physical)

Although the Aristotelian view on matter as 'an inert receptacle of form superimposed from the outside' took centre stage during the modernist movement, truly generative material exploration into design was still being explored in radical academic architectural ventures throughout the 20th Century. These ventures eventually evolved into the contemporary design paradigm of 'New Materialism'.



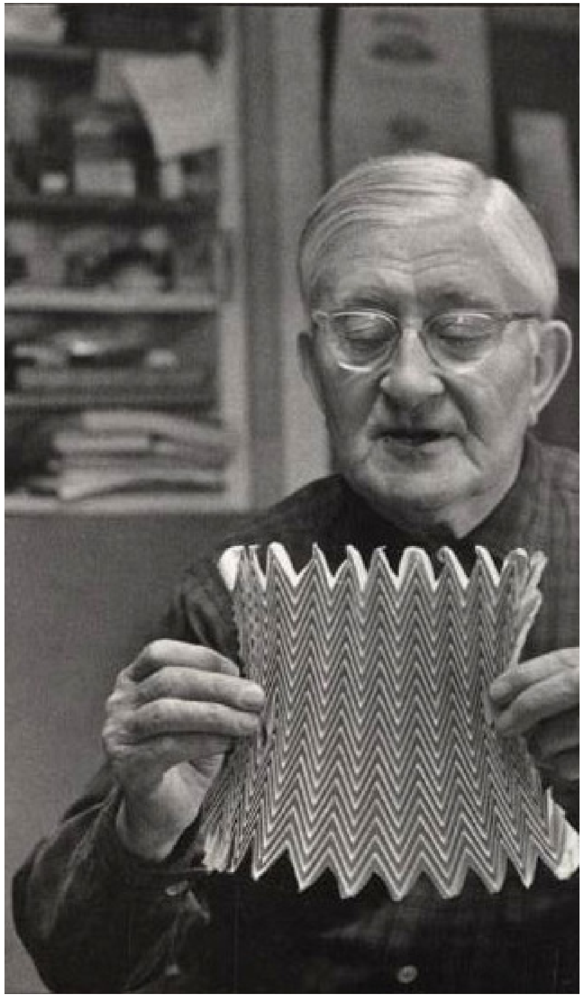
^ From left
Fig. 15. Sony Aibo Robotic Dog (Sony Aibo)
Fig. 16. Tree Branching Structure ()
Fig. 17. Stuttgart Terminal, Branching Columns (SBP Architects)

.2.0.3. Material Intelligence

Origins
Josef Albers' material studies conducted in his foundation course at the Bauhaus in the late 1920's, as well as his later pursuits at the Black Mountain College in North Carolina, proved to be a corner stone of material experimentation-driven design method.

Instead of employing established processes of materialization rooted in professional knowledge (of which he claimed stifled invention), Albers identified the material behaviour itself as a 'creative source for developing new modes of construction and innovation'. (Horowitz and Danilowitz)

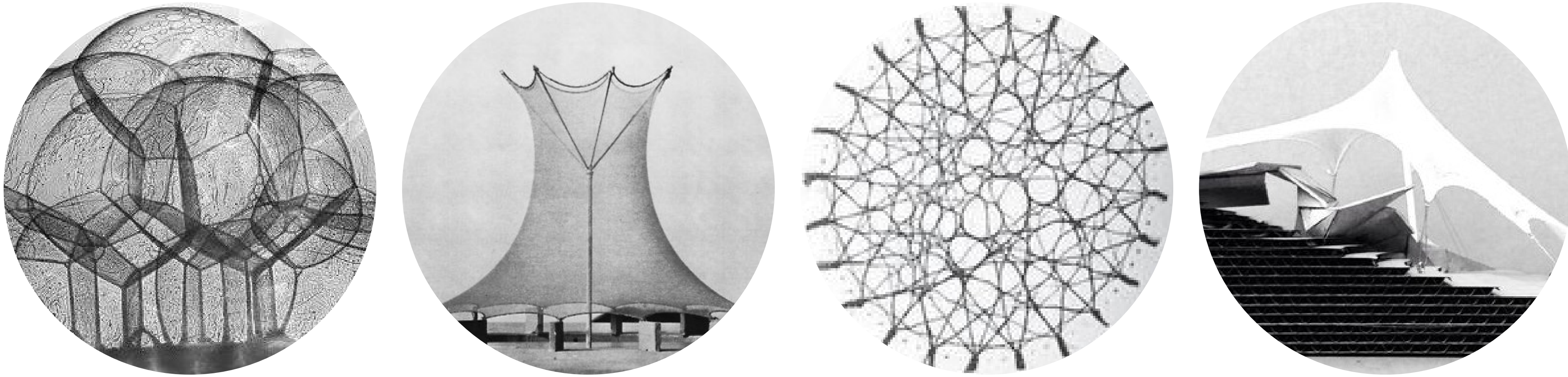
Albers' studies were not conceived as scalar models, nor representations of ideas, but as a generative unfolding of material behaviour in space and time. His methods used material to search for design outcomes, from which previously unsought design possibilities could originate. From the opening line of Werklicher Formunterricht Albers writes:



"ours is an economically oriented age… economic form arises out of function and material. Study of material naturally precedes understanding of function. Thus, our attempt to come to terms with form begins with study of the material." (Albers)

Josef Albers' material studies established a precedent for the possible enrichment of design processes, through a materialization-based approach to architectural design.

< Fig. 18. Josef Albers Material Constrast Study (Kroll)
^ Fig. 19. Josef Albers Fabric Study (Kroll)



^ Fig. 20-23. Frei Otto and Material form- finding experiments. (Yunis)

Frei Otto

Fast forward to the works of German engineer/architect Frei Otto. His work undertaken at his institute at the University of Stuttgart from the 1960s to the 1980s illustrated the alternative end of the spectrum of material-driven design approach.

His development of form-finding methods involved conducting extensive series of experiments with various material systems. He pioneered research using materials ranging from soap bubbles and sand, to grid-shells and cable-nets, to study their inherent capacities to physically compute form. Otto's research constantly sought to understand the 'equilibrium state of system', examining the 'intrinsic material behaviour under extrinsic forces'. (A. Menges)

Otto's development of architectural designs through studying material behaviour were also in opposition to the modernist perception of 'top-down determination of form and space'. (A. Menges, Coalescences of Machine and Material Computation) Otto considered his approach to designing 'Natural Constructions' a key theme in his works.

In 'Lightweight Construction, Natural Design', Rainer Graefe defines these constructions as optimized structures which deliver maximum performance for minimum outlay, and in which 'form and force are in harmony, constructions that cannot simply be stipulated; they are formed in processes which he regarded as analogous to the form-finding processes of nature, and therefore, a 'quasi-natural processes''. (Graefe)

Counter Modernism

As a counterargument to the modernistic thought prevalent during his studies, Otto proclaimed of his structures: “It is impossible to design these buildings. All one can do is help them, through constant searching, to take on their ultimate appearance. Thus, these buildings are not ‘made’; they are sought and found. They are not manipulated, but permitted to come into being.” (Songel) In his view, architects of the time were guilty of arbitrary design consisting of “almost unsurpassably strange, and exotic freedom of form”. (Klotz)

Otto’s architectural idea of natural and ecological building is often mistaken for an exhortation to imitate nature in a bionic sense. In fact, it was through his studies of technical load-bearing structures that Otto became aware of the existence of ‘analogous structural forms, and analogous form-finding laws in nature’. (Songel)

The experimental approach of Albers through his employment of material as a driving force in an open-ended design process, and Otto's scientific rigour in conducting related design research in the contemporary context of form-finding, underpin the emerging 'New Materialism' design paradigm.

< Fig. 24. Frei Otto Olympic Stadium (Inkulte)

.2.0.4. New Materialism

Introduction

'New Materialism' is an emerging thought of 21st century computational theory that proposes a significant challenge to both current digital design approaches that are devoid of material logic, and to the modernist 'truth to materials' perception that remains apparent in today's design thinking.

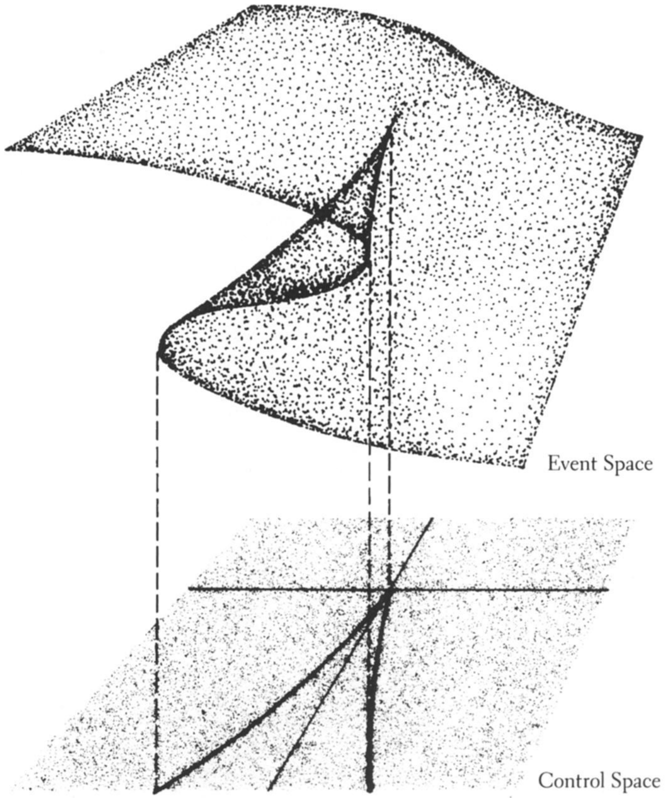
New Materialism capitalizes on the affordances of computation, in their ability to iteratively simulate complex generative design models to conceive forms that would otherwise be impossible to imagine.

Origin

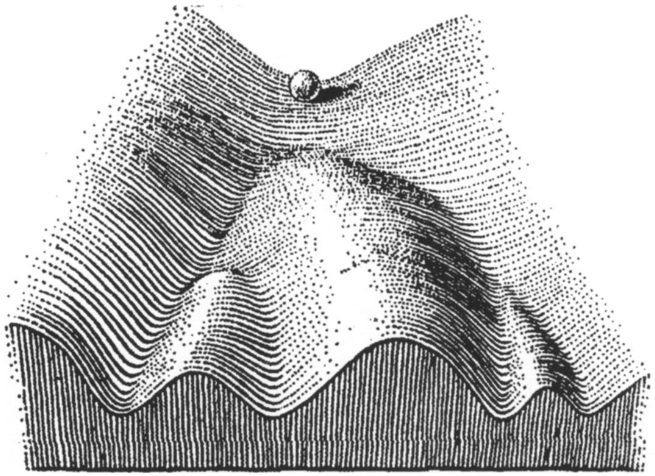
Philosopher Manuel DeLanda is credited with coining the term 'New Materialism' and is a leading protagonist of this novel perception of the material world. In his 1997 book 'A Thousand Years of Nonlinear History', he introduces a new understanding of materiality that stems from the philosophy of Baruch Spinoza and Gilles Deleuze. De Landa provides a framework of application of computational philosophy to the theoretical realm of architecture. (DeLanda, A Thousand Years of Nonlinear History)

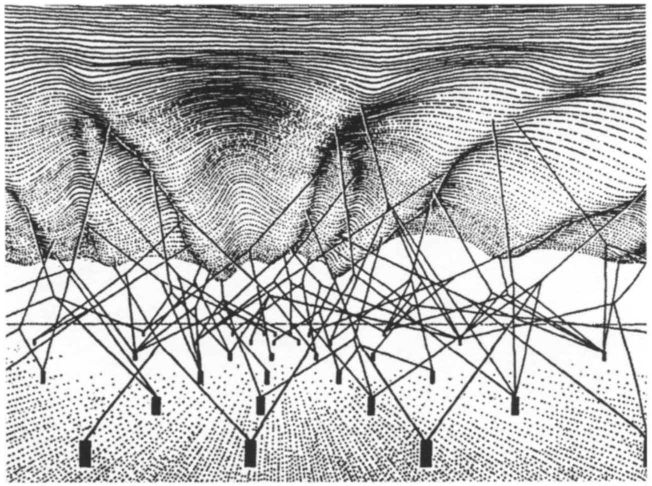
DeLanda's new vision of the nature of materiality is a counter argument to the imposed deterministic perception of materiality, a discernment that is inherently linear, 'the production of one event by another'. (Bunge) This deterministic perception implies that 'every cause always has the same effect, therefore we should be able to follow the chain all the way to a first cause and vice versa… there would be no novelty in the universe'. (DeLanda, The New Materiality)

DeLanda's New Materialism perception provides framework for perceiving matter as inherently active, empowered by its own tendencies and capacities to interact within a continuum of space and time. His framework outlines physical form as merely a 'stable moments' within a perpetual process of being and becoming.



^ Fig. 25. Epigenetic Landscape, Event and Control Space (Kwinter)





^ Clockwise From Top Left:
Fig. 26. Epigenetic Ladscape Surface (Kwinter)
Fig. 27. Boccioni's 'Stati d'animo': Les Adieux (Boccioni, States of Mind I: The farewells)
Fig. 28. Boccioni's 'Stati d'animo': Ceux qui Partent (Boccioni, States of Mind II: Those Whos Go)
Fig. 29. Boccioni's 'Stati d'animo': Ceux qui Restent (Boccioni, States of Mind III: Those who are left behind)
Fig. 30. Epigenetic Ladscape Subsurface of Influence (Kwinter)

Visualising New Materialism

Sanford Kwinter's essay 'Landscapes of Change: Boccioni's "Stati d'animo" as a General Theory of Models' provides a visual representation of DeLanda's theories in a critique of Umberto Boccioni's trilogy of paintings completed in 1911. These futurist paintings depict the departure and arrival of a train at a railroad station. Kwinter writes:

"Forms represent nothing absolute, but rather structurally stable moments within a system's evolution." (Kwinter, Landscapes of Change: Boccioni's Stati d'animo as a General Theory of Models)

This definition feeds into Kwinter's later discussion, in which he illustrates DeLanda's theory as an 'epigenetic landscape'. In this depiction, he outlines form over time as a continuously evolving network of interactions within an underlying event space, that determine physical manifestations upon the projected surface or the control space. Physical changes upon the manifestation are considered 'catastrophe moments', caused by disruptions in the events space over time.

Kwinter is describing a reality that is happening on a variety of levels, of 'both seen and unseen forces that unfold upon a continuum of influence over time and space'. (Kwinter, Landscapes of Change: Boccioni's Stati d'animo as a General Theory of Models)

Design Application

In adopting the perception of physical manifestation of form as merely a moment of torpor within an underlying network of potential capacities, the deterministic linear view of 'being' is traded for a nonlinear alternative. It proposes a view that every system is made of other systems, all continuously leaking information to one another in a way that links them along a single continuum of influence.

Computation, simulation and cyber physical production ultimately shift the role of the designer to exploit the divergence and multiplicity latent in materials, conceiving material systems as individual constructs, rather than derivatives of a given type. The role of the designer is shifted from the 'assembler' of inert materials, to the 'orchestrator' of material effects. Through developing a mathematical rule-based understanding, the designer can simulate these tendencies digitally to capitalize upon their internal tendencies.

< Fig. 31. Fibro.City. Robotically Woven Carbon-Fiber Structures
(Papadimitriou, Castro and Komar)

Material Application
It is within this New Material framework that this research is undertaken. Part Four of this research in particular seeks to understand and exploit the inert capacities and tendencies of elastic materials.

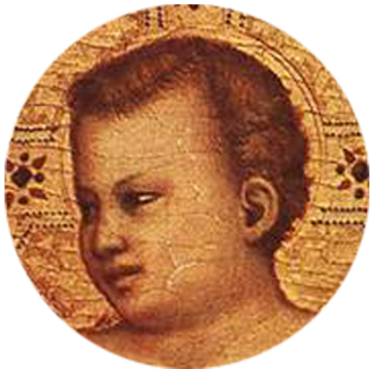
Through disrupting and varying fibre rest lengths at a micro level, new global emergent forms are discovered.

.2.0.5.

Natural Morphogenesis of Complex Geometries

Introduction

Enrico Coen is a leading researcher in plant biology. He recently correlated genetic cellular tendencies to the developmental growth of asymmetric flowers. His concepts of morphogenesis through conflicting differential growth are presented in his book 'The Art of Genes'. His theories here are illustrated through the art of the Byzantine Period and the M. C. Escher's Lithograph 'Balcony'. (Coen, The Art of Genes)



< ^ Fig. 32. Madonna and Child painting of the Byzantine Period (Giotto)

Nonlinear Growth

An alarming feature of this Madonna and Child painting of the Byzantine period is the abnormal sense of proportion.

The head of a child is normally bigger in relation to its body than that of an adult; yet in the Madonna and Child painting the child is shown with adult proportions, making its head seem unnaturally small, and vice versa the head of woman is seemingly unnaturally large.

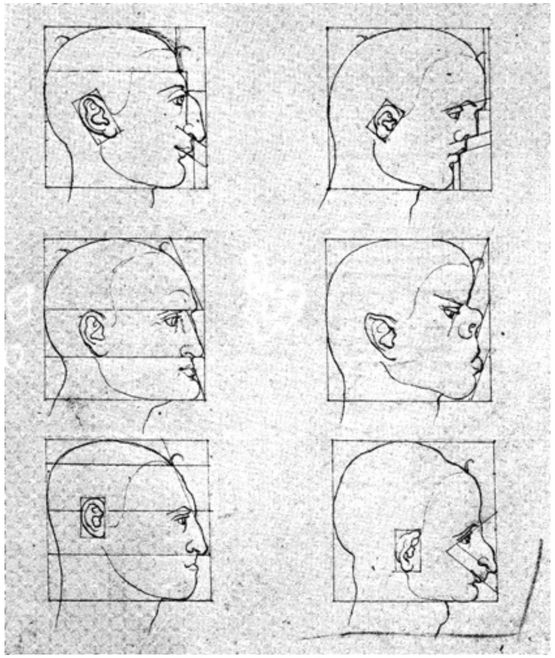
The reason for the difference in proportion between child and adult has to do with the way humans and all biological life grow. A child's head grows much more slowly than the rest of its body, so that by the time adulthood is reached relative head size is greatly diminished. Through examining this painting, among others from the period, it becomes clear that 'artists of the Byzantine period seem to have taken little concern with this, hence the child looking strangely mature for its age'. (Coen, Shifting Forms)

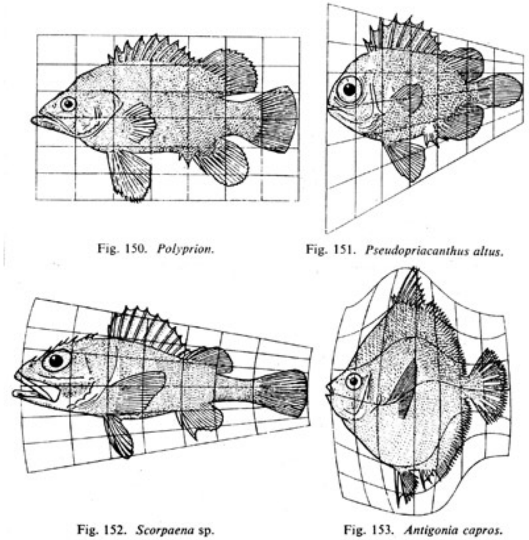
Another example of this becomes apparent in Rene Magritte's painting, 'The Spirit of Geometry'. This highlights that it is not only the head that grows at different rates to the body, but points out that facial proportions also grow at different rates.

^ Fig. 33. The Spirit of Geometry (Magritte)
> Fig. 34. Deformable Heads (Durer)

In this painting the head of the mother and baby are swapped and scaled to proportion, leaving the woman with a disconcertingly large pair of eyes, highlighting the distinctive difference in facial proportions between infants and adults.

These differences fundamentally illustrate how the regions of an organism grow at different rates, and to different extents as it develops. If it were not for these differential growth rates, adults would appear just as scaled versions of babies, or could be extrapolated further to scaled up embryonic forms. (Coen, Growth and Hidden Colours)





The Deformable Grid

The view of deforming proportions through simple mathematical functions is a prevelant thought in the realm of biology. Stretching or compressing an original form in various directions (eg. a square is deformed to a rectangle through stretching out in one direction) to give rise to new form can first be found in Albrecht Durer's 'Four Books of Human Proportion', published in 1528. (Durer)

In his book, Durer describes how the human body should be depicted. Through applying simple deformations of compressing or stretching certain regions of 'a standard proportioned human' inscribed in a grid, he illustrates a method in which 'a whole new repertoire of facial types and expressions could be made available to artists, from the beautiful to the monstrous'. (Conway)

D'Arcy Thompson

It was not until the early 20th Century with the release of biologist D'Arcy Thompson's book 'On Growth and Form', that the theory of deformation was applied as a more generally to geometries found in natural shapes. (Thompson)

< Fig. 35. D'Arcy Thompsons Deformed Fish (Thompson)

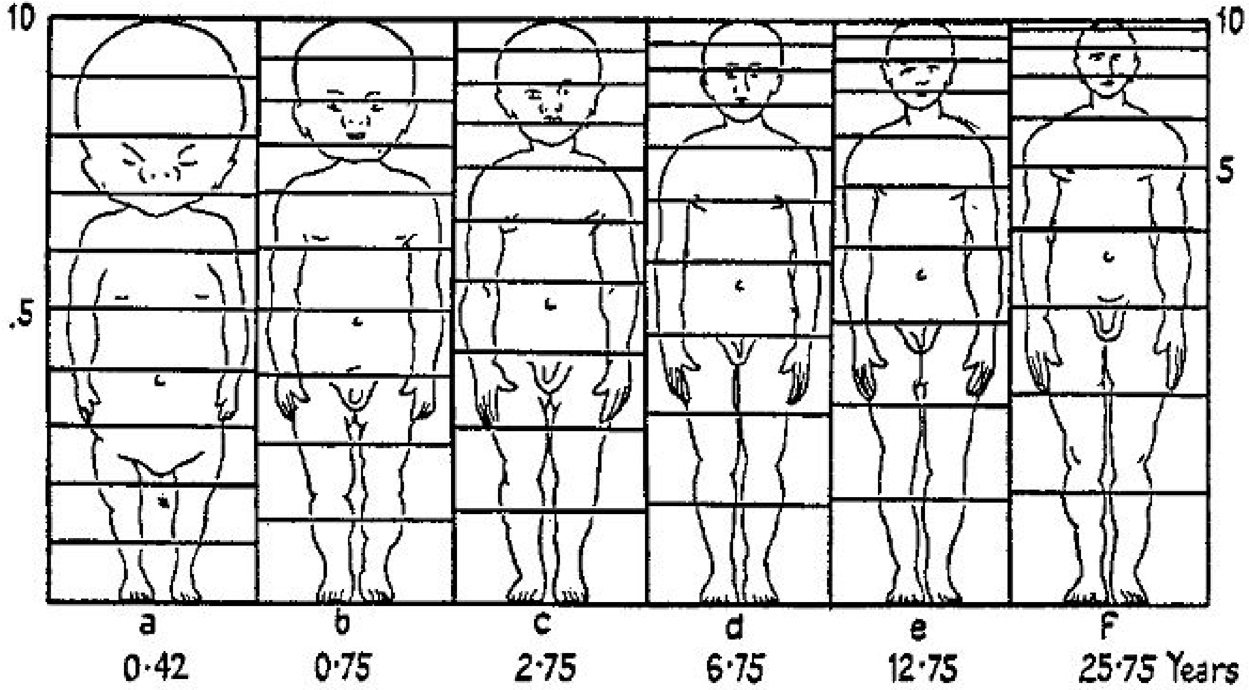
Most famous was his study exploring the deformation of a grid applied to a fish. By deforming the grid in different ways Thompson could obtain shapes that came close to other fish species that existed in nature.

Mathematical Deformations
The importance of this method was its simplicity, and economy.

Without the grid, each fish would look different in many distinguishable micro counts, but with the deformable grid, all the aspects are seen as to flow from much simpler mathematical deformations. Through application of simple geometric operations, seemingly unrelated and complex differences between two species could become related.

Enrico Coen points out that 'although Thompson's approach provides a very useful and immediate way of appreciating relationships... it has an important limitation. Because he is comparing different adult forms, the deformations he shows are indirect.' (Coen, Shifting Forms)

He is illustrating that although they can be placed under a common 'species' umbrella, through simple mathematical transformation, does not mean that one adult fish species is a deformed alternative. They are different adults that evolved completely autonomously.



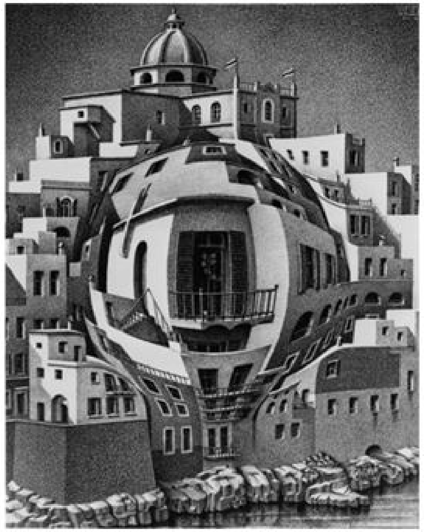
^Fig. 36. Differentiated growth rates from Baby to Adult (Medawar)

Differential Deformations
British biologist Peter Medawar published a paper in 1945 that attempted to apply Thompson's deforming grid processes to derive a proportionately accurate man starting from a baby. (Medawar)

He illustrates this method should not be applied across species, but rather to relate various developmental stages within one species: "There can be no doubt… that its true field of application lies in the development, and not in evolution; in the process of transforming, and not in the fait accompli.' (Medawar)

This application of deformation to the growth development of a single species, underlies Enrico Coen's 'hidden colour' theory regarding differential growth.

Hidden Colours
In his research, Enrico Coen further explored the process of morphogenesis through the proposition that growth occurs at predefined defined differential rates, not just at a surface level, but continuously from embryonic stages, to full evolved adult form.
Where Thompson imposed asymmetry from outside the organism (for example in his experiments of tying rags around regions of growing fruit to impose various developed forms), Coen's studies provide understanding on how form could arise from internal cellular asymmetries within growth processes.



^ Fig. 37. M. C. Escher's Lithograph 'Balcony' (Escher)

Coen researched the effect of conflicting growth rates in areas of plants caused by genetic cellular variation. He explains this concept of growth through a patchwork of 'hidden colours', that dictate the triggering of growth, via gene activation that vary plants rates of growth locally. Through the differentiation in local growth rates, complex global geometries arise. He studied how simple variations of these conflicting growth rates can give rise to novel complex forms when simulated over time.

This type of deformation is illustrated through M. C. Escher's lithograph, 'Balcony'. Escher's original sketch before deformation shows an accurately proportioned scene of buildings. Upon localized deformation (growth), the centre of the image stretches radially, and gives the appearance that the illustration is bulging towards you.

In this instance, it is as if the centre of the canvas can be interpreted has having a patchwork of hidden colour, of which influence its extent of local growth of the canvas.

“*The key point is that the sheet of cells, the canvas, both supports and is modified by the colours. It would be as if every time an artist put a colour on the canvas, the newly coloured region might start to grow or shrink relative to the rest of the picture.*” (Coen, Growth and Hidden Colours)

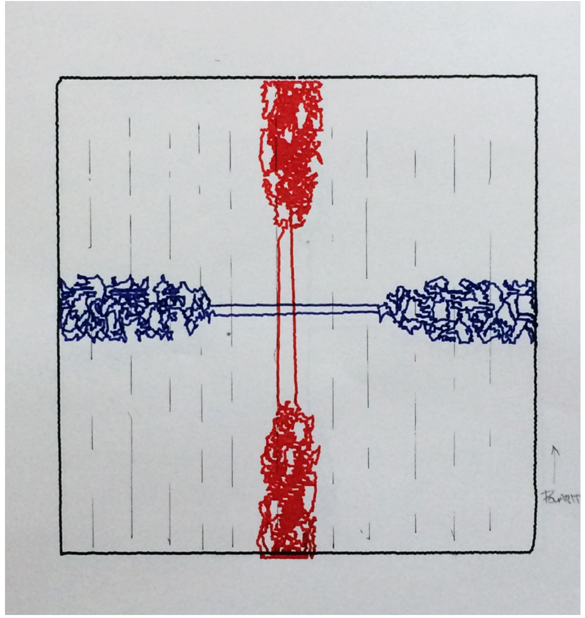
Enrico Coen’s later research on the asymmetrical development of the snapdragon flowers’ growth utilized computational modelling to study the effect of various initial cellular patchworks patterns. This research resulted in a computational tool to simulate the emergent growth of the geometrically complex flower. Once developed, Coen and his research team could then vary the initial starting ‘hidden colour’ patchworks patterns of cell growth, to digitally invent new flower species from the same underlying growth principles.

Design Application

Through applying Coen’s ideas to the computational design environment, this framework provides a theoretical base that underpins the complex geometries found in nature.

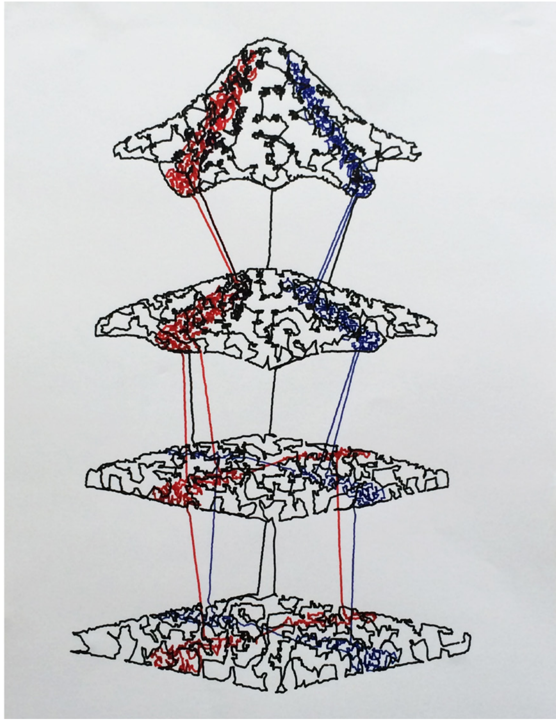
Through implementing digital tools, morphogenesis through conflicting growth can be simulated in the biomimetic development of complex surface structures.

< Fig. 38. Hidden colours, Uniform direction growth (Author)

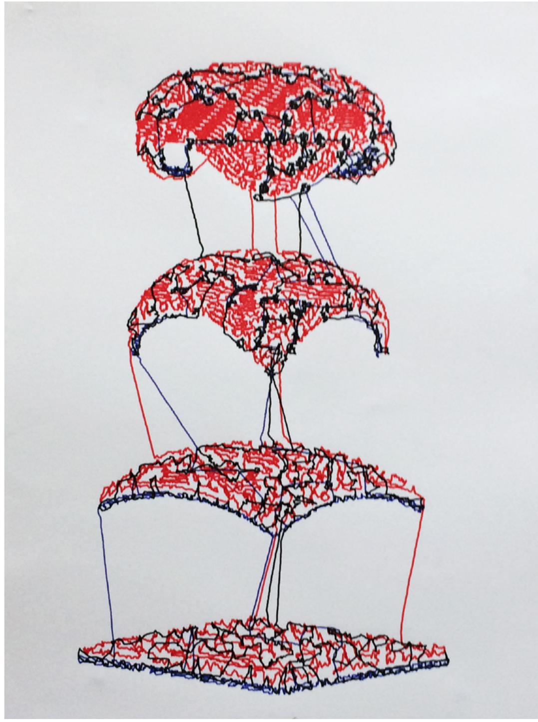


^ Fig. 39. Hidden colour patchwork, Directional conflict growth (Author)

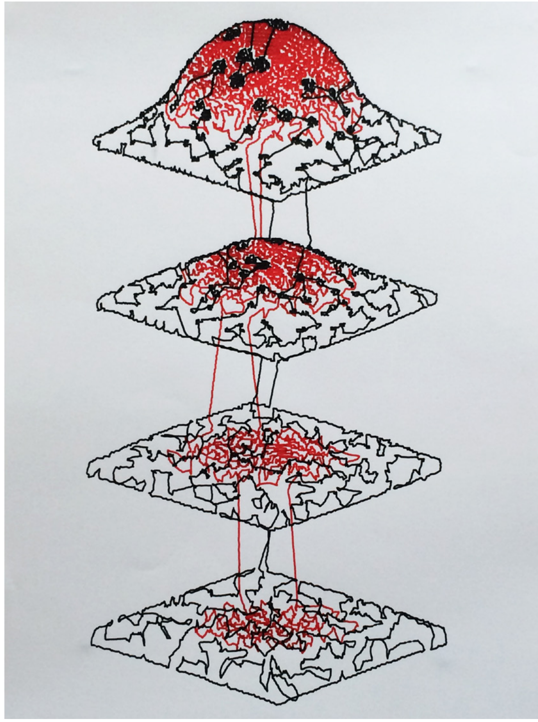
It is this principle biological understanding of pattern defined differential growth that that this research seeks biomimetically to explore. Coen’s theories on differential growth provide a biological principle of developing and producing more economically and material efficient production methods of geometrically complex surface structures.



^ Fig. 40. Result of Directional conflict growth (Author)



^ Fig. 41. Result of Surface conflict growth (Author)



^ Fig. 42. Result of Aereal Growth (Author)

.2.0.6. 4 D Printing

Digital Fabrication
The development of digital fabrication technologies, and their growing accessibility, has been diminishing the gap between design computation and physical materialisation.

CAD/CAM technologies enable the direct (and indirect) manufacturing of digitally generated architectural parts and components, by plotting them in a 3D output device. (Kocaturk)

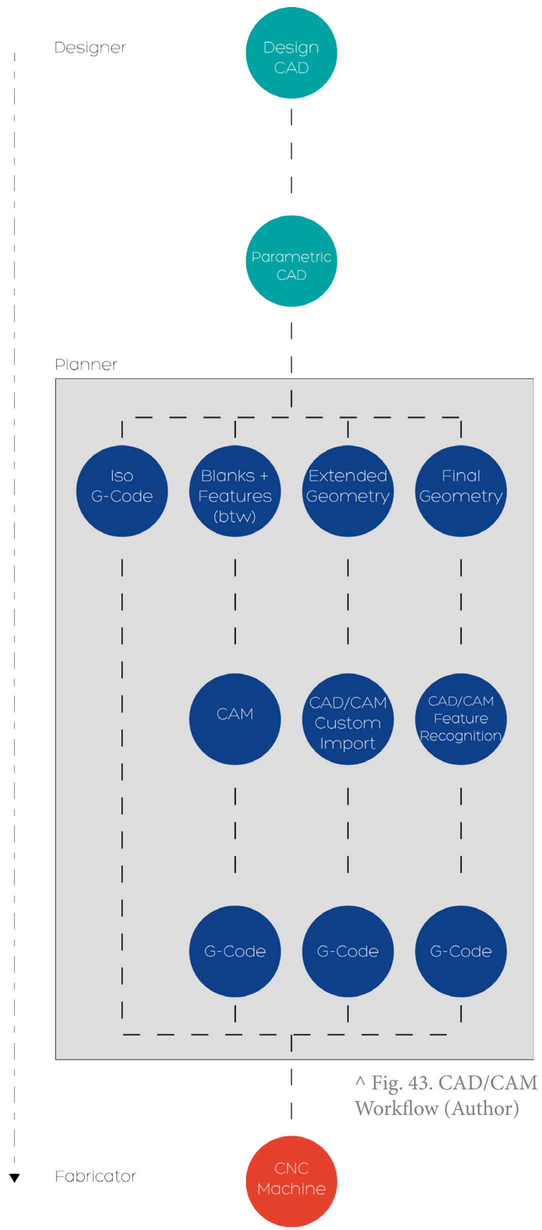
Since their inception in 1984 by Charles Hull, additive manufacturing and rapid prototyping methods have developed for use in countless industries across the globe. The architect's role has expanded to exploit the developments in computer numerically controlled (CNC) machines also, in both the rapid prototyping, and production of customized componentry.

CAD/CAM Workflows
Using CAD-CAM workflows allow the architect to design digitally via a 3D virtual interface, and fabricate physical representations of their designs through precision CNC machining. Digital fabrication has become an extension of the design process, giving architects direct control over all aspects of the production of architecture, from conception to production. (Marble)

Digitally integrated design systems are capable of 'shortening the feedback loop between design intent (input), and design results (output).' (Doscher) This offers architects an accurate production method of producing customized, complex, non-orthogonal components not just as an output, but as feedback during the design cycle.

3D Printing
Additive manufacturing (3D Printing) finds its origins within the food, toys and proof-of-concept prototyping industries. Unfortunately, as yet it has fallen short of the visions held by architects in its potential to revolutionize the construction industry.

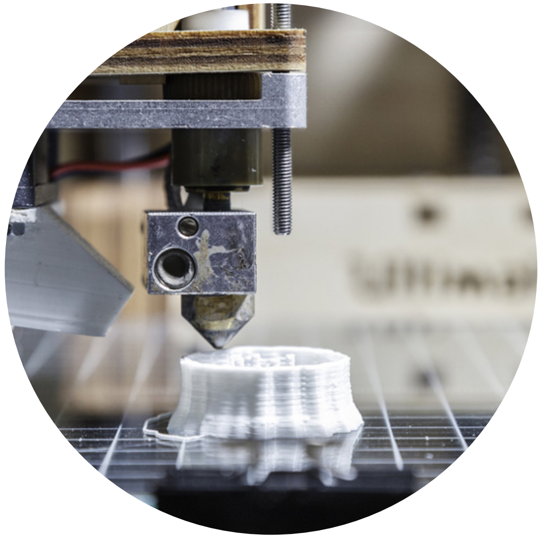
Boeing's Michael Hayes highlighted this issue by outlining the main hurdles that lie ahead for additive manufacturing, including: 'a larger build-envelope, and increased scale



^ Fig. 43. CAD/CAM Design Workflow (Author) for printing applications; structural materials that can be used in functional and high performance settings; and multi-functional and smart/ responsive materials’. (Hayes)

The Issue

The ability to mass produce customized componentry, without substantial increases in time, material or inefficiency, has been coined as one of the revolutionary advantages of additive manufacturing. However, the realities of the current capabilities are ‘far behind our expectations and visions for additive manufacturing technologies’. (Chandler) Current mass customization methods ‘ignore the time and energy needed after custom parts have been printed, requiring excessive sorting and labour-intensive assembly’. (Tibbits)



< Fig. 44. Fused Deposition (FDM) 3D Printer (Tibbits)

^ Fig. 45. Ceramic 3D Printing (Herpt)

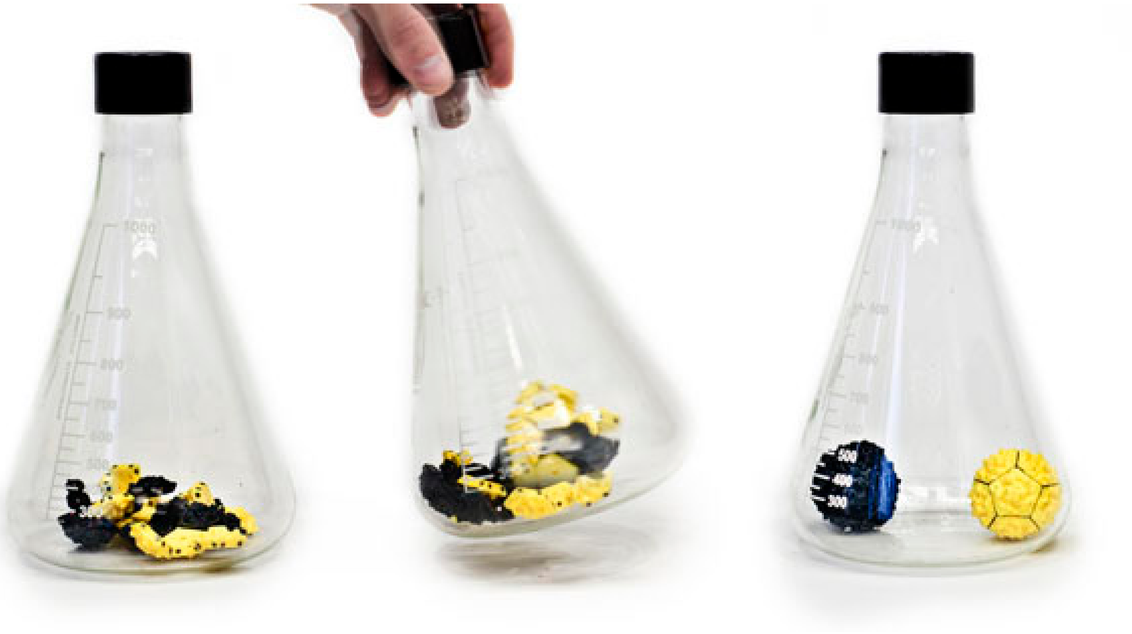
Fig. 46. Large scale 1:1 Concrete Printer (Rudenko) >

4D-Printing
Skylar Tibbits, and the Self-Assembly Lab at MIT, are leaders in disrupting traditional CAD-CAM workflows in pursuit of printing programmable materials, a process the Self-Assembly Lab refer to as 4D Printing.

Typically, 4D printing entails multi-material prints that have the capacity to ‘self-assemble post physical production, in reaction to external environmental stimulus’. (Ding)

Skylar writes: ‘This technique offers a streamlined path from an idea to reality, with performance-driven functionality built directly into the materials… The fourth dimension is described here as the ‘transformation over time’, emphasising that printed structures are no longer simply static, dead objects; rather, they are programably active, and can transform independently.’ (Tibbits)

4D printing offers a new frontier to mass production of geometrically complex artifacts, ushering in new hope for the widespread implementation of rapid prototyping CAD/CAM technologies to the architectural discipline.



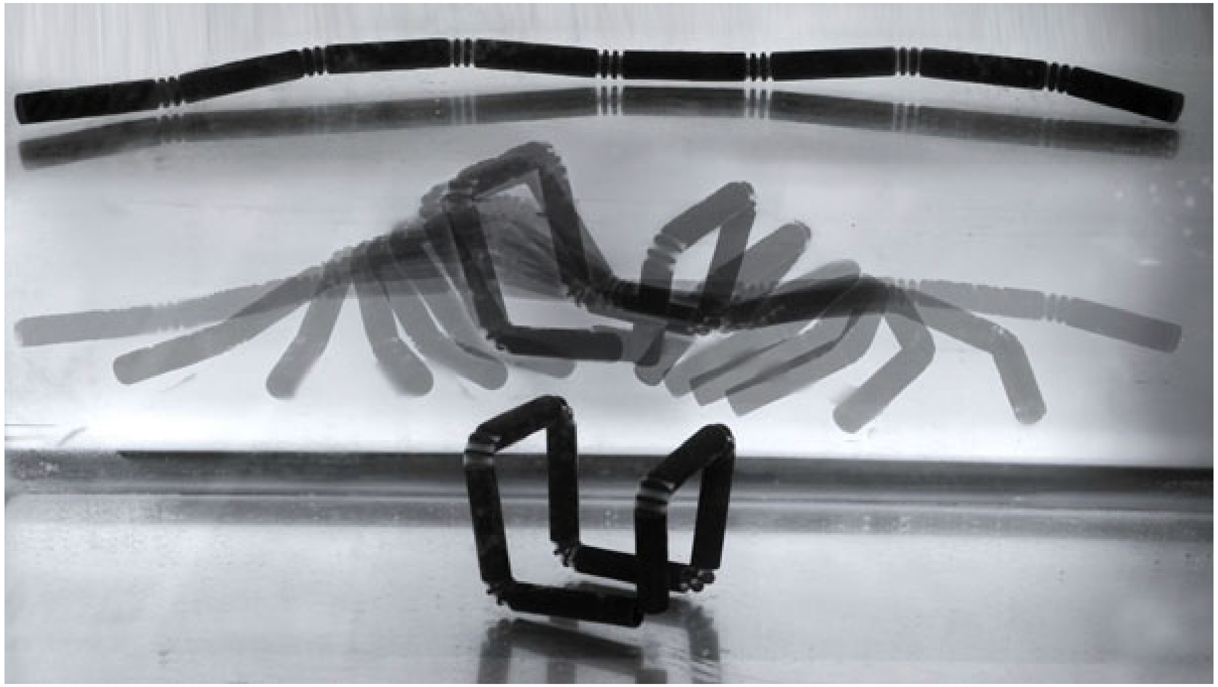


Fig. 47, 48, 49 & 50. 4D Printing utilizing inert material capaciteis (Tibbits, 4D Printing: Multi-Material Shape Change) > >>

Machine, Material & Geometric Program

At the core of 4D printing are three key capabilities: 'the machine, the material and the geometric program'. (Tibbits)

4D printing seeks to bridge the gap between CAD-CAM methodologies, and physical realization, using a more material- economic and less labour intensive approach. In doing so, it provides the potential of further democratizing complex freeform geometry, through programable material's ability to self-assemble without external human input.

This model of production takes advantage of material inherent intelligence and capacities, another example of how a 'New Materialism' approach is disrupting traditional architectural production workflows.

Practitioners such as Tibbits, Achim Menges and Neri Oxman are leading demonstrators of exploiting materiality through CAD-CAM workflows as a generative design driver, rather than an applied afterthought.

Fabrication and material technologies are slowly moving from a solid inactive state to a level that has its own 'generative significance'. (Oxman, Programming Matter)

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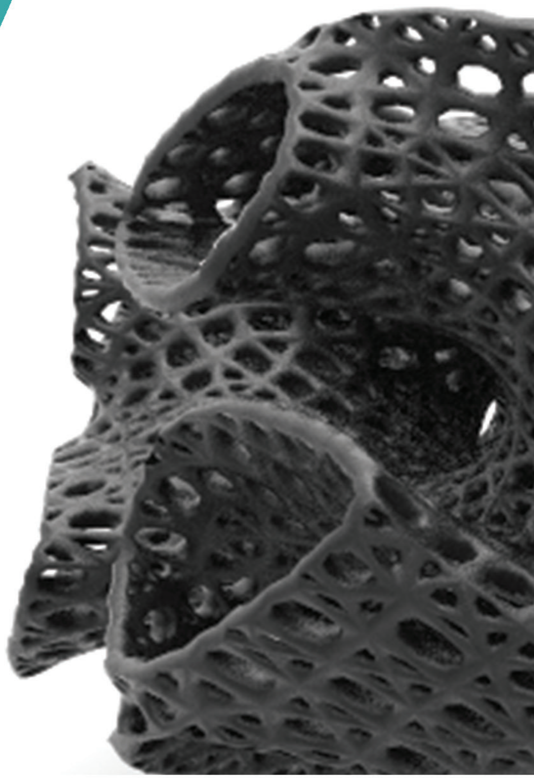
Preliminary Design



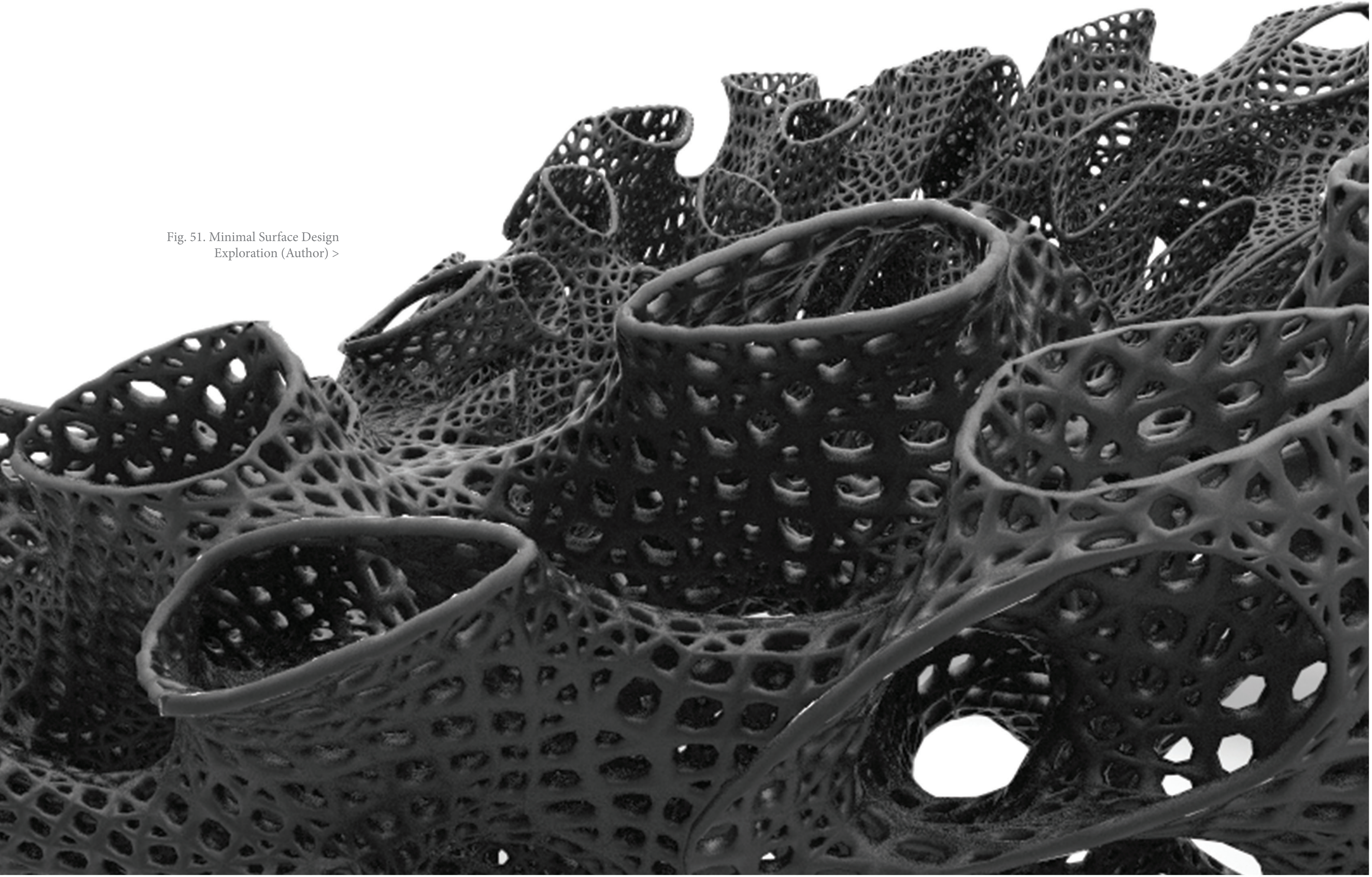


Fig. 51. Minimal Surface Design Exploration (Author) >

.3.0.1.
Preliminary Design Exercise

Introduction

The idea of form finding is a powerful one. Its goal, that of using real-world information as the material from which a design's final outcome is made, offers the opportunity to ground design in a solid reality.

Achim Menges argues that form finding "externalises the relation between the process of formation, the driving information, and the resulting form." (A. Menges, Material Information)

When used for form finding, the computer simulation of a building's performance (something traditionally conducted late in design), is instead pushed forward into the design's generation.

These computer simulations can then drive parametric models of entire projects, fixing geometries based on simulation feedback, rather than of a designer's explicit decision. Neil Leach argues, "Performance goals are now being embraced as positive inputs within the design process from the outset… (this) aims to locate architectural discourse within a more objective framework, where efficient use of resources supersedes the aesthetic indulgences of (previous) works." (Leach)

This chapter outlines a series of preliminary design exercises that were undertaken to build an understanding of how physical, material based form finding exercises could be further explored within the digital environment. Three traditional surface form finding methodologies were studied, and their micromechanics algorithmically interpreted, for simulative modeling within 'Grasshopper', a parametric design plugin for CAD software 'Rhino3D'.

The chosen form finding methods were selected based on both their historical significance within field of material based design, and their capacity to be further expanded within the digital realm, through the affordances of iterative computation simulation.

Exercise Workflow

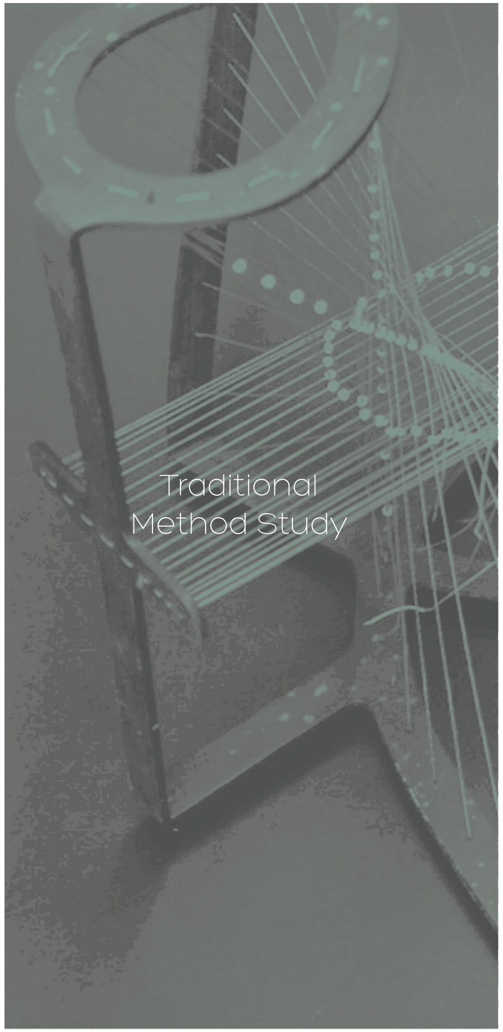
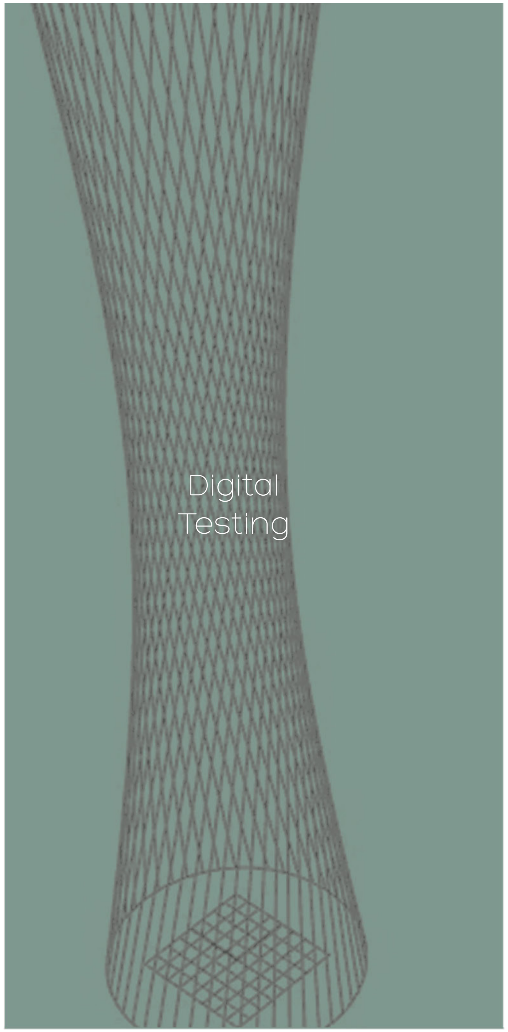
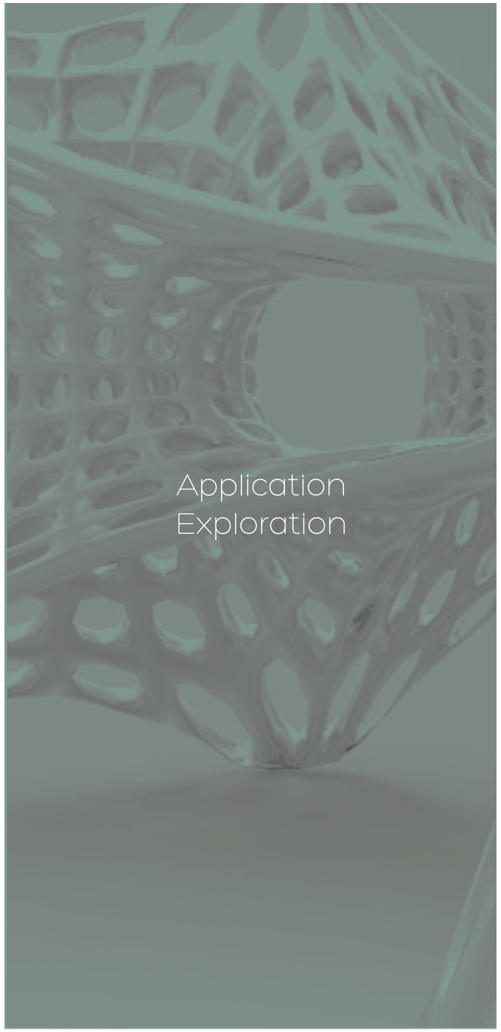


Fig. 52. Preliminary Design Methodology (Author) >


Algorithmic
Decoding


Digital
Testing


Application
Exploration

.3.0.2.

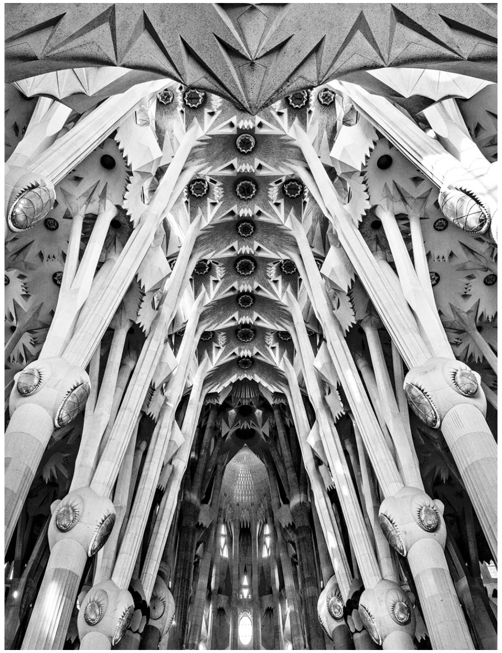
Ruled Surfaces: *Antoni Gaudi*

A ruled surface is generated by sweeping a straight line through space. For every point on a ruled surface there is at least one straight line which lies on the surface. (Flory and Pottmann)

Architect Antoni Gaudi employed ruled surfaces extensively in the design of the Sagrada Familia. His application of this mathematical surface to the design provides an extraordinary example of a pragmatic, yet elegant design approach, that represents "an outstanding cultural and intellectual achievement". (Fischer, Herr and Burry)

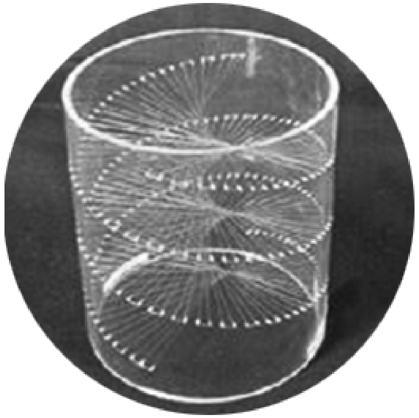
In place of conventional construction drawings, Gaudi communicated his design of the Sagrada Familia through an elaborate array of physical models, developed through 'ruled surface' geometry, most recognisably in the design of his double helix columns.

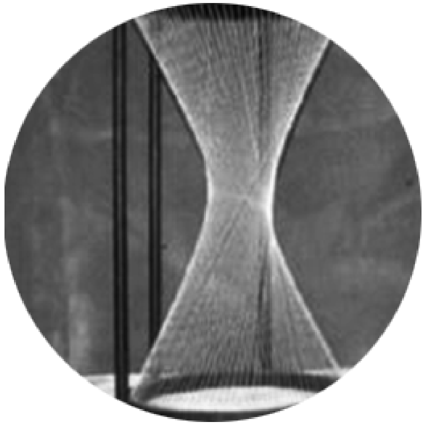
Throughout many variations, Gaudi made extensive use of the generative possibilities of this principle, to establish extensive variation based on a simple rule set. Mathematically ruled surfaces are simple to physically model through using rigged string systems, the following design exercise examines a series of ruled surface to translate into the digital from their mathematical principles.

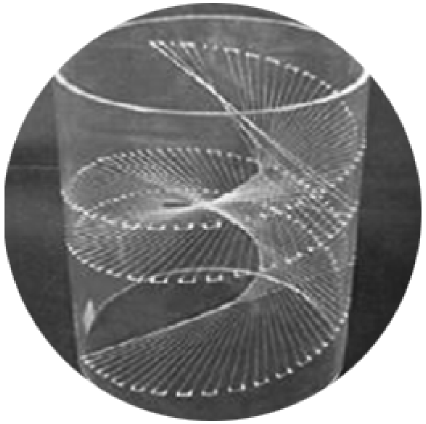


^ Fig. 53. Columns of the Sagrada Familia (Filler)

Fig. 54-57. Ruled surface Modelling (Flory and Pottmann) >







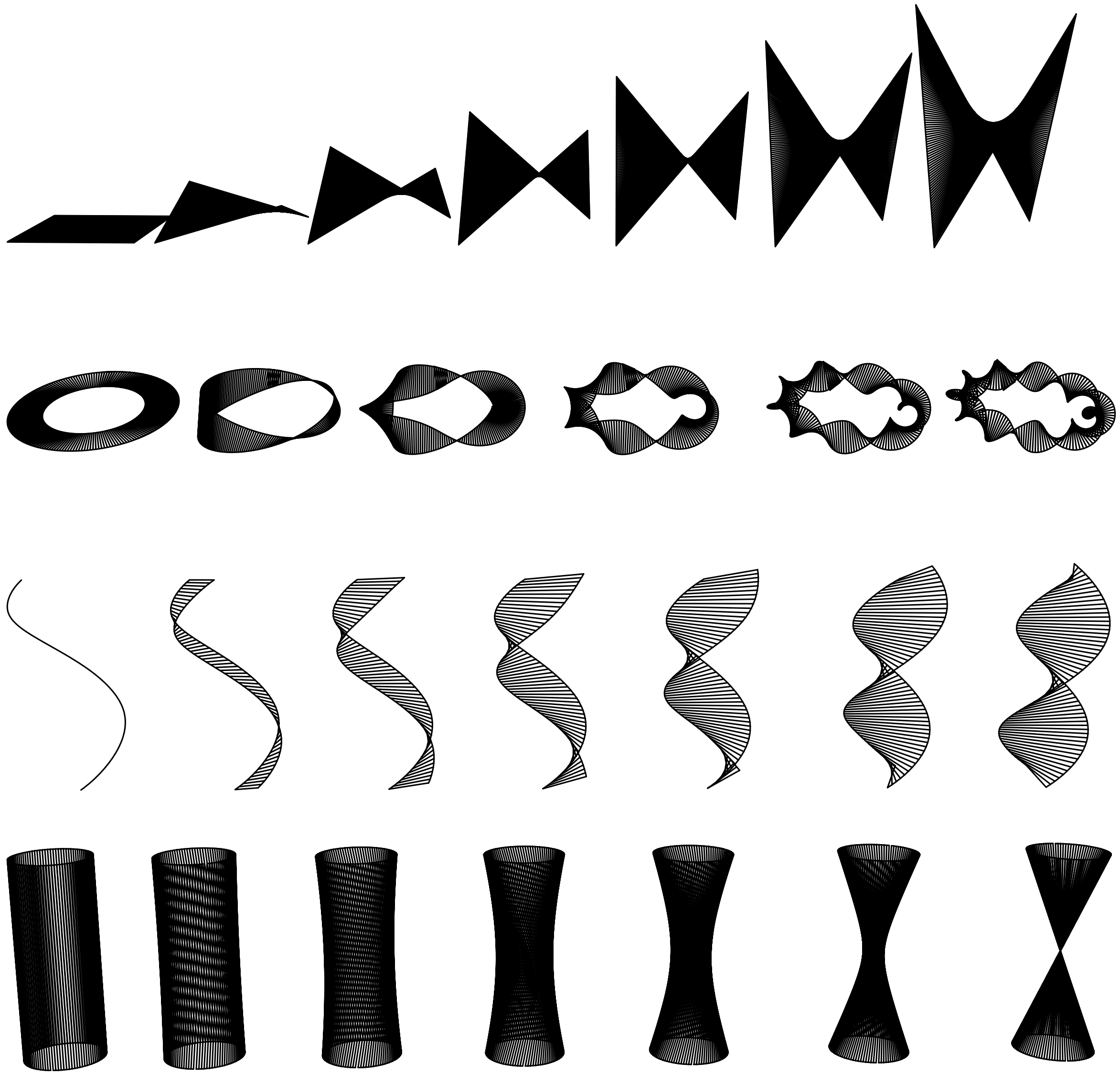
.3.0.3. Digital Translations

Hyperbolic Paraboloid

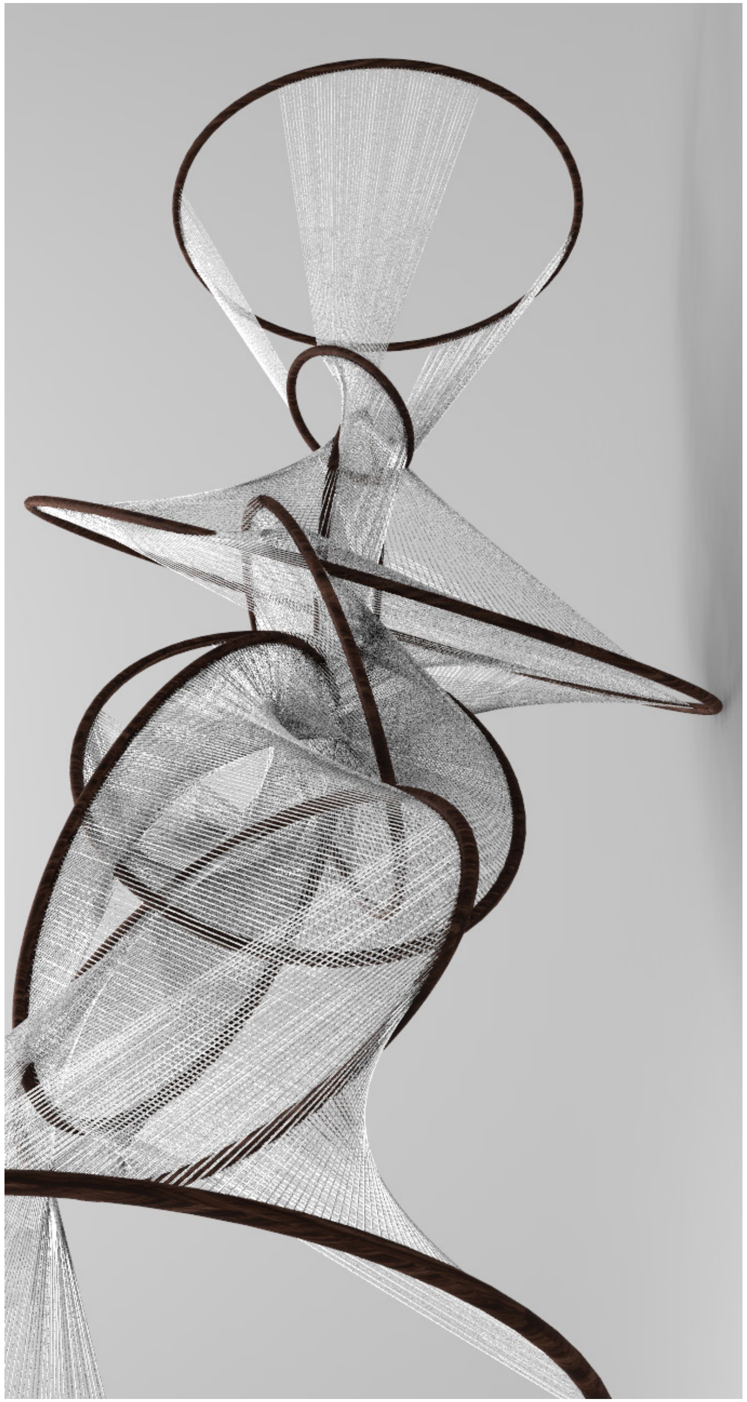
Mobius Strip

Helicoid

Hyperboloid



^Fig. 58. Basic Parametric Modelling Translation of Ruled Surfaces (Author)



Formal Experimentation

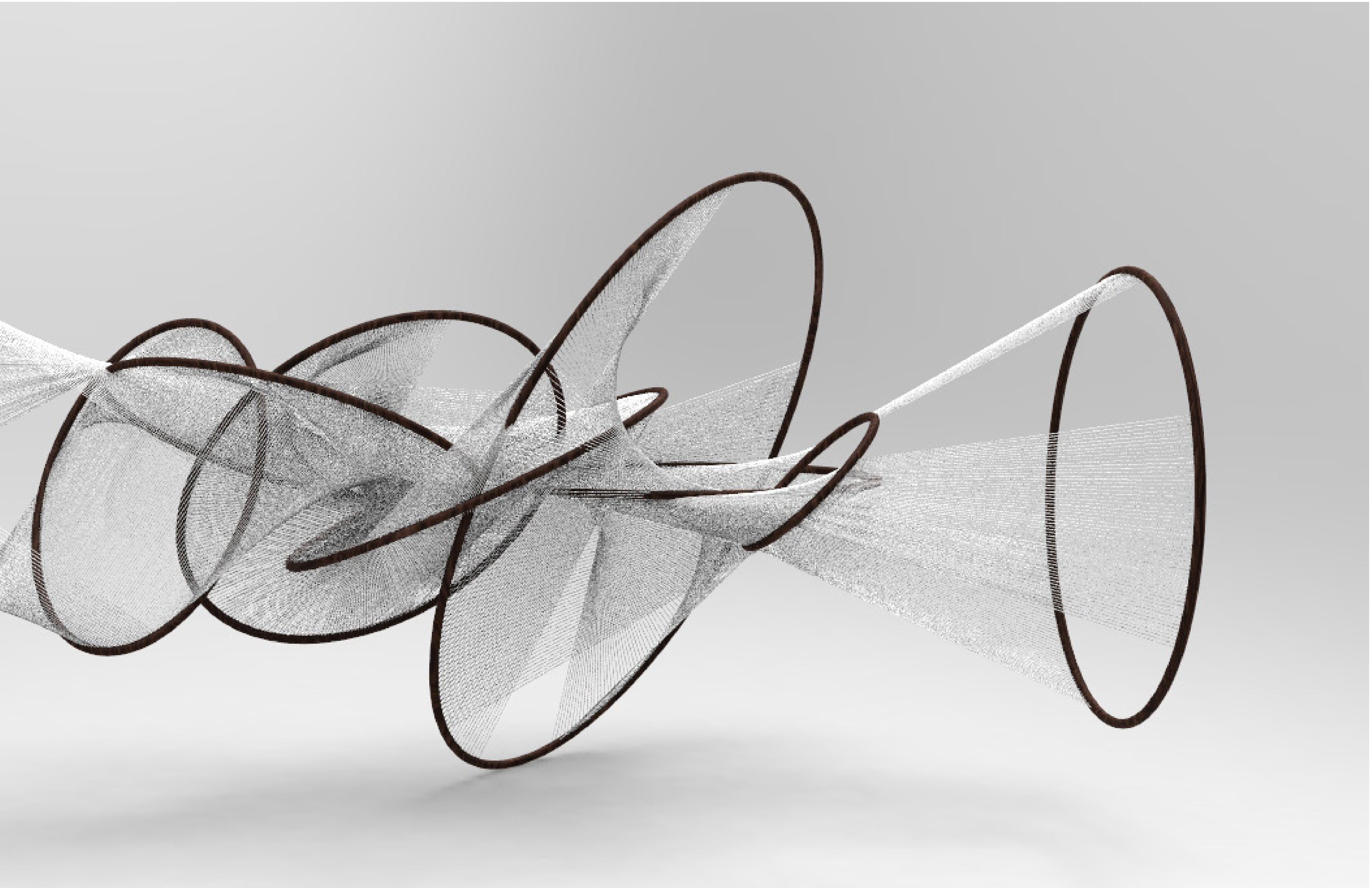
Through implementing various ruled surface equations, a series of digital explorations were conducted to examine further design potentials and aesthetical values. Ruled surfaces proved simple to model using the parametric modelling tool 'Grasshopper'.

Geometric frames were divided along their naked edges into points that act as 'anchors' for the string. These anchors were then matched to those of another frame, and a line drawn between.

Through modifying one of the frames, either through translation, rotation, or deformation etc., the points remained linked. The digital realm allowed for instant changes to the system, and the use of infinite string lines. This resulted in quick exploration of unique forms, and instant visual feedback through the visual interface.

< Fig. 59. Ruled Surface Scultpture (Author)

Fig. 60. Ruled Surface Scultpture (Author) >



.3.0.4.

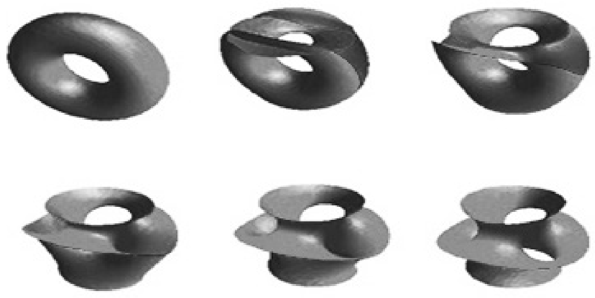
Minimal Surfaces *Frei Otto*

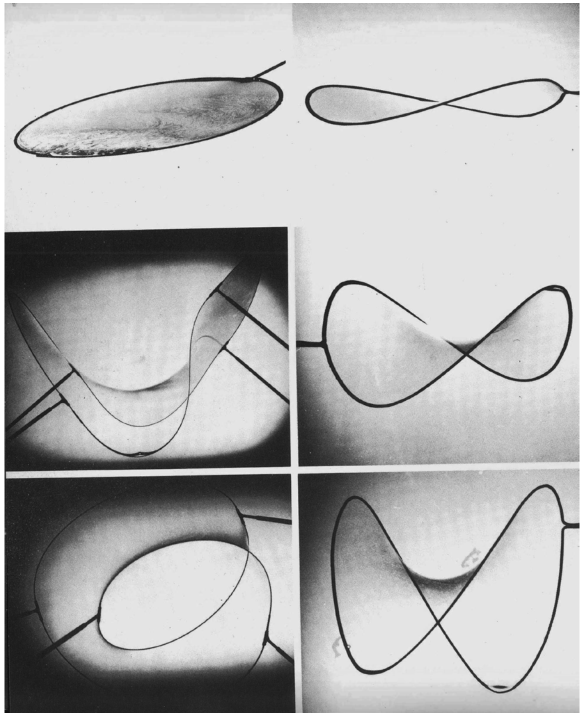
Minimal Surfaces

Minimal surfaces are the surfaces of the smallest area spanned by a given boundary. (Ljubica, Radivojevic and Stankovic) The application of minimal surfaces within architecture was made famous by engineer/architect Frei Otto, who conducted extensive physical tests in which closed wire loops were dipped into soap solution, with the wire as the boundaries the soap film will always calculate the surface of least area.

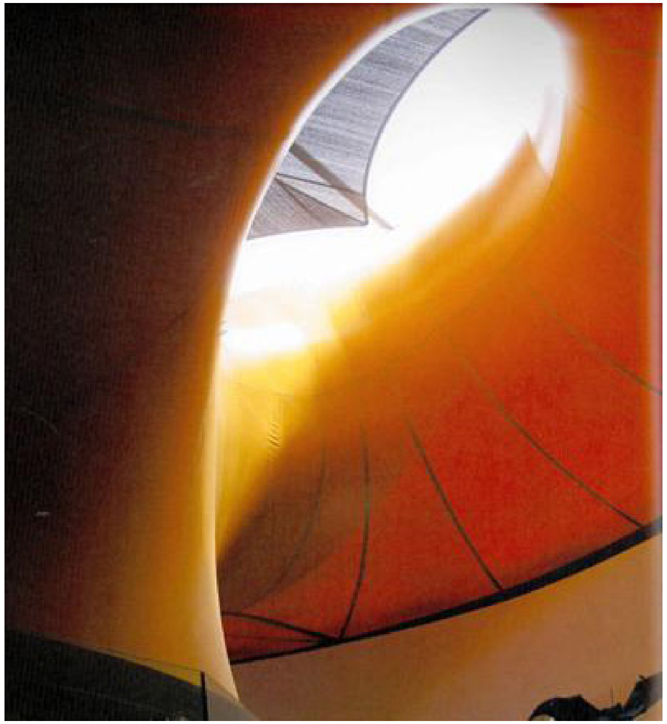
For Frei Otto, 'lightness' was the overarching paradigm that connected his widely-separated fields of research. Lightweight structures were his primary focus, as at the time a 'material efficient' design was seen as being analogously equivalent to an energy-saving, environmentally friendly, and cost-effective design. (Knippers) Minimal surfaces are extremely stable as physical objects, through using computational tools, much interest has been generated about the possibility of adapting them for use within structural design.

This section explores the digital translation of minimal surfaces equations, for use within the digital design environment. Extensive generative variations are conducted on an array of minimal surface equations, to examine the emergent formal effects. From these, a selection of minimal surfaces are applied to a standard mobius strip surface geometry, in the design of a series of ring like artefacts



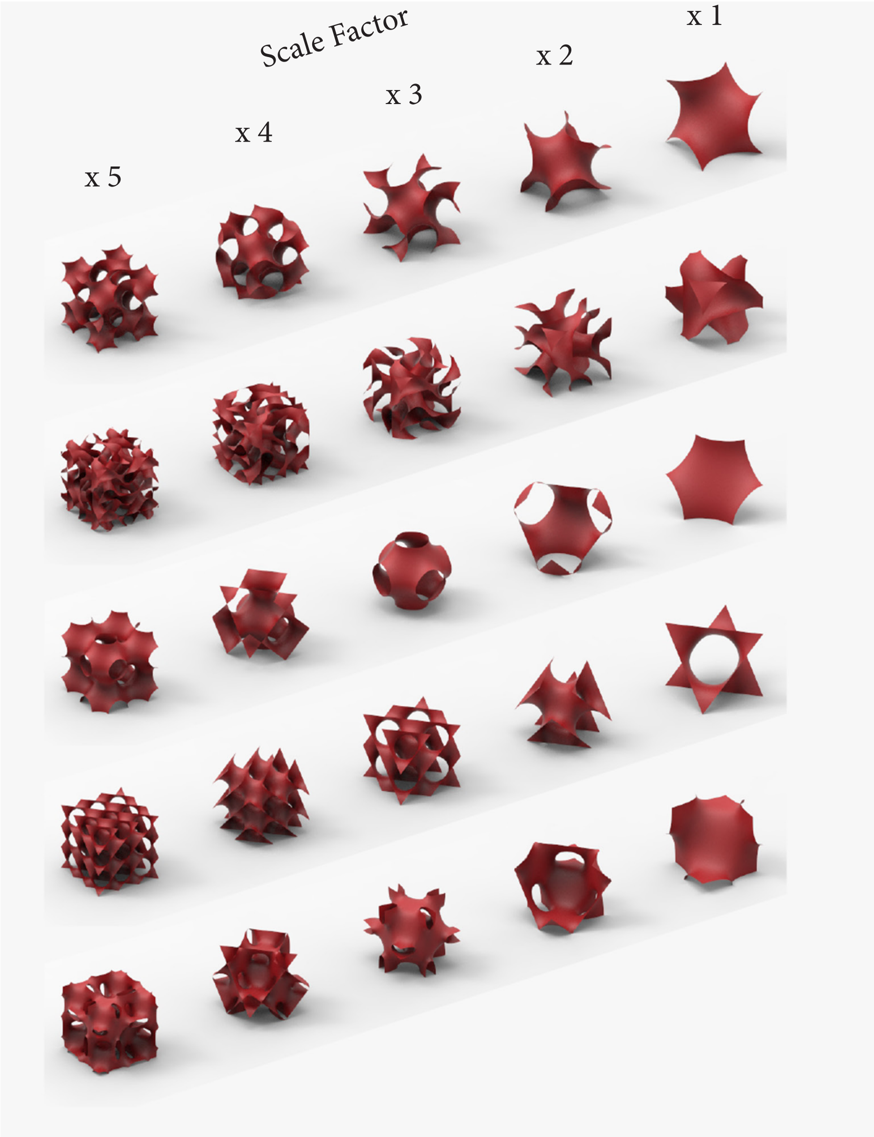


^ Fig. 61. Soap film minimal surface studies (Otto, Video: Frei Otto Experimenting with Soap Bubbles)



^ Fig. 62. Australian Wildlife Health Centre, Minimal Surface Inspired Architecture (Burry and Burry)

.3.0.5. Digital Translations



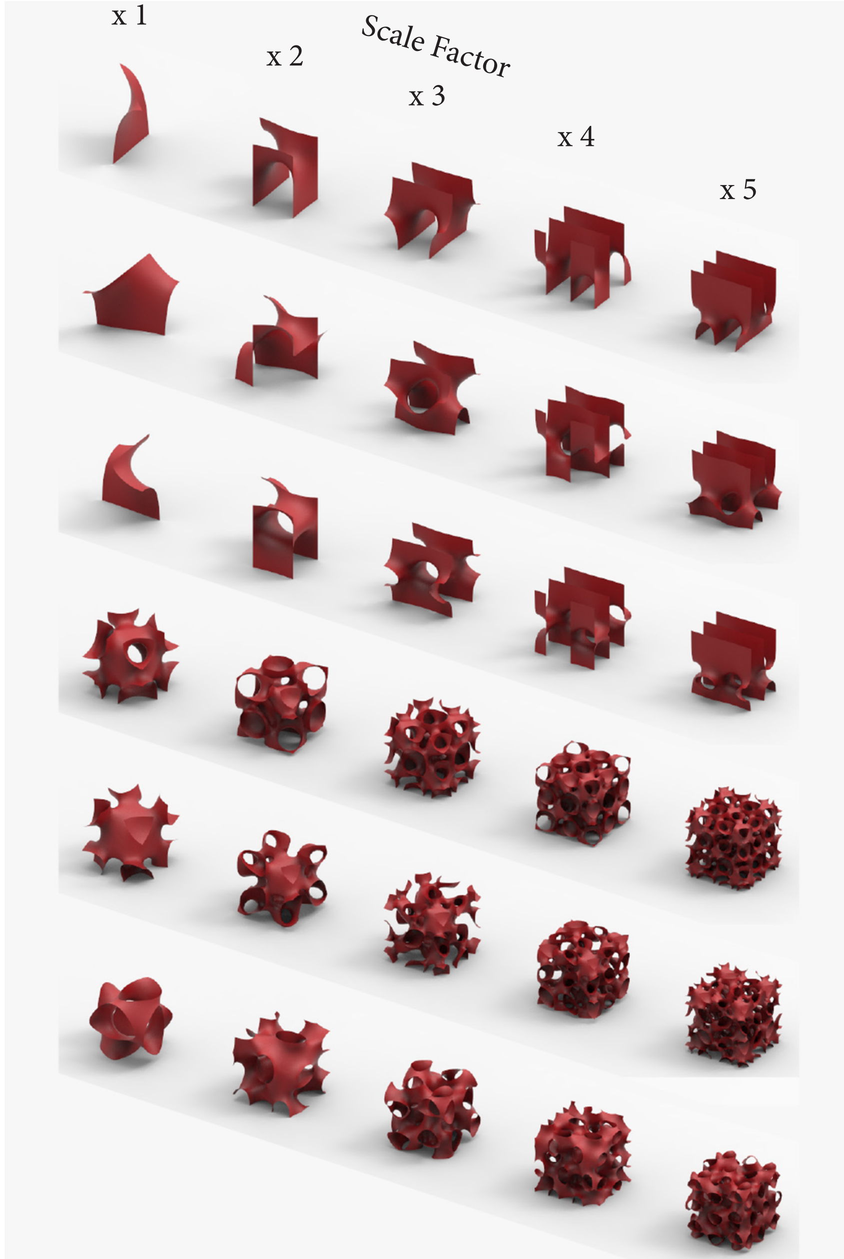
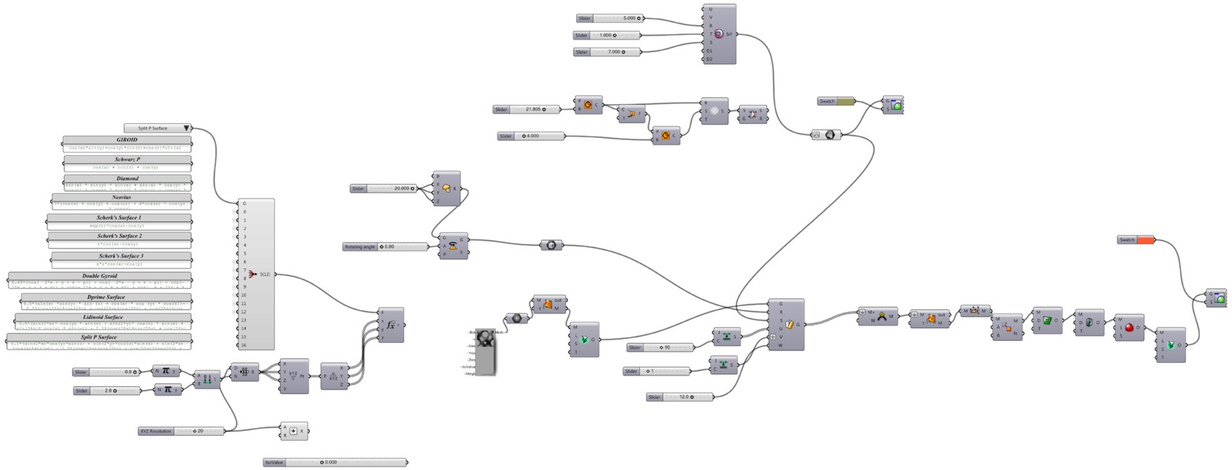
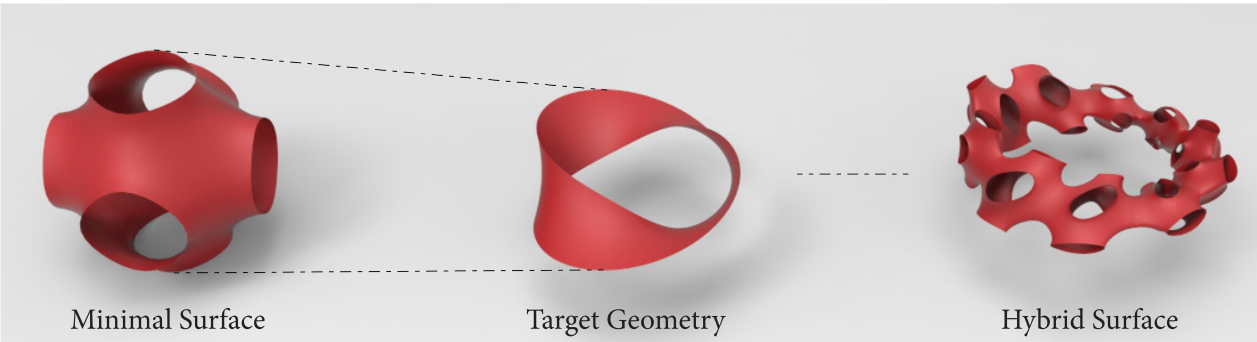


Fig. 63. Initial minimal surface digital translation study (Author)





^
Above: Fig. 64. Developed Grasshopper Algorithim
Below: Fig. 65. Application of Minimal surface morphologies to host geometry (Author)

Formal Experimentation

Through extracting the resultant surfaces mesh edges, interesting formal qualities emerge, in particular the surface displayed various levels of porosity, that related to the extent the original minimal surface needed to contort to fit the goal surface.

Ring 1: Giroid

Ring 2: Scherk's Surface 1

Ring 3: Neovius

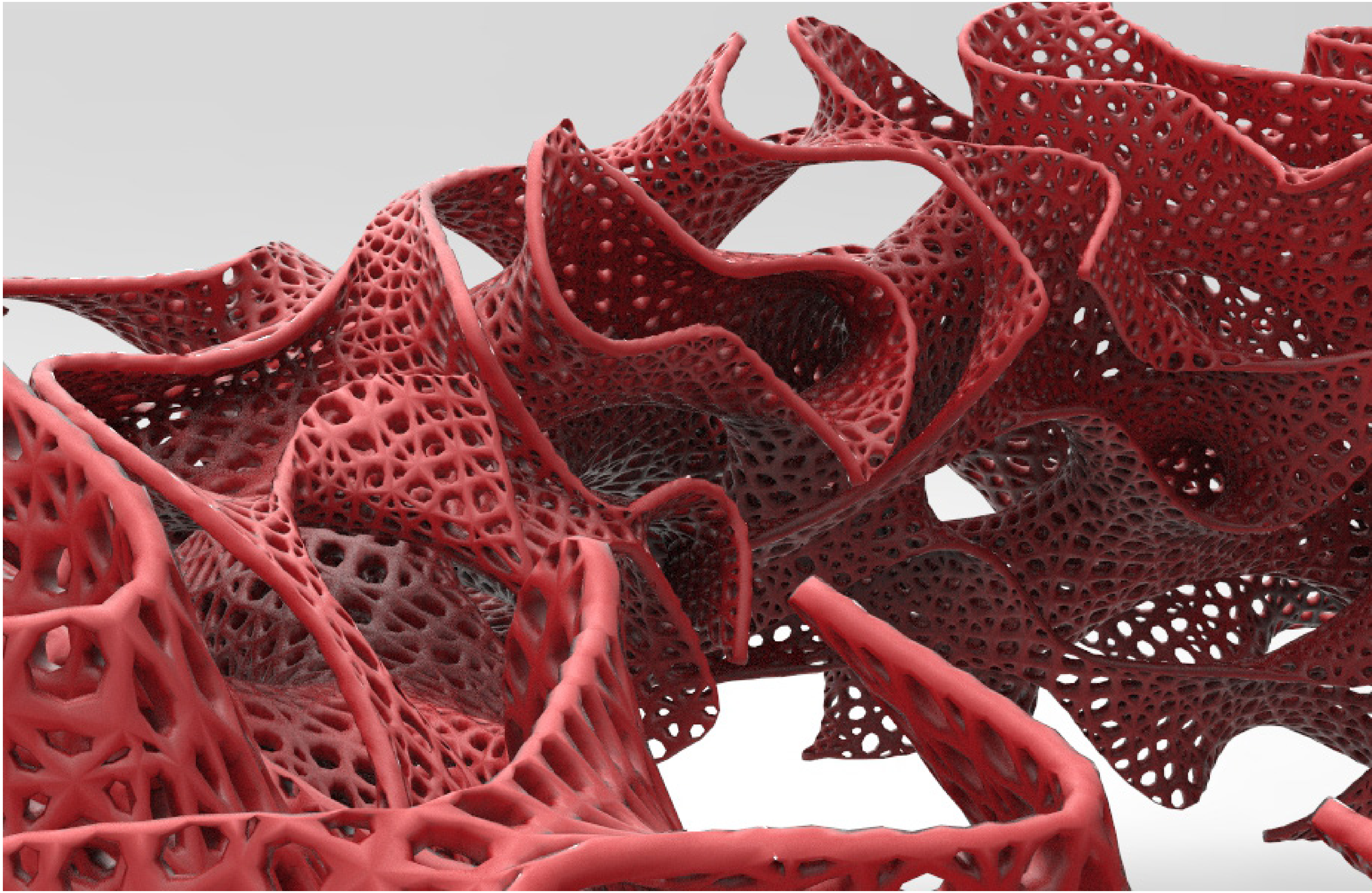
Ring 4: Schwarz P

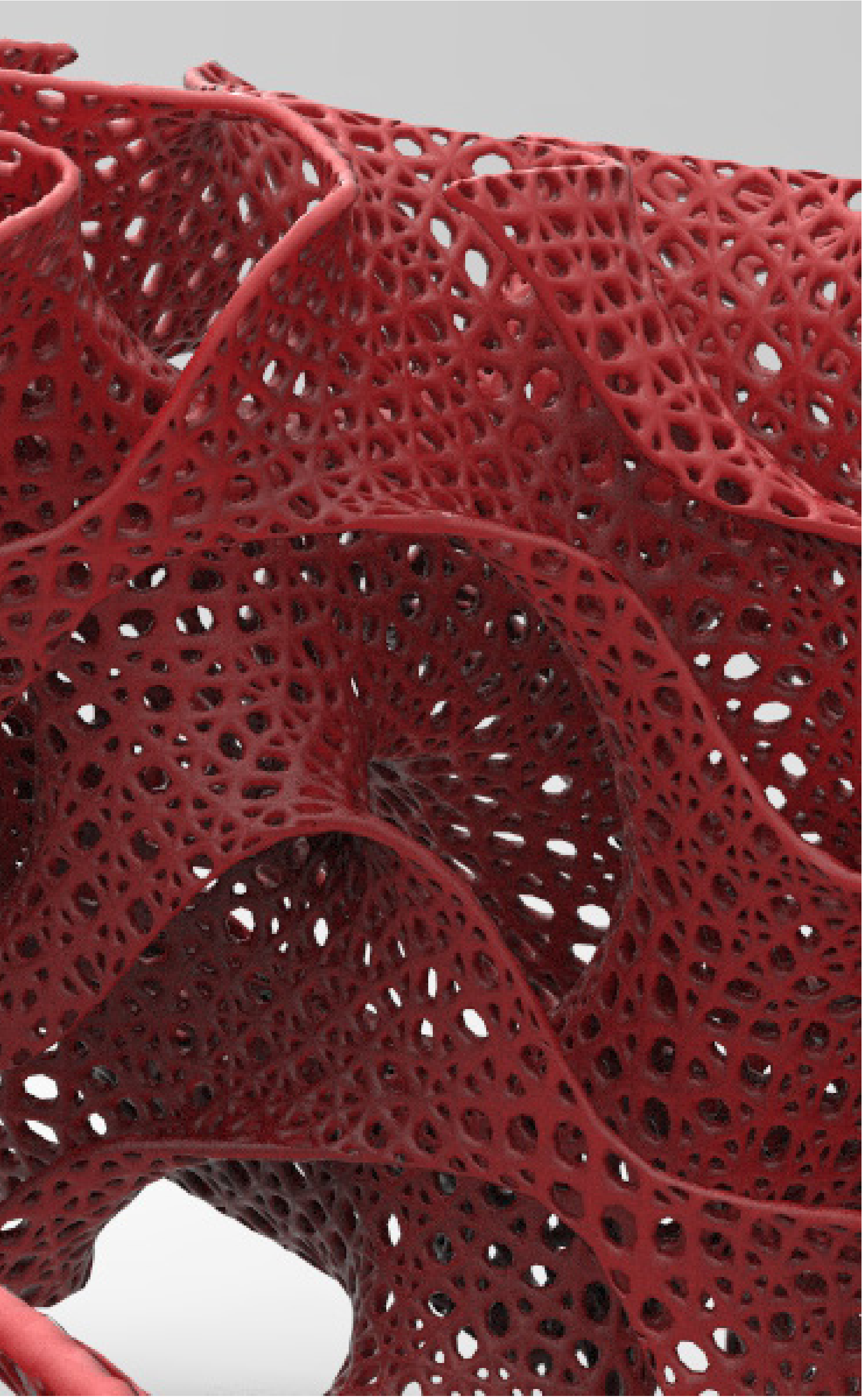
^ Fig. 66. Giroid Ring

^ Fig. 67. Scherk's surface Ring

^ Fig. 68. Neovius Surface Ring (Author)

^ Fig. 69. Schwarz P Ring (Author)





< Fig. 70. Minimal surface modules mapped to generic surface structure (Author)

.3.0.6.

Funicular Shells: *Hanging Models*

Hanging Cloth Models

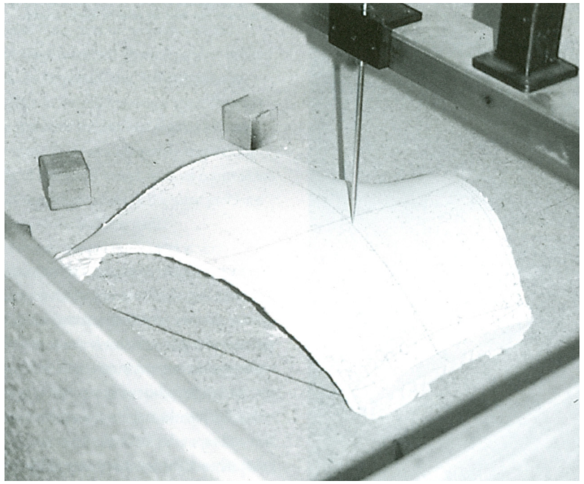
Hanging models are one of the oldest, yet relevant methods of physical form finding. They are valuable because they can be used to simulate the family of structures known as 'funicular' structures. Funicular structures are ones in which forms takes its shape in response to the magnitude, and location of forces acting upon it. (Schodek)

One example is that of a rope, suspended from two level points, will form a "V" when a single point load is added at midpoint. The same rope will form a catenary when under an evenly distributed load. If made rigid and inverted, that same form converts into a system that is in pure compression. (Rippmann and Black)

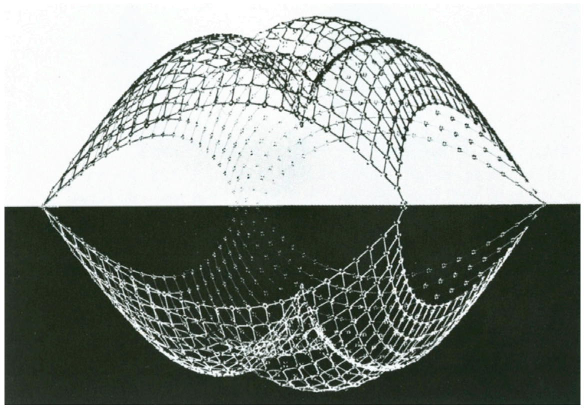
Whilst in pure compression, materials do not experience any bending due to structural load, therefore extreme material efficiencies can be obtained. This is made particularly evident through the long spanning thin shell structures of the 1950's and 60's by architects/ engineers such as Felix Candela Eliado Dieste, and Heinz Isler.

This form finding method is traditionally conducted using networks of chains, strings weighted with calibrated sand bags, and cloth weighted with plaster or epoxy resin. These methods work very well, but are physically very labour intensive, and require incredibly accurate measurement equipment. (Edward)

This makes it an ideal case study for translation to the digital form-finding design environment. This exercise utilizes a mass spring model within the physics simulator 'Kangaroo Physics' plugin, for parametric modeling software 'Grasshopper'.



^ Fig. 72. Precise Measurement of Physical Funicular Surface Study (Wilson)

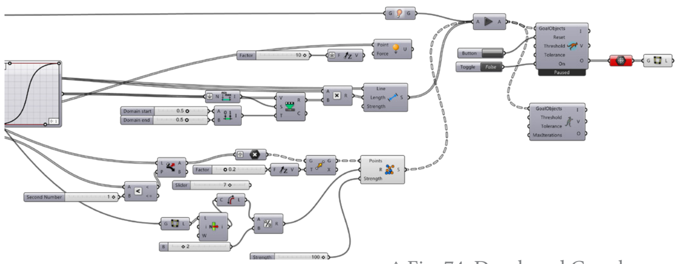


^ Fig. 71. Funicular Concept (Wilson)

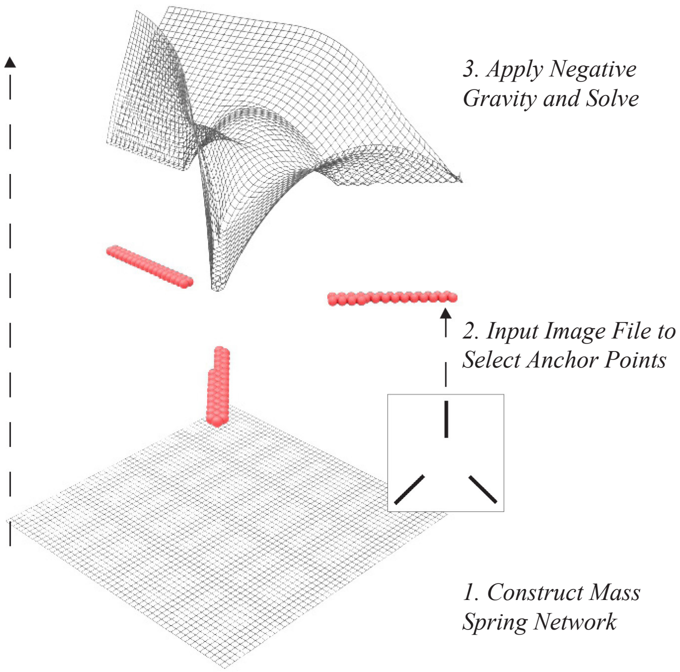
^ Fig. 73. Heinz Isler's Dietlingen Sud Gas Station (Clarke)

.3.0.7.

Digital Translations



^ Fig. 74. Developed Grasshopper Definition (Author)



^ Fig. 75. Algorithmic logic to funicular structure simulation (Author)

Anchor Input Images

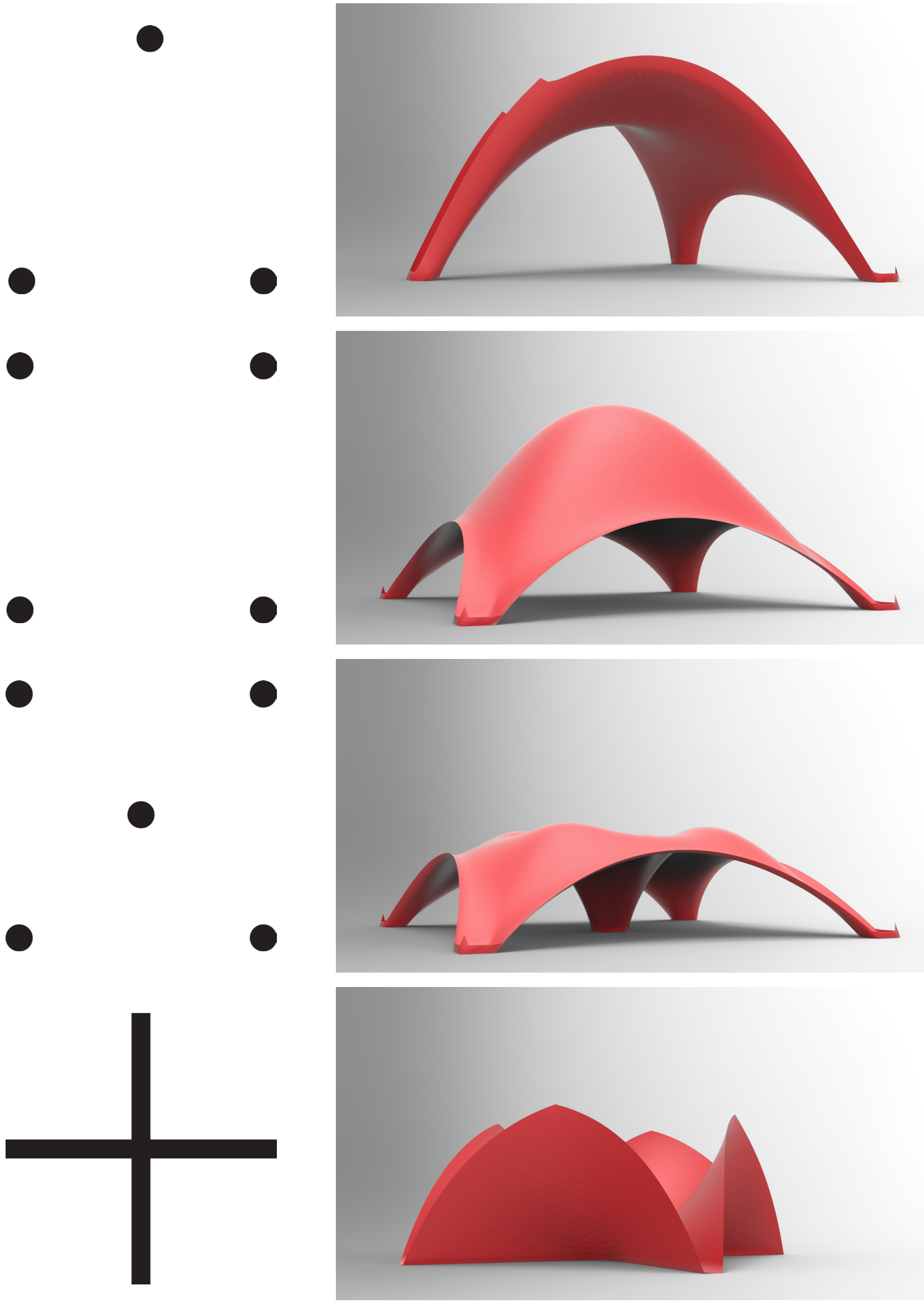
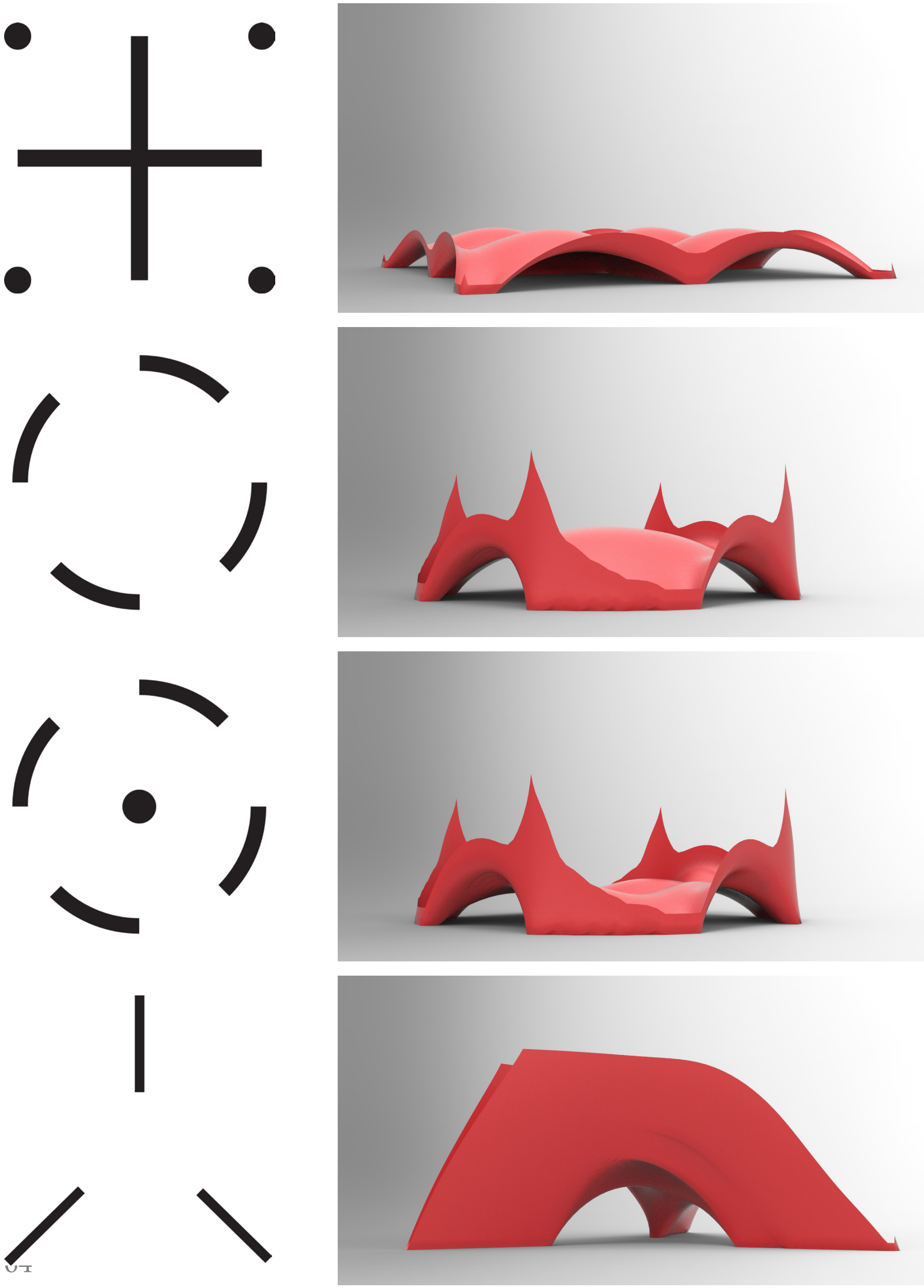


Fig. 76. Emergent Funicular Forms (Author) >

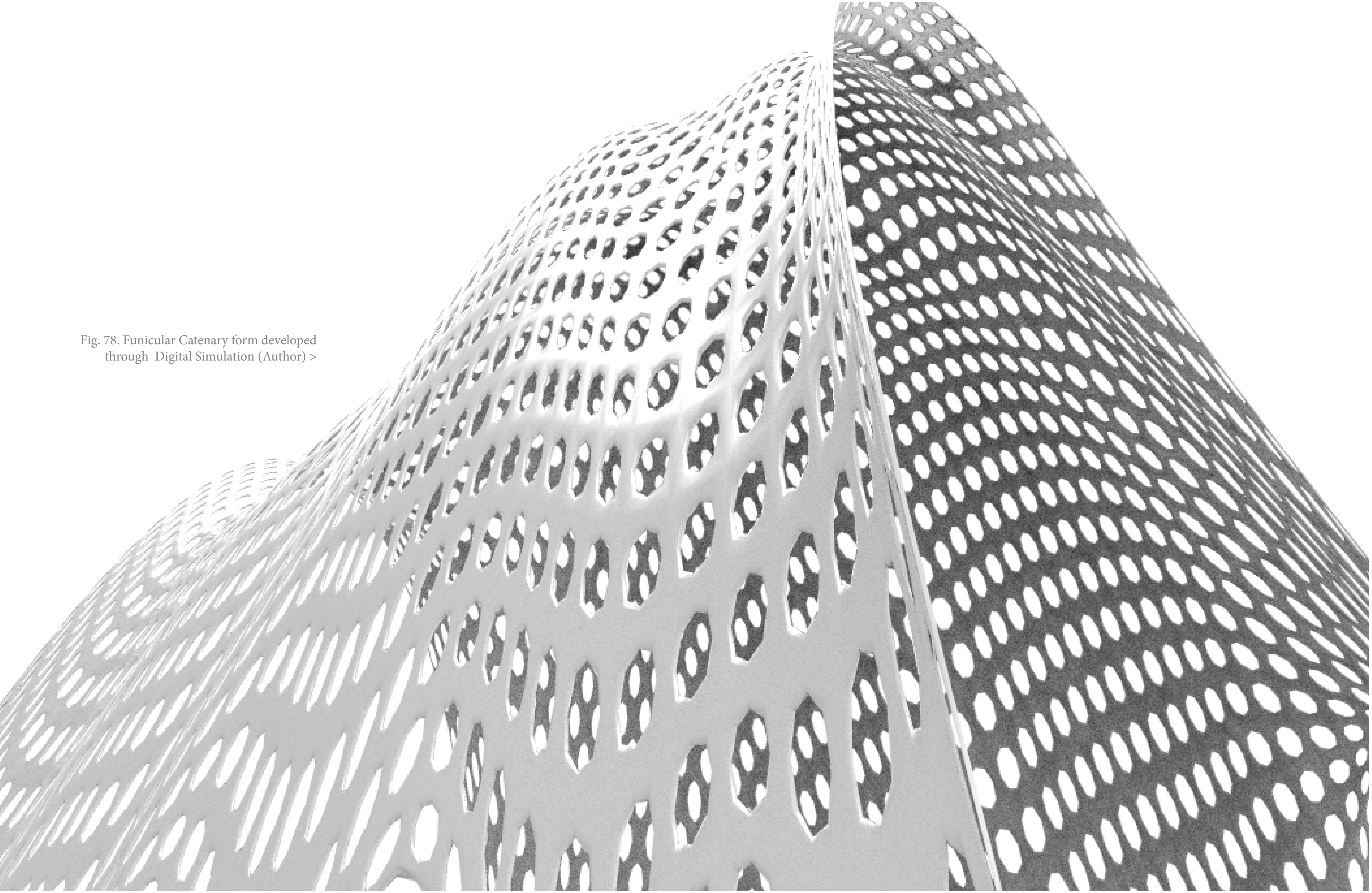


< Fig. 77. Emergent Funicular Forms (Author)

Review

The true benefits of decoding this method for use in the parametric software, proved to lie in the rapid visual feedback provided through the CAD environment. This allows for a continuous feedback loop in which the emergent forms could be assessed against a set of predefined criteria, be it programmatic, environmental, or aesthetical. In many cases, the anchor point arrangements, spring rest lengths, stiffness, gravity force, etc. were modified on the fly, and the results animated in real time. In physical modelling making changes to these variables, if possible, would take hours to re-rig and measure.

Fig. 78. Funicular Catenary form developed through Digital Simulation (Author) >



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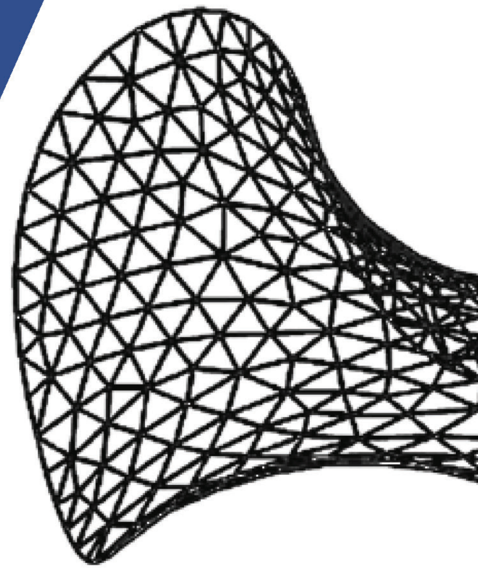
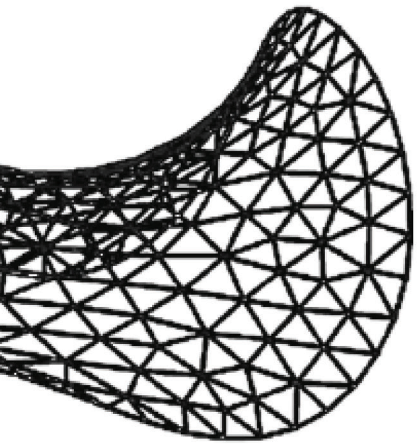
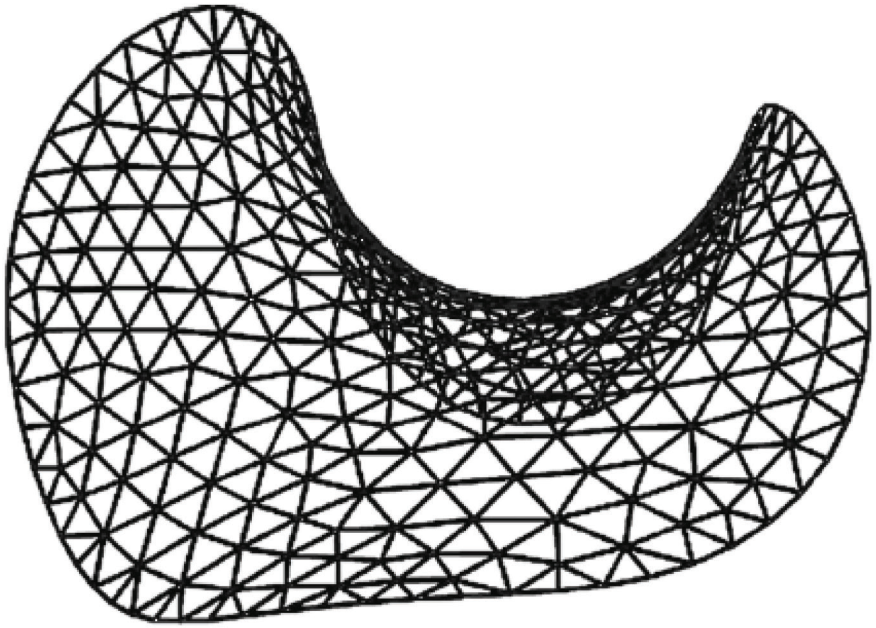
Architectural Application







^ Fig. 79. Digital Simulation of Membrane Behaviour (Author)

.4.0.1.

Introduction

Introduction

This design study extrapolates from the preliminary surface structure explorations, through exploring the effect of 3D printing rigid plastics onto pre-stretched elastic surfaces. Extensive physical modelling is undertaken to develop a compendium of forms that relate to the specific resin patterns with which they have been impregnated. The physical research seeks to develop a mathematical understanding of the relationship between pattern, and emergent 3D curved surface forms which arise due to the stretched materials inherent capacities and tendencies.

As in the previous section, the physical method is then translated into the digital environment via a purpose-built parametric modelling algorithm, for further development and analysis of its potential architectural application. The development of the algorithm examines how the micro-mechanics operate locally within the material study, for future use in simulating the form-finding process.

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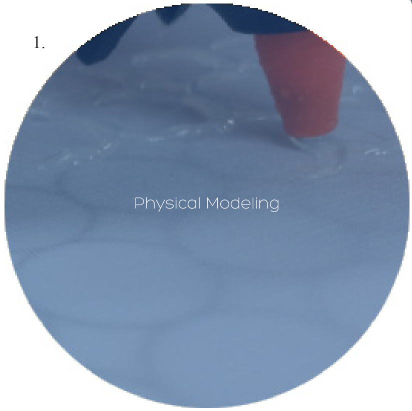

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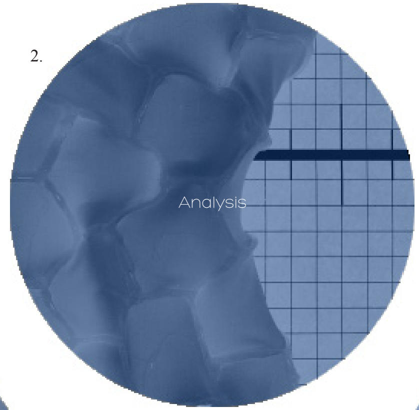

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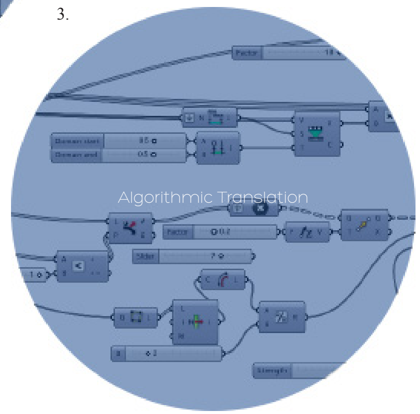

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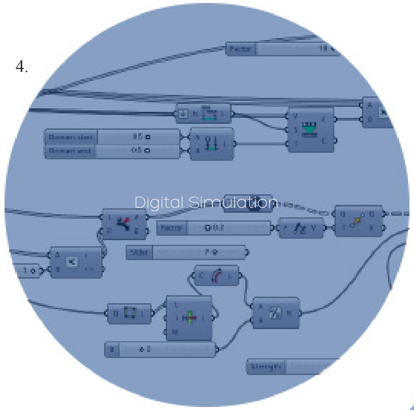

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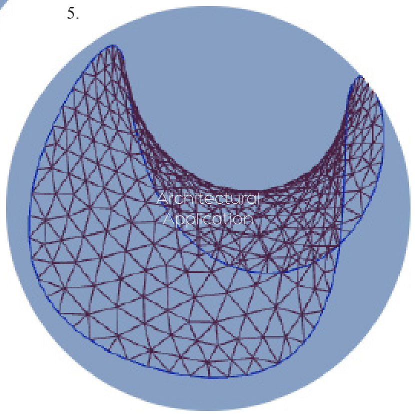


^ Fig. 80. Part four design research methodology (Author)

This section concludes with the conceptual design of a series of habitable pavilions that self-assemble from specific, two-dimensional deposition patterns. This proposal speculates a system for ideal use in non-conventional construction environments, that require material efficiency, minimal construction knowledge, and rapid assembly, such as disaster relief scenario. The proposed system is accompanied by a prototype design and build of a low cost, portable 4D-printer, capable of large scale 2D pattern deposition upon pre-stretched membranes.

.4.0.2.

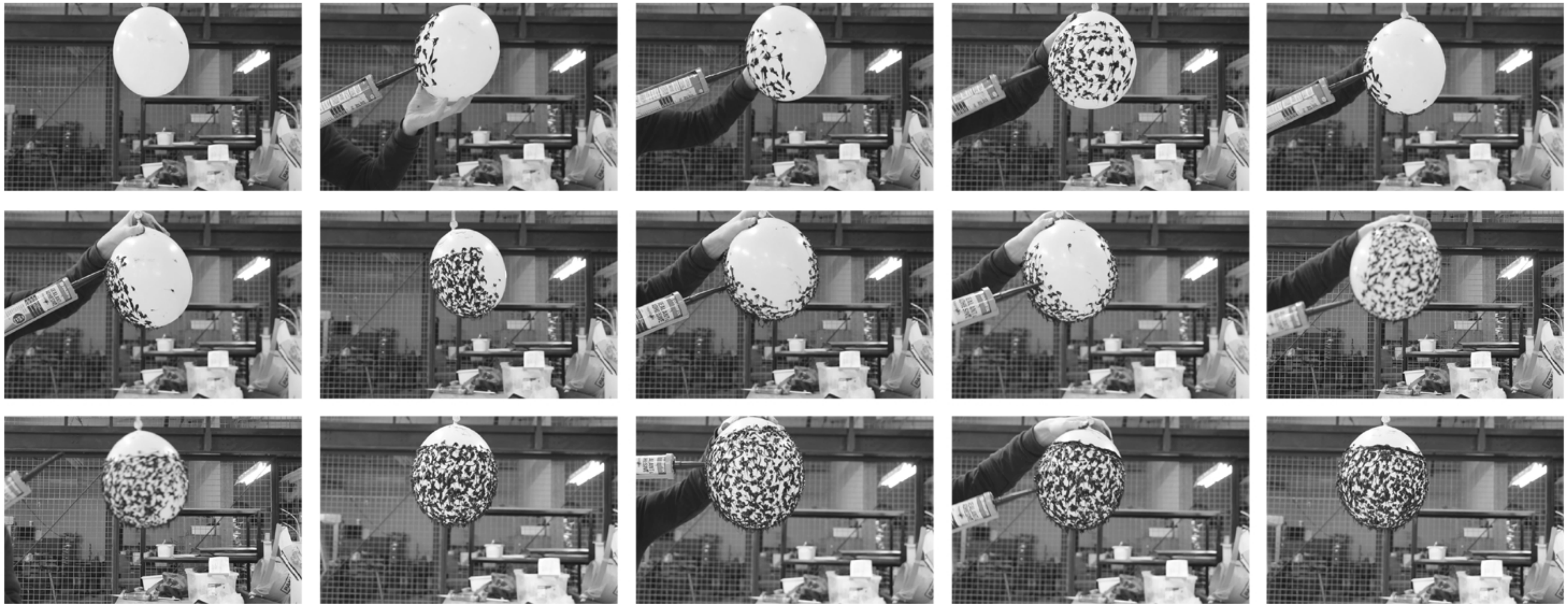
Initial Material Study

Balloon Study

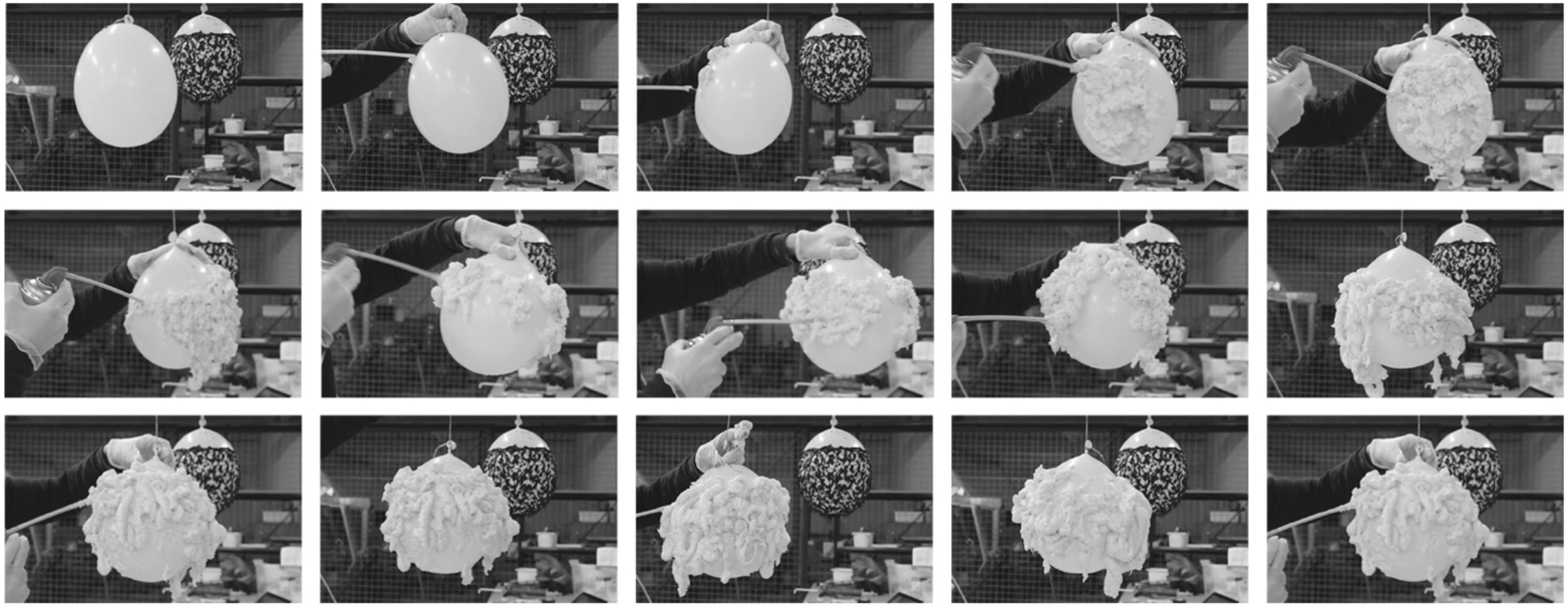
An initial open-ended modelling study was conducted to develop potential design exploration avenues, relating to the deposition of semi-plastic materials onto pre-stretched membrane surfaces.

In this exercise, materials of differing plasticity and viscosity were extruded onto balloons, to explore how the material behaved once the tension support (the pneumatic pressure) was taken away through popping.
This exercise served as a preliminary 'sketch-modelling' procedure. Little focus was intentionally put into a controlled method, allowing for forms to emerge purely through the material's inert material capacities and tendencies under the externally imposed conditions.

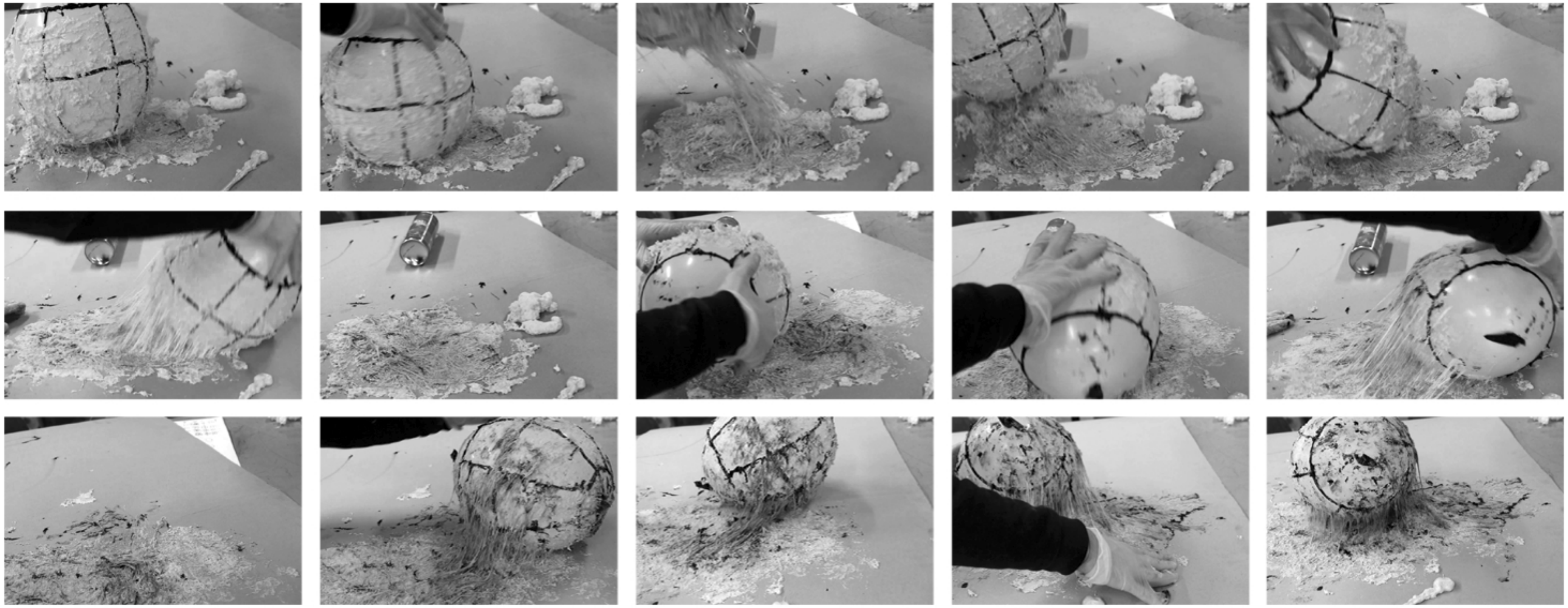
Fig. 81. Preliminary Balloon 'Sketch' Study (Author) >



^ Fig. 82. Deposition of semi plastic extrudable materials onto pre-stretched membrane (Author)



^ Fig. 83. Deposition of extrudable foams onto pre-stretched membrane (Author)



^ Fig. 84. Deposition of extrudable foams onto pre-stretched membrane (Author)

^ Fig. 85. Emergent
Material Effect
(Author)

Findings

Although uncontrolled, this 'sketch-modeling' exercise generated some interesting findings surrounding deposition upon pre-stretched membrane surfaces.

It became apparent that the pattern of deposition had a predominant effect on the emergent, collapsed structures. It was the more semi plastic materials that yielded the most dynamic results, including complex, doubly curved surfaces and interesting localized deformities.

The resultant models illustrated both synclastic (bowl-like positive curvature) and anticlastic curvature (saddle-like negative curvature). This was a promising result to further explore.

Fig. 86. Emergent Material Effect (Author) >

. 4 . 0 . 3 .

Controlled Surface Deoposition

Introduction

Introduction

To gain a greater understanding of the direct effect the impregnating pattern has on emergent form, a second surface deposition study was undertaken.

In this repeat study, the method was stringently controlled, and studied only two materials. This study implemented 'Lycra' stretched to 120% as the reciprocal, and hot glue thermoplastic, extruded at 5mm thickness as the catalyst. An expansive series of patterns were generatively developed, each iteratively increasing in complexity.

Method

The process begins with cutting the nylon sheets to 80% of A3 paper size (237.6x 336.0mm). The sheets are then stretched back up to A3 (297 x 420mm) and uniformly clamped around the entire perimeter. This ensures that the sheet is under uniform tension.

The deposition pattern is then carefully traced using a hot-glue gun and left to dry for 10 minutes. Once dry the pattern is released from the board and the resultant form revealed. The intent of this study was to build a fuller understanding of the effect the paths of the patterns have on the emergent final form upon release of the fabric, through cutting around the pattern outline.

Fig. 87. Controlled deposition study Process (Author) >

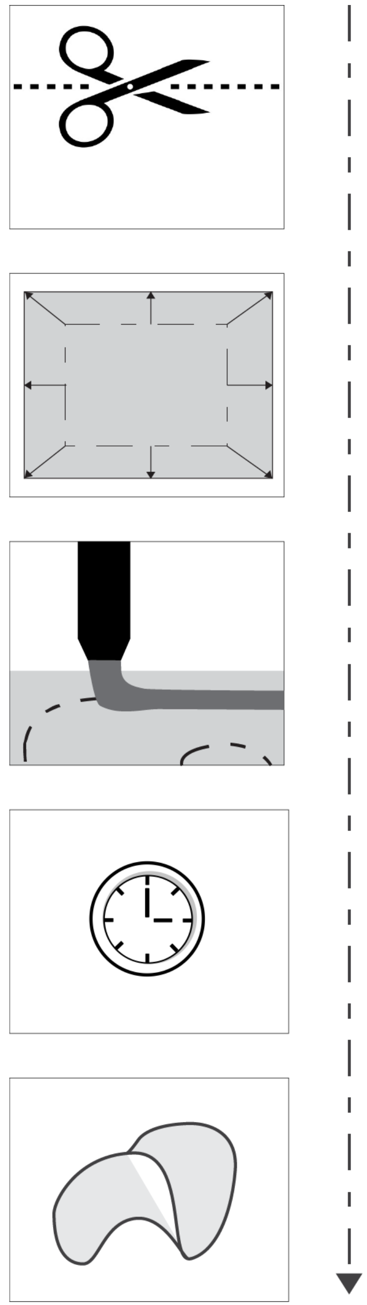
1. Cut Nylon Segments

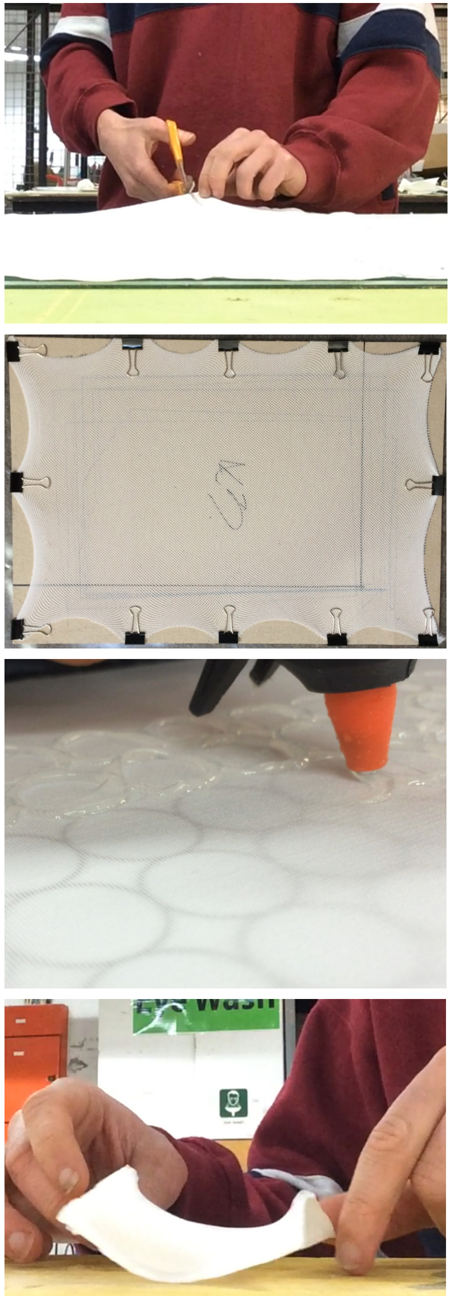
2. Stretch 120% Rest Length

3. Trace Pattern with Thermoplastic Extrusion

4. Rest Until Thermoplastic Sets

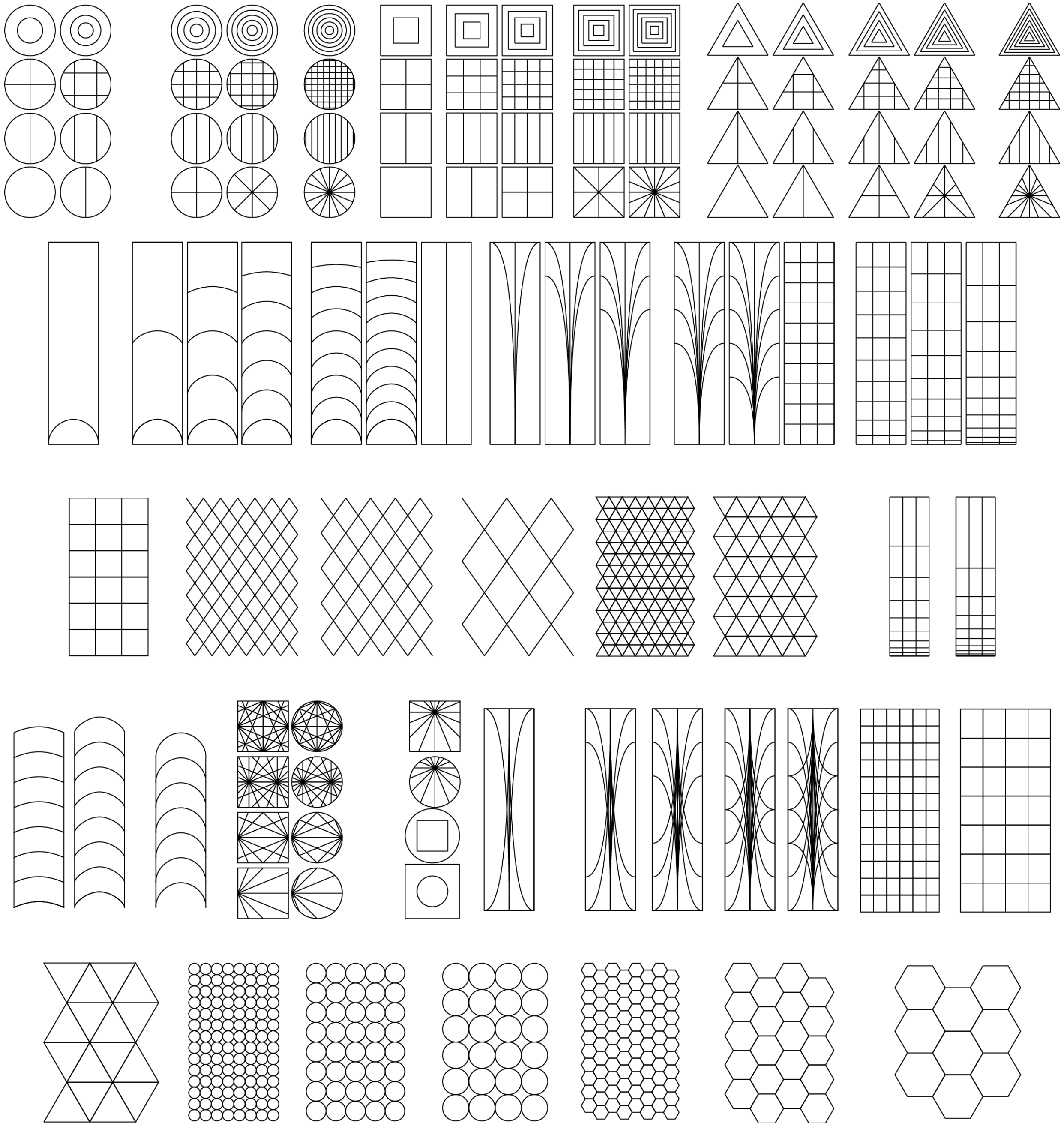
5. Cut Around Pattern and Release Form





< Fig. 88 - 92 modelling process (Author)

Fig. 93. Compendium of Patterns explored (Author) >



.4.0.4.

Results: Pattern/ Form Relationship

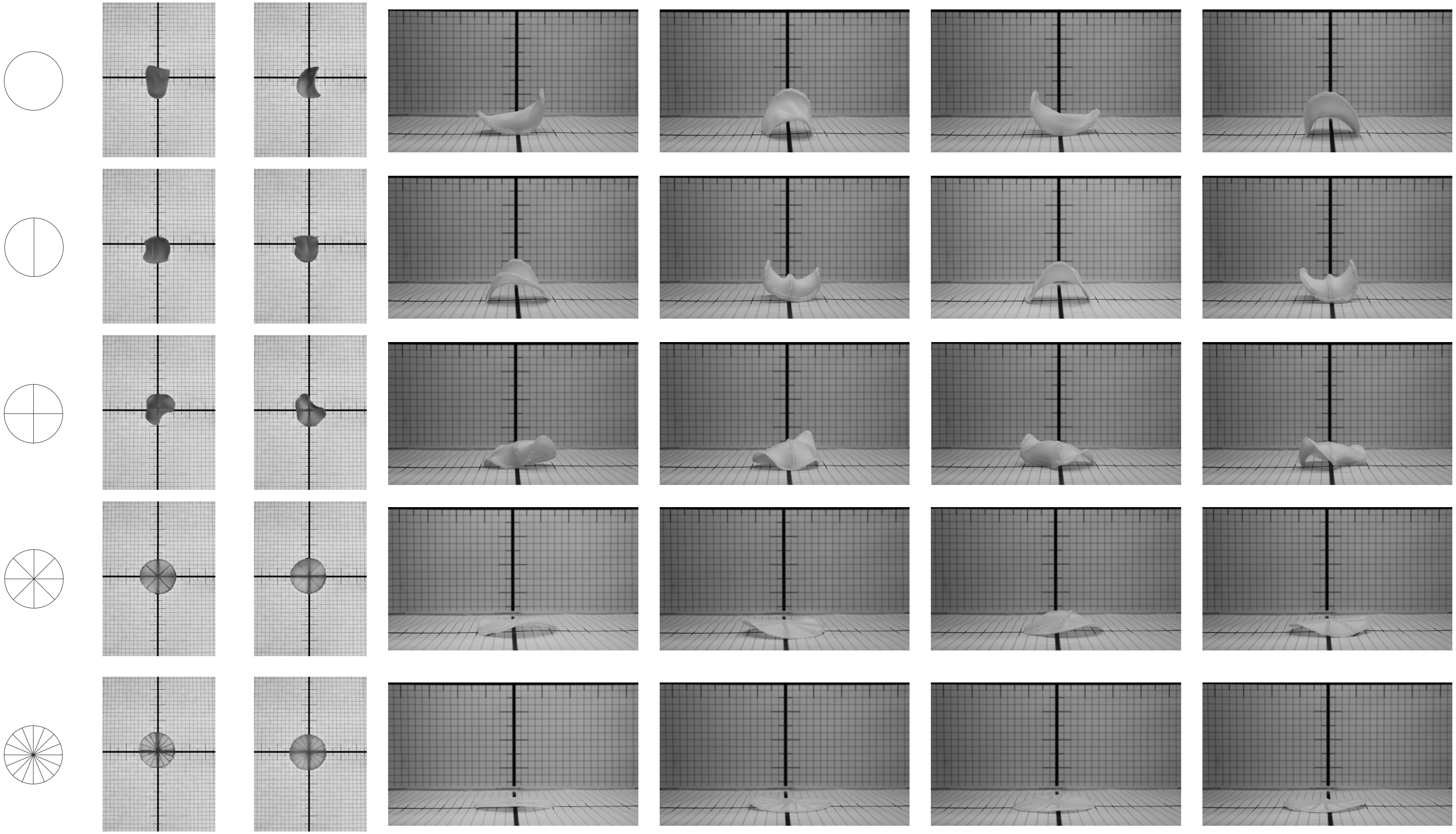
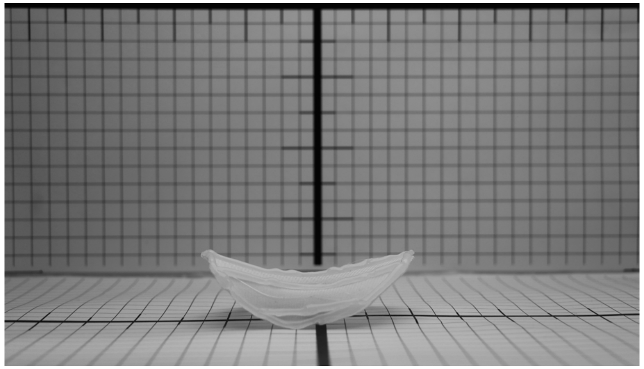
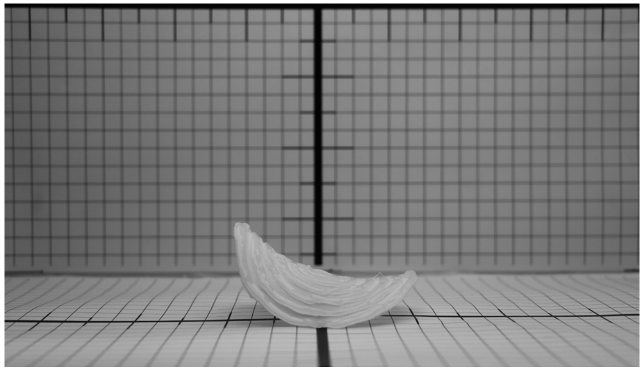
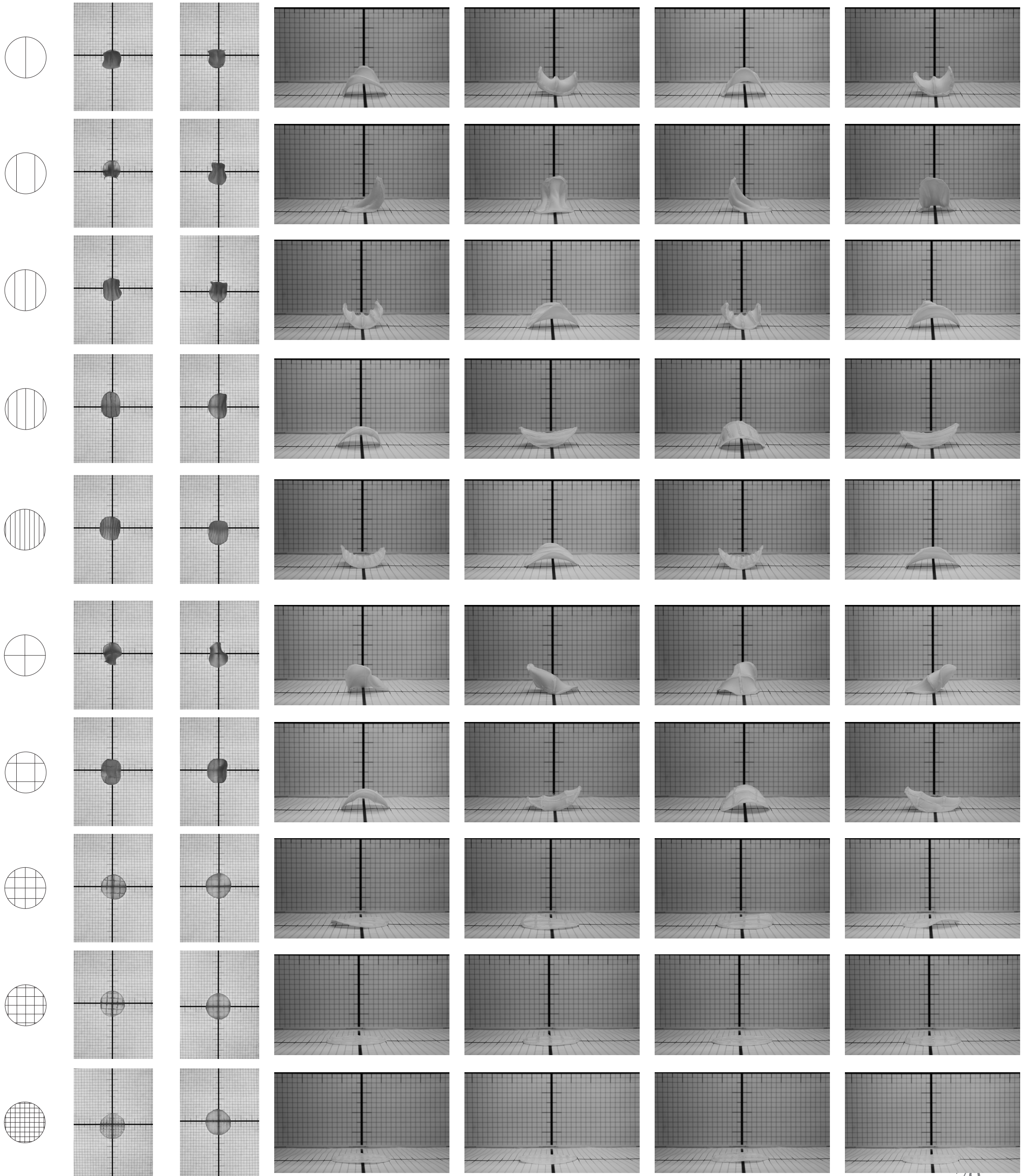


Fig. 94. Physical Modelling Results (Author) >







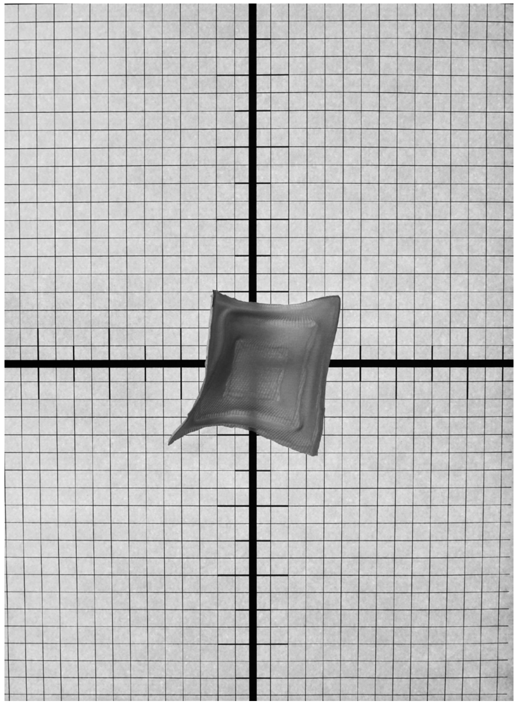
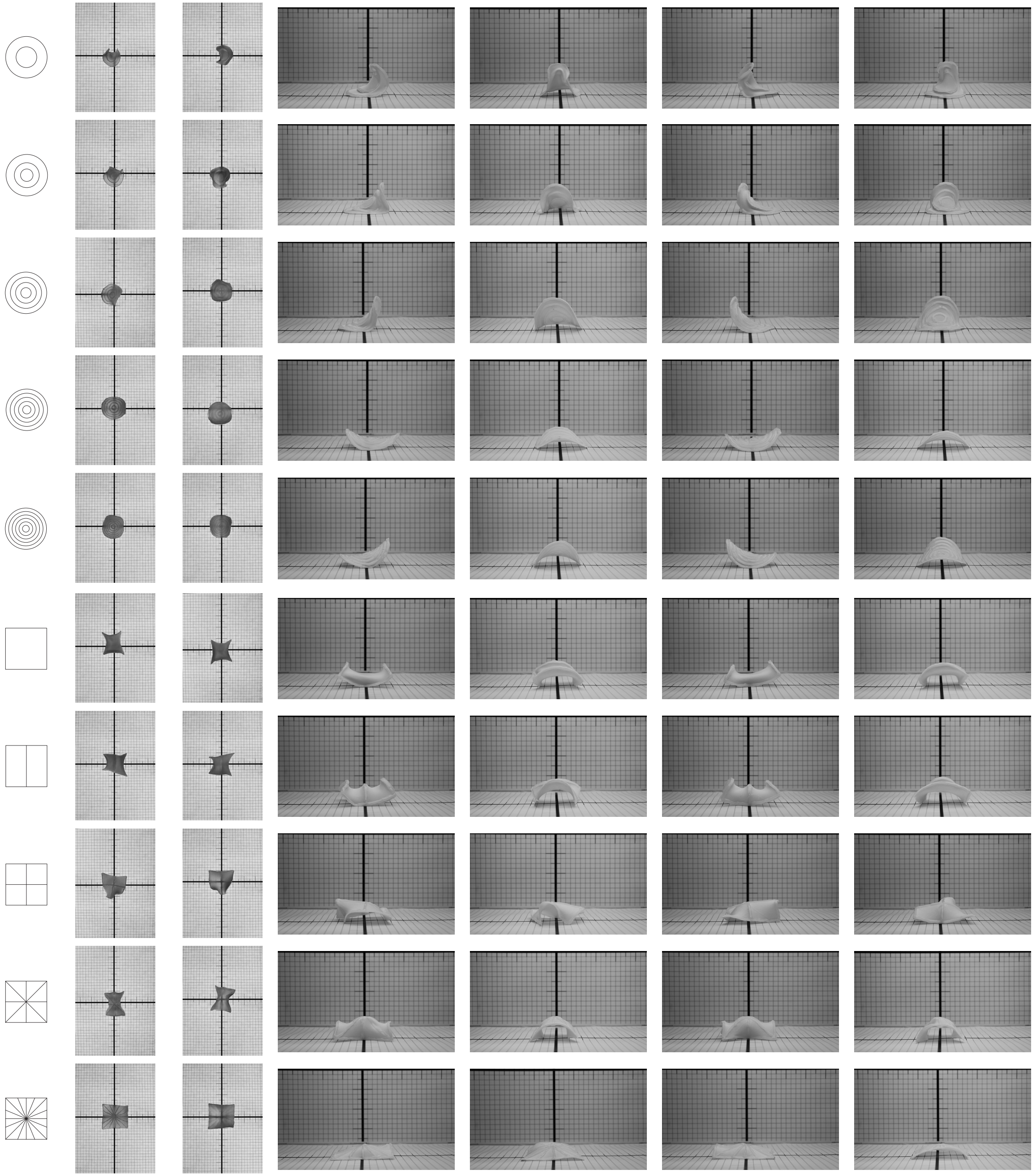
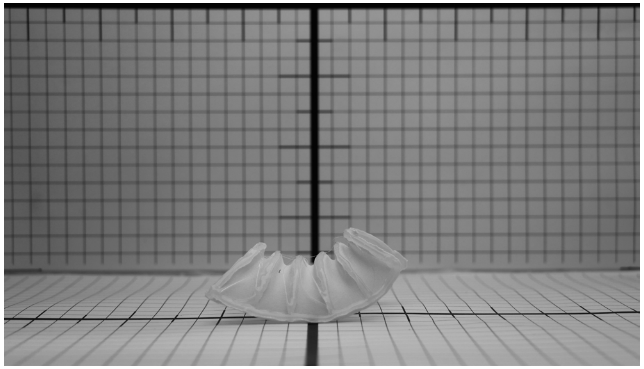
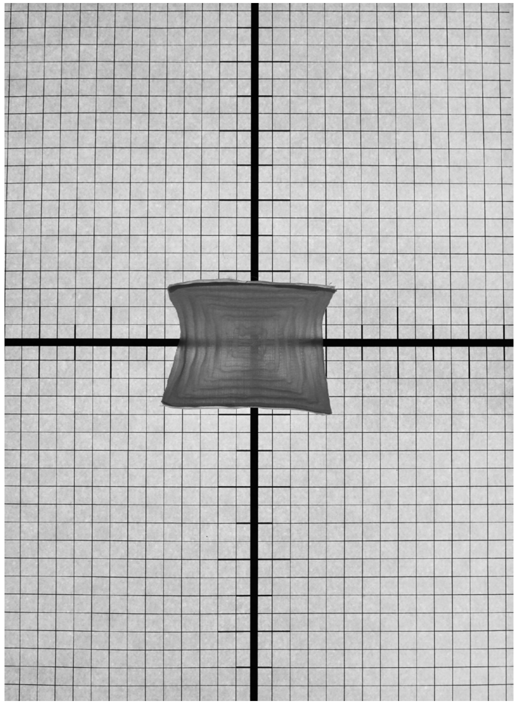
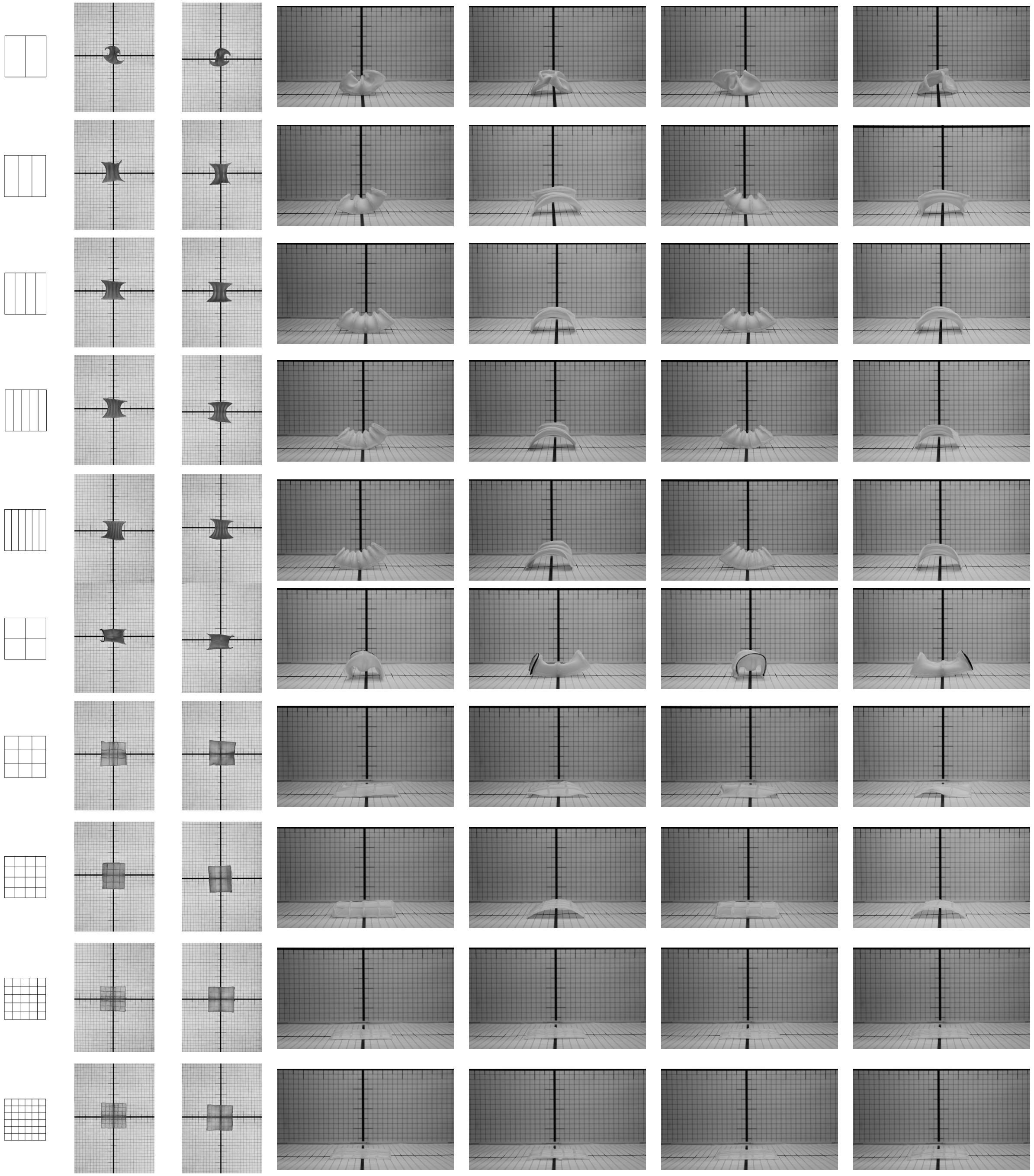


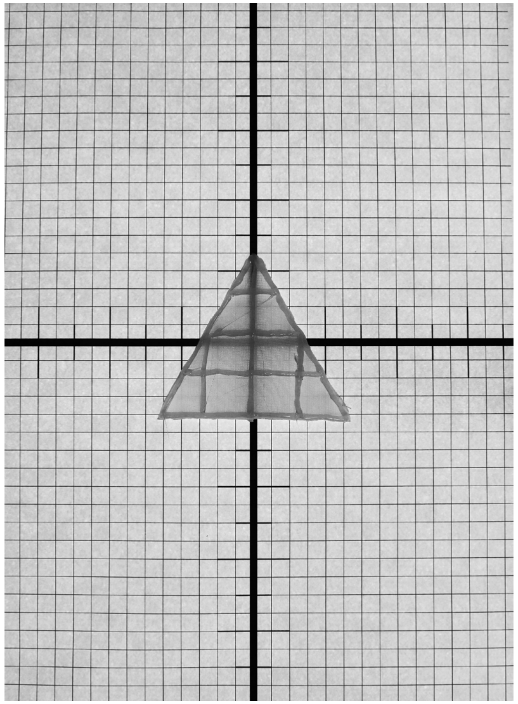
Fig. 95. Physical Modelling Results (Author) >











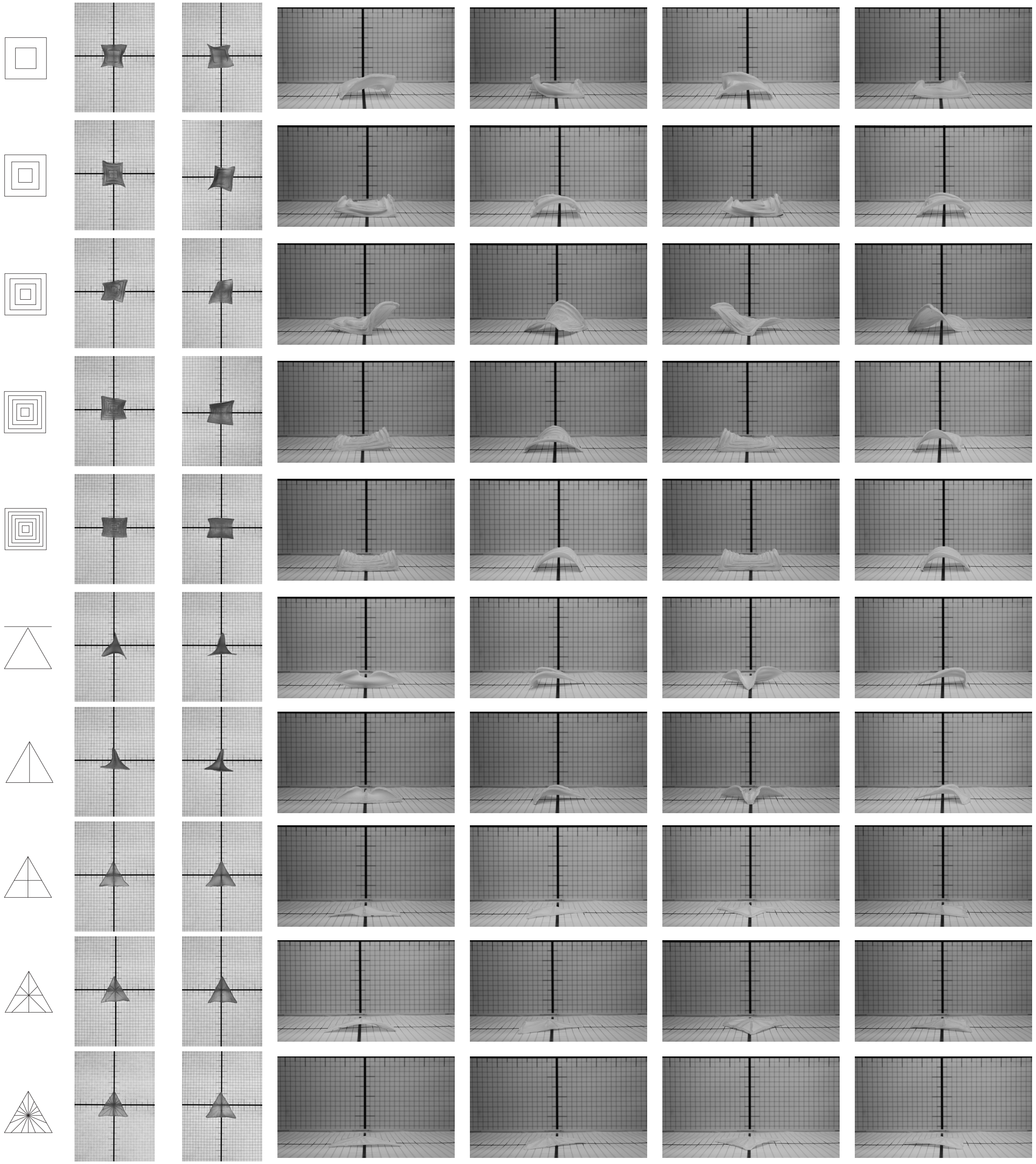
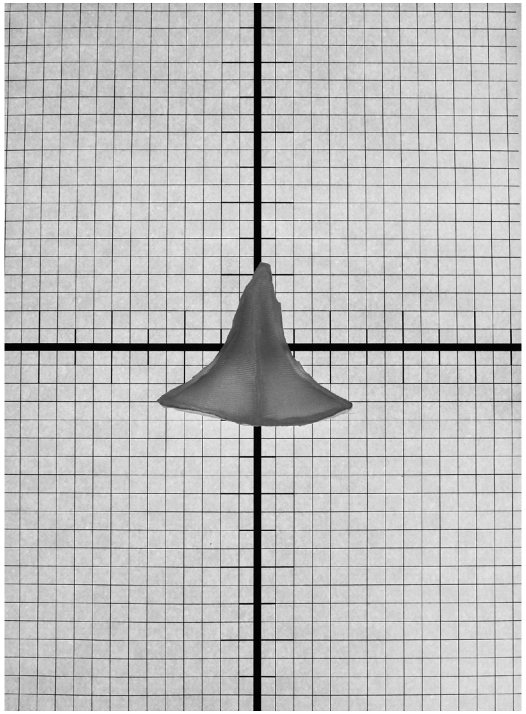
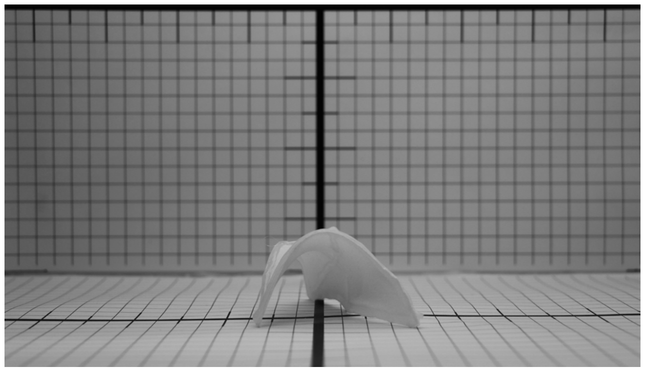
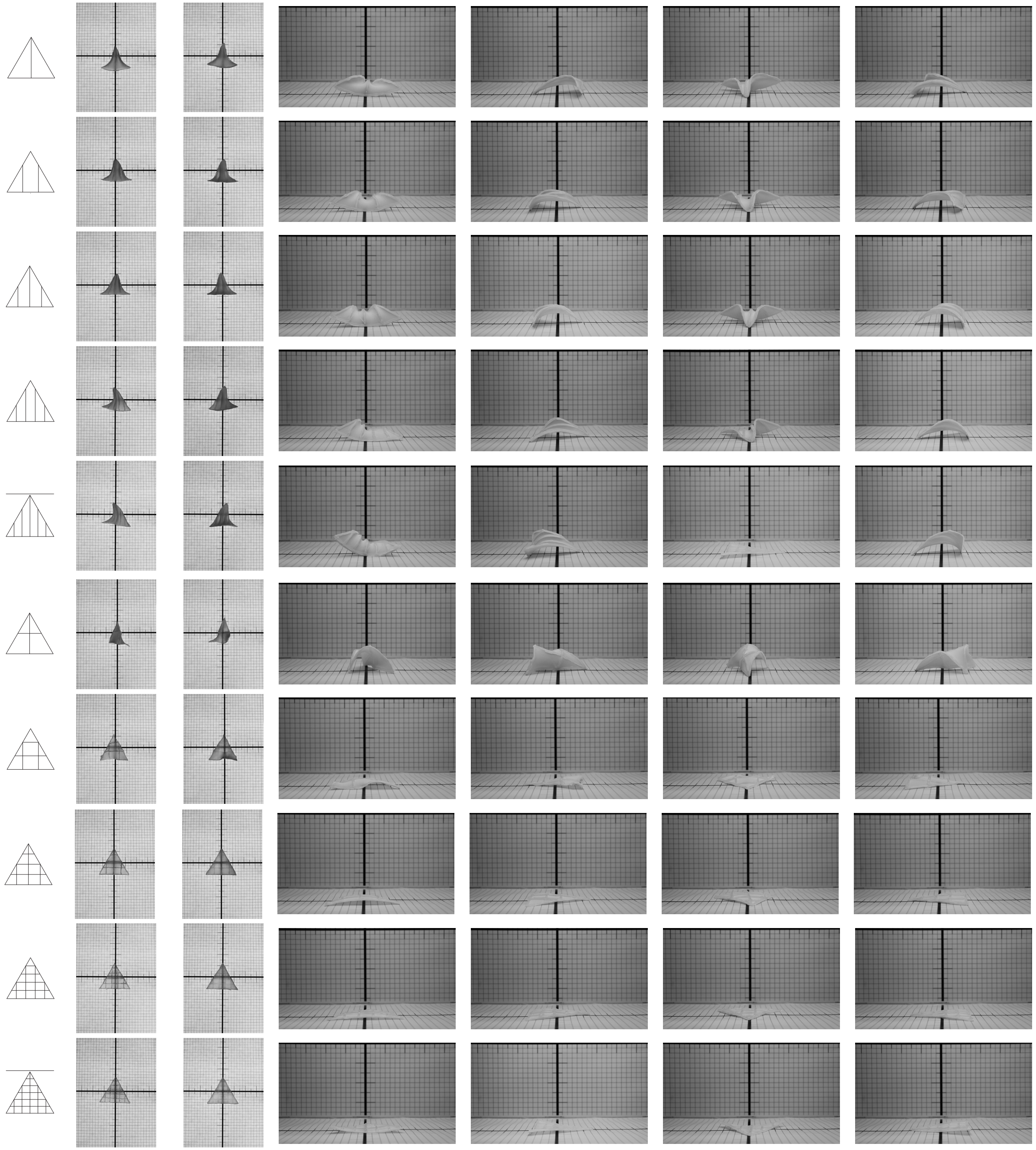


Fig. 96. Physical Modelling Results (Author) >







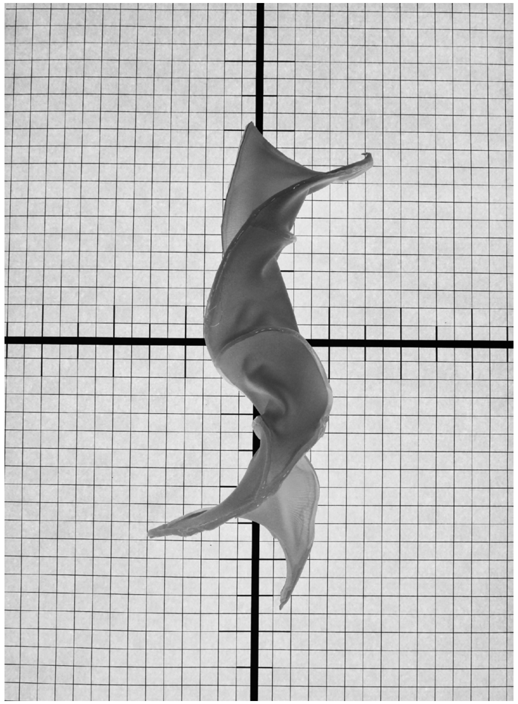
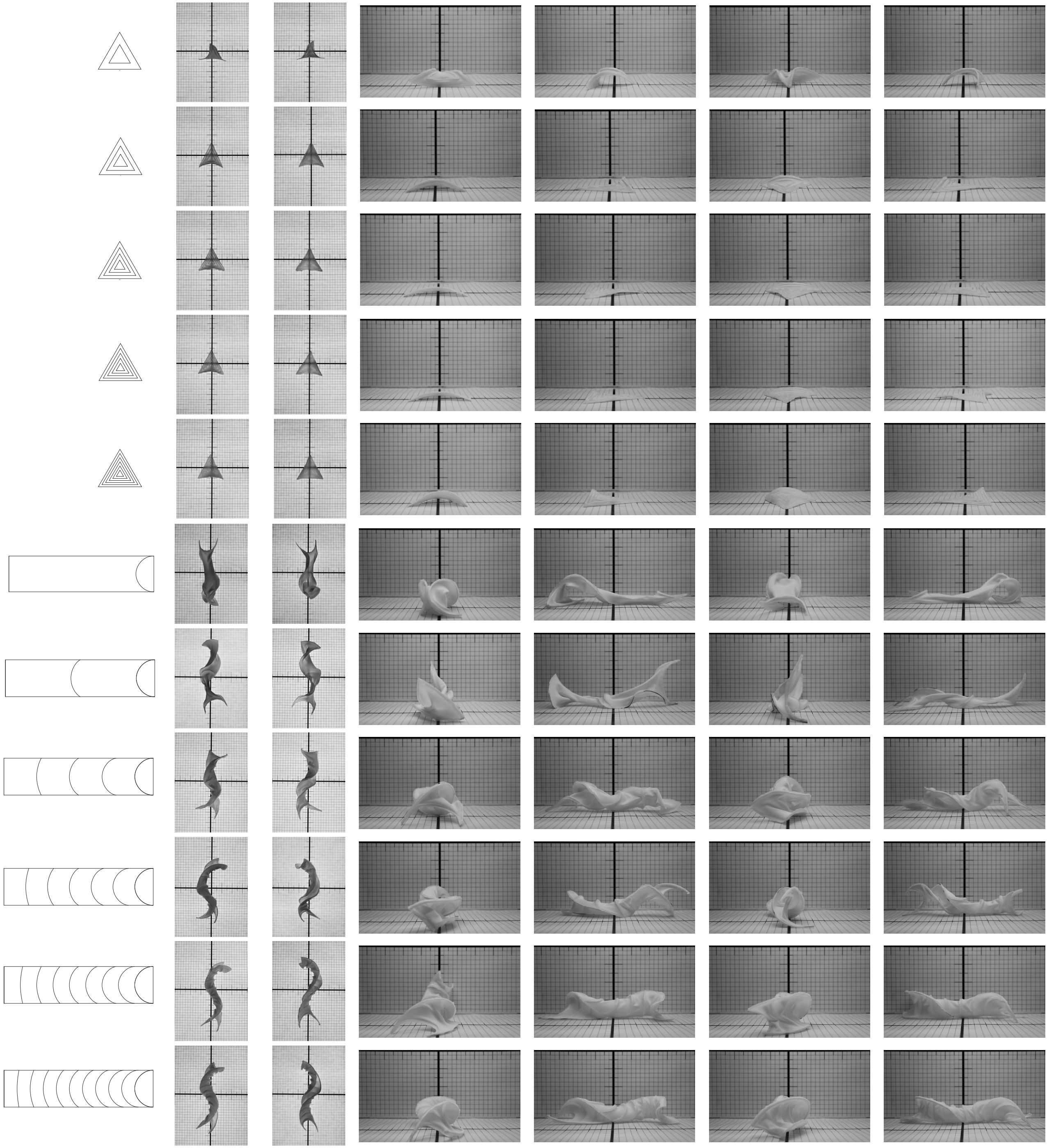
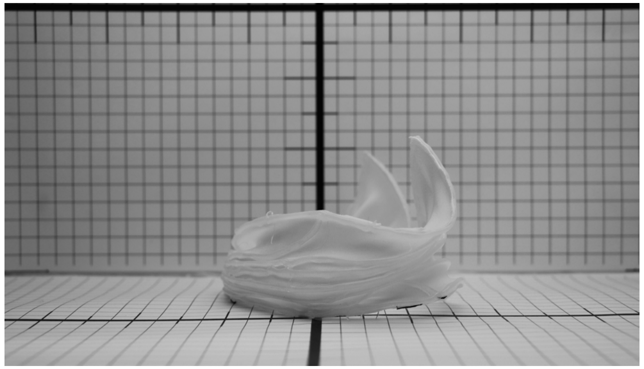
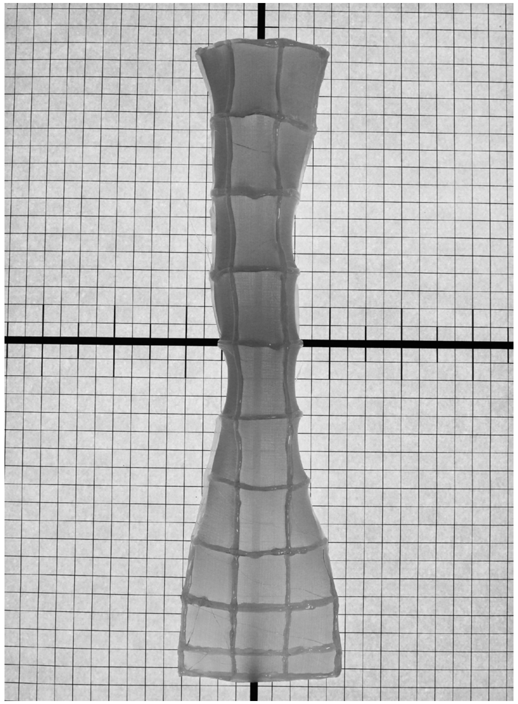
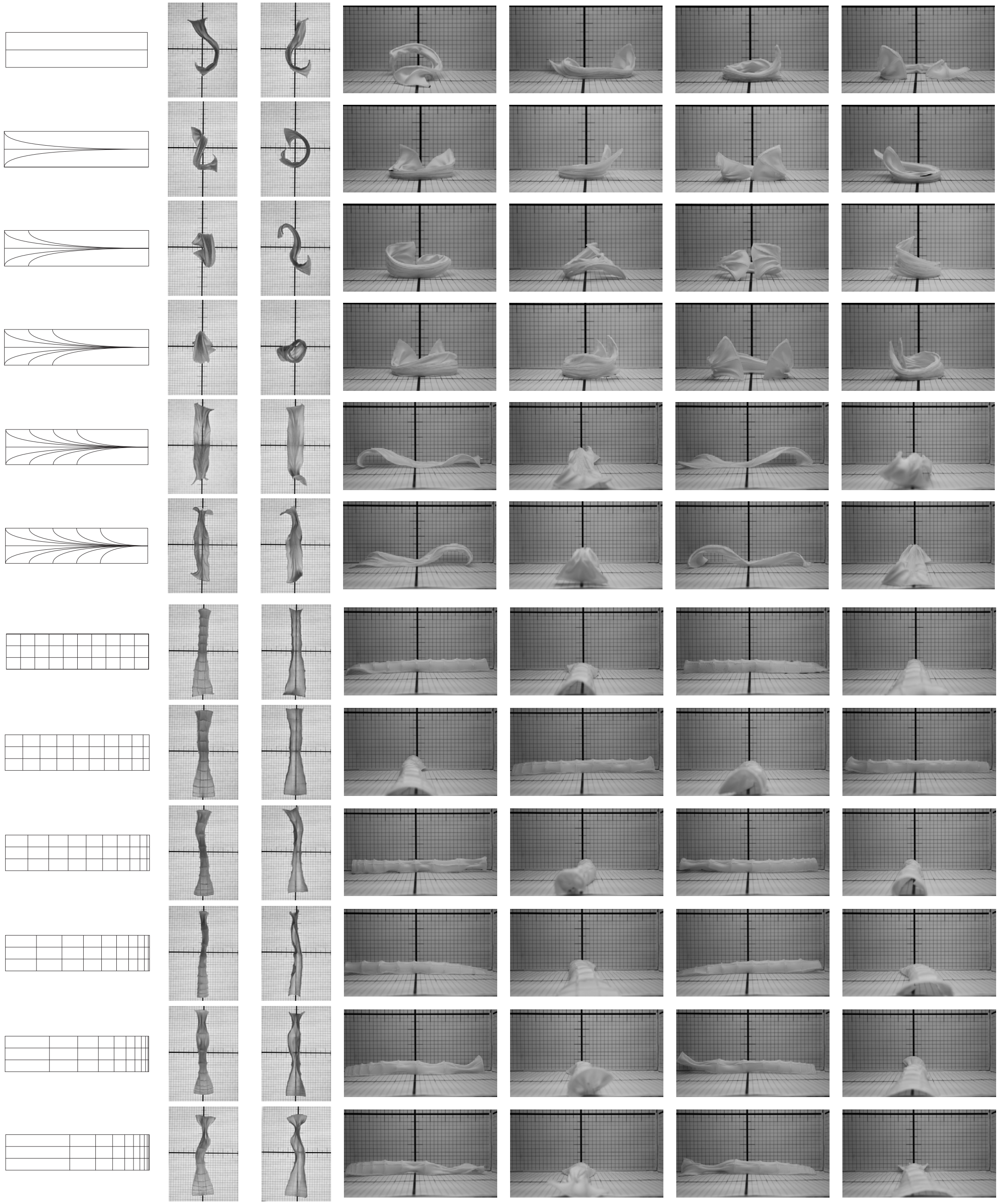


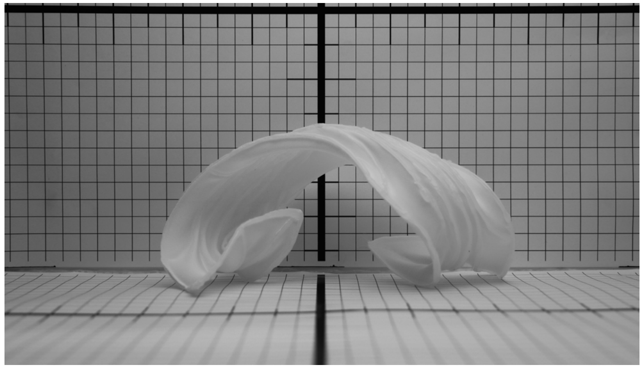
Fig. 97. Physical Modelling Results (Author) >

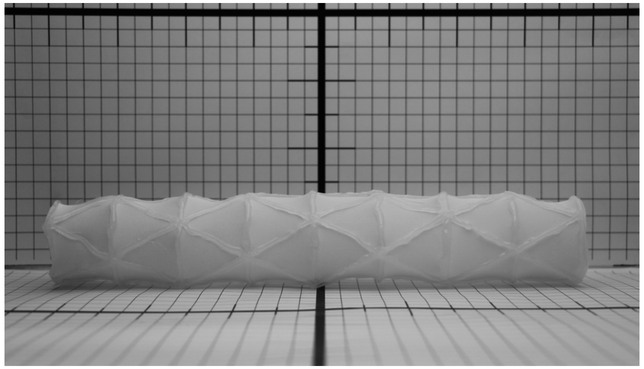












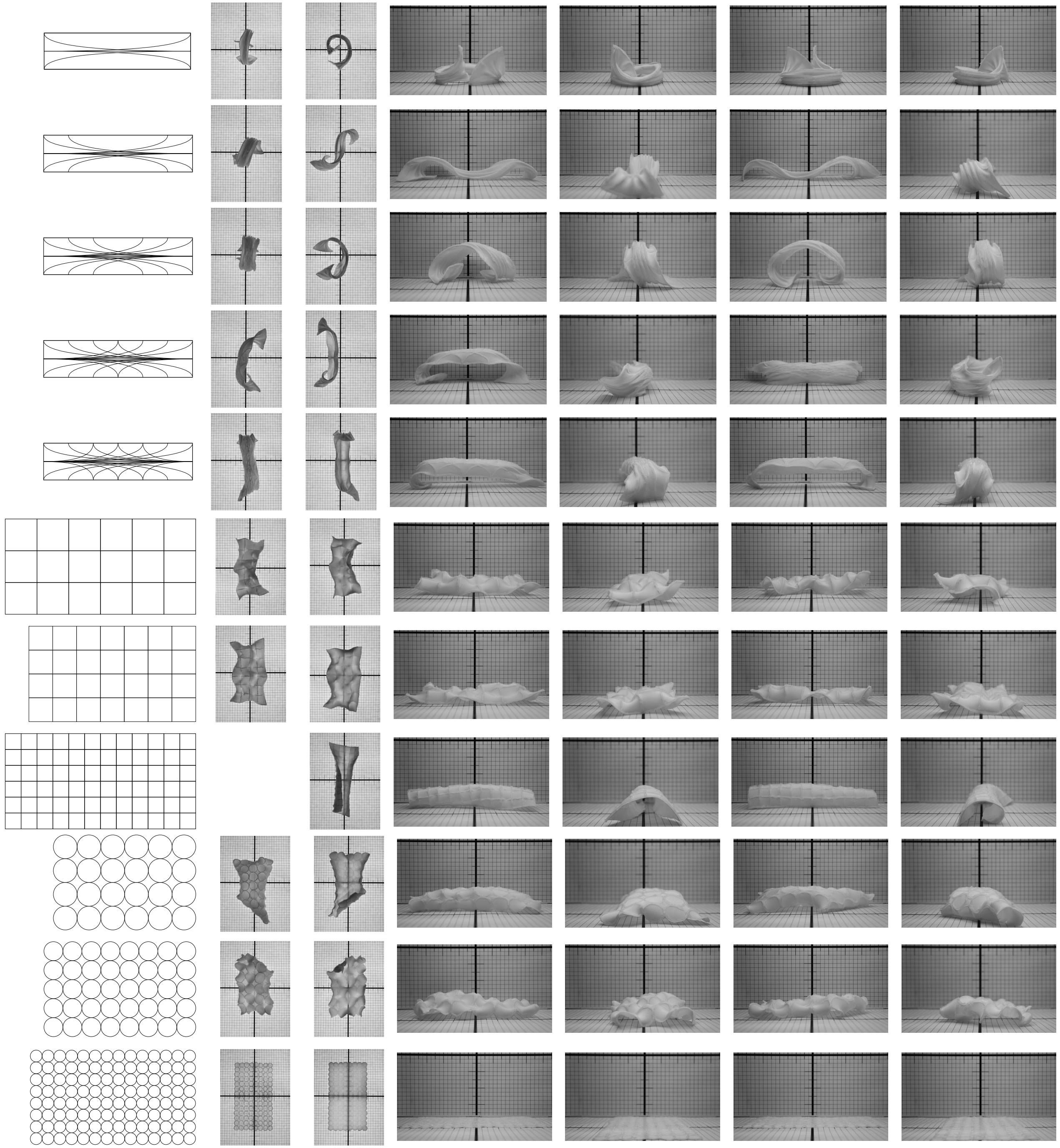
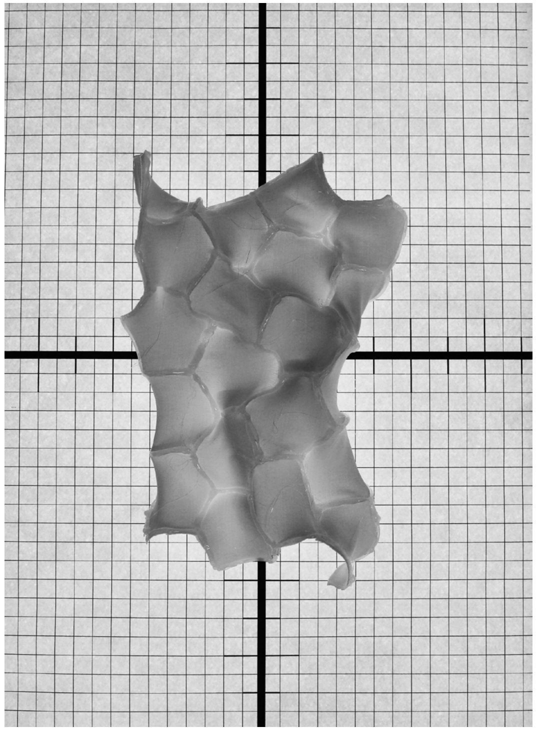
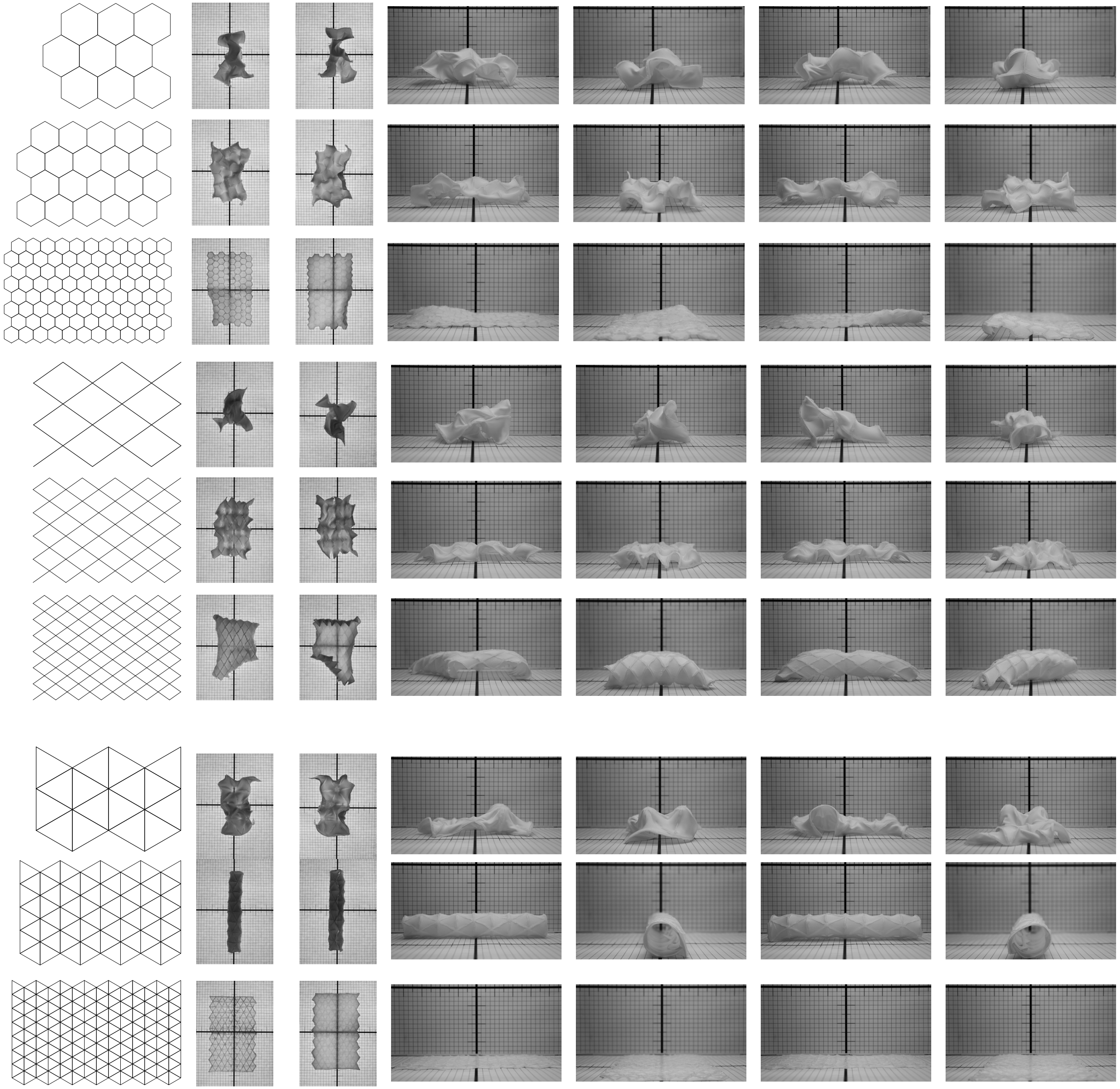


Fig. 98. Physical Modelling Results (Author) >





.4.0.5.

Results: Pattern/ Form Relationship

The release of the tension within the models triggered a dramatic change in their global geometry. The impregnation, or freezing, of the fibres, through the pattern deposition of the thermoplastic, permanently altered the rest length of the strands effected. This in turn propagated local conflict within the micromechanics of the material system. The disruption of shrinking capacity caused by the plastic, resulted in differential shrinkage rates, and emerged a series of new global surface curvatures.

The natural analogues of this system are exemplified by nastic plants motions, whereby a variety of organs such as their tendrils, leaves and flowers respond to environmental stimuli (e.g. light, humidity, touch etc.).

They do so by 'varying their internal turgor, which leads to dynamic conformations governed by the tissue composition and microstructural anisotropy of cell walls'. (Gladman and Matsumoto)

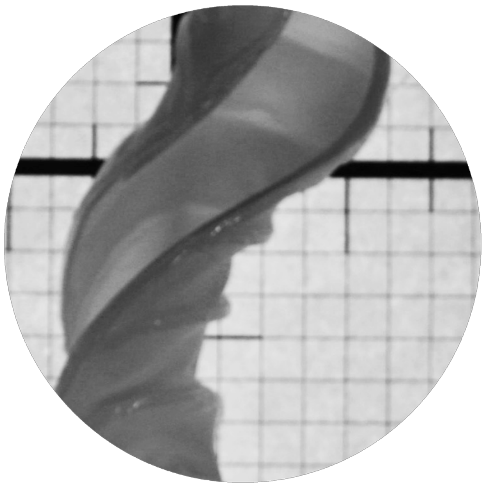
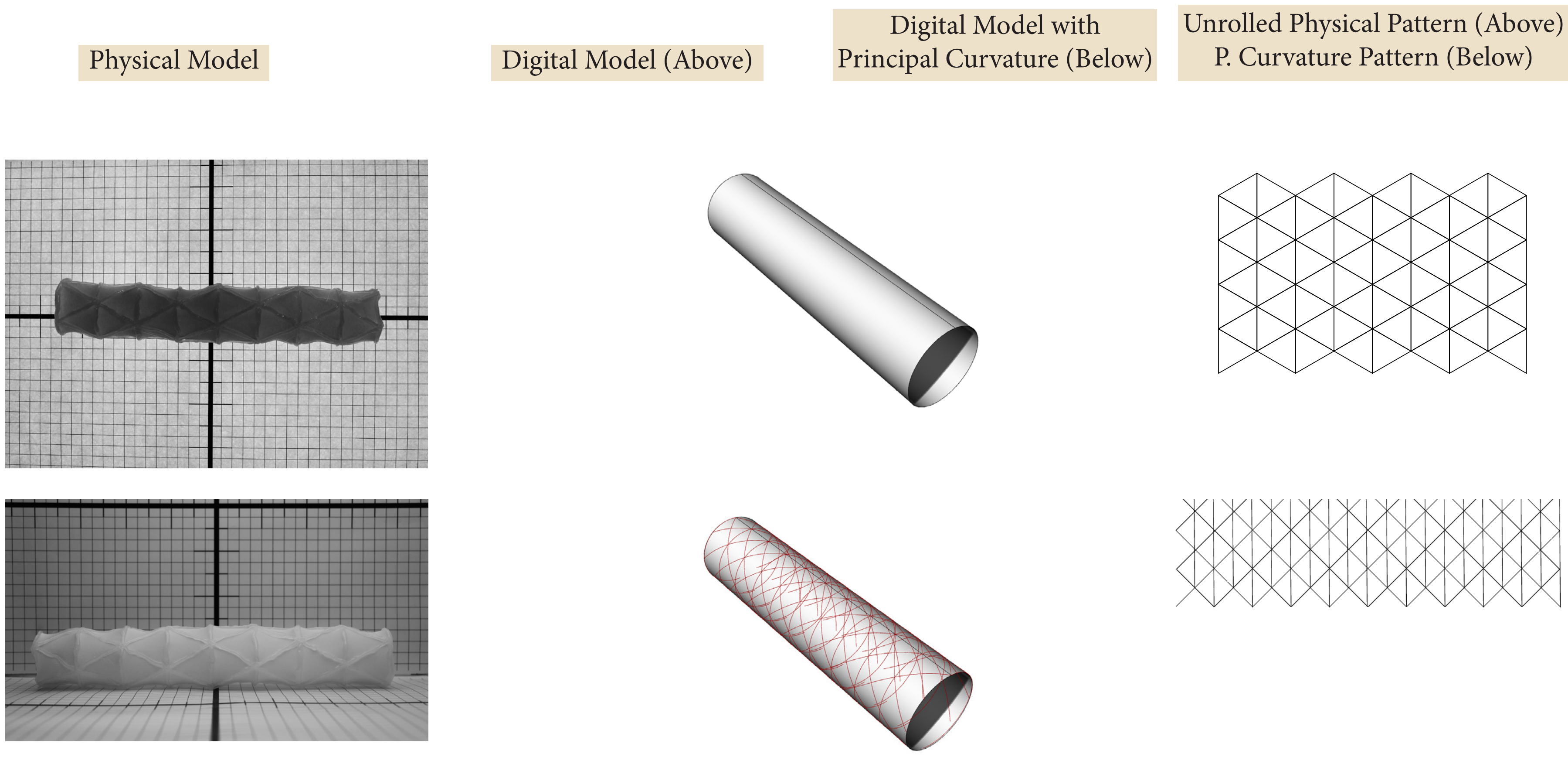


Fig. 99. Emergent Complex Geometry (Author) >

^ Fig. 100. Pine-cone actuating in reaction to changes in humidity (Menges)



^ Fig. 101. Principal Cruvature lines & Deposition pattern comparison (Author)

Principle Curvature

Through analysing the resultant geometry via remodeling within the digital environment, it became apparent that the lines of principal curvature upon the forms of the emergent surfaces, correlated to the printed patterns once rolled back out.

This finding suggests then, that from a digitally modelled surface, a corresponding principle curvature based print pattern should be attainable via a reverse engineering of the digital process.

To test this theory, a custom visual algorithm within Grasshopper was developed to simulate the emergent forms, from initial starting patterns to equilibrium state, that were then checked against the physical models.

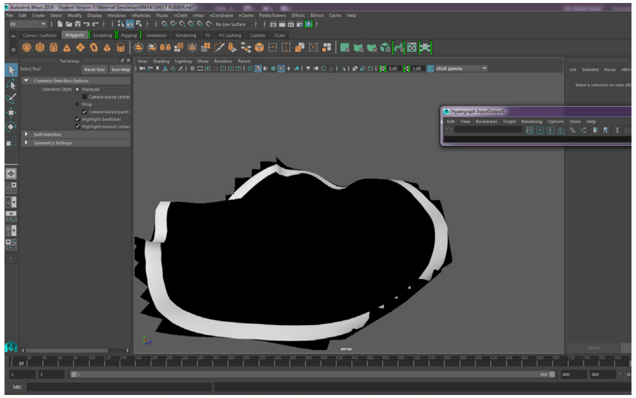
.4.0.6.

Digital Translation

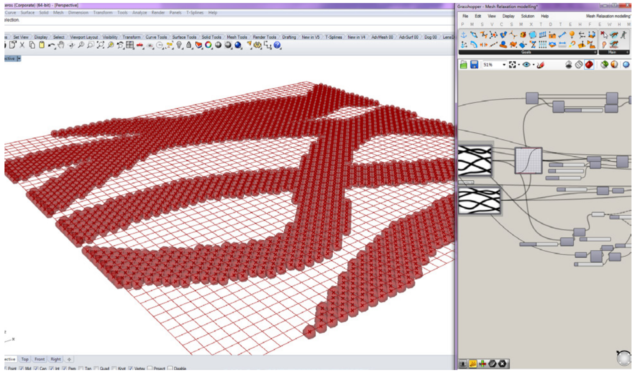
TThe next step was to design a parametric algorithm, in which to test the theory developed in the previous section of utilizing principal curvature lines as pattern generators to reach goal surface forms.

Physically-based cloth simulation has been around for more than a decade, and still challenges the community of computer graphics when confronted with the need to accurately describe the properties and behaviour of physically informed deformable surfaces. (Baraff and Witkin) The animation modelling software 'Maya' was initially implemented, utilizing the built-in fabric physics simulator 'nCloth'.

Although a powerful, and widely utilized tool within the animation and graphics industry, Maya fell short in its ability to provide instant numerical feedback of specific performance data. Instead, it was decided to build off the fabric simulation developed in the preliminary design study using the physics engine 'Kangaroo' within the plugin 'Grasshopper' for 'Rhino 3D'.

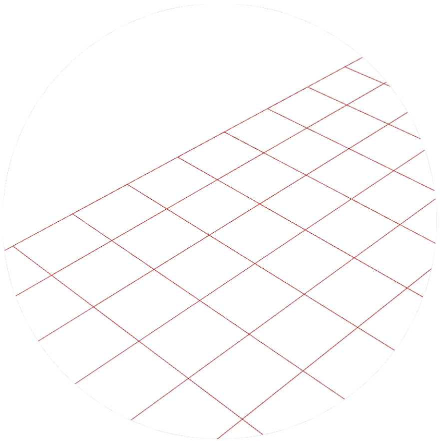


^ Fig. 102. Initial Studies in 'Maya'

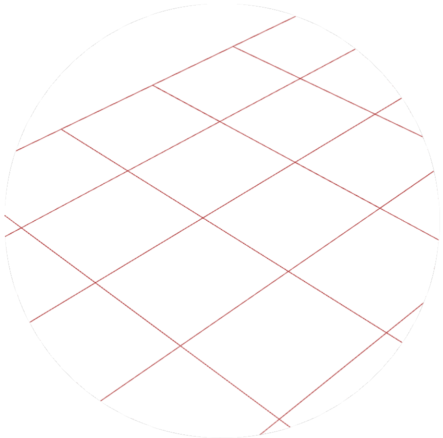


^ Fig. 103. Developing Grasshopper definition (Author)

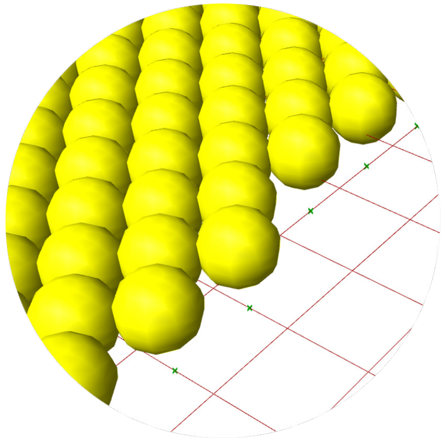
This section outlines the final method in which the physical simulations were recreated within the digital environment.



Spring Mesh



120% Rest length

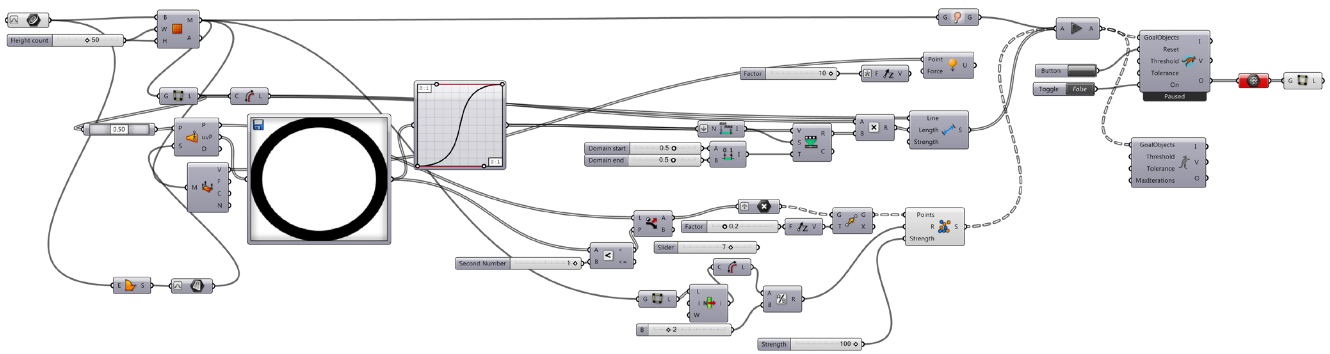


Sphere Colider

Definition Walkthrough

The final Grasshopper definition (visual algorithm) consists of a trimmed mesh, in which each edge (clothed and naked) acts as a spring. Each spring is connected to its adjacent at the end points, creating a mass spring surface model, that mimics the internal fibres of the physical experimentation. The springs span both in the X and Y direction upon the surface, so that the surface is stretchable in two directions and accurately represent the physical simulation. From the starting mesh the springs are set to 120% of their individual 'natural' rest length, so that once the simulation begins, the mesh relaxes and shrinks.

To simulate the fibre impregnation and rest length freezing by the applied thermoplastic, each spring that will be effected has a sphere anchored to its center point, with the radius of half the springs length. When the simulation is run, these spheres collide, and prevent their correlated spring from reducing in length. These spheres are set up 5mm above the spring mesh surface to generate the differential shrinking rate observed in the physical study. When executed, this simulation is set to run until the mesh reaches a state of equilibrium, when the average particle movement is less than a given defined threshold.



^ Above: Fig. 104. Developed mass spring locking system with sphere coliders. (Author)
Below: Fig. 105. Developed Grasshopper simulation Script (Author)

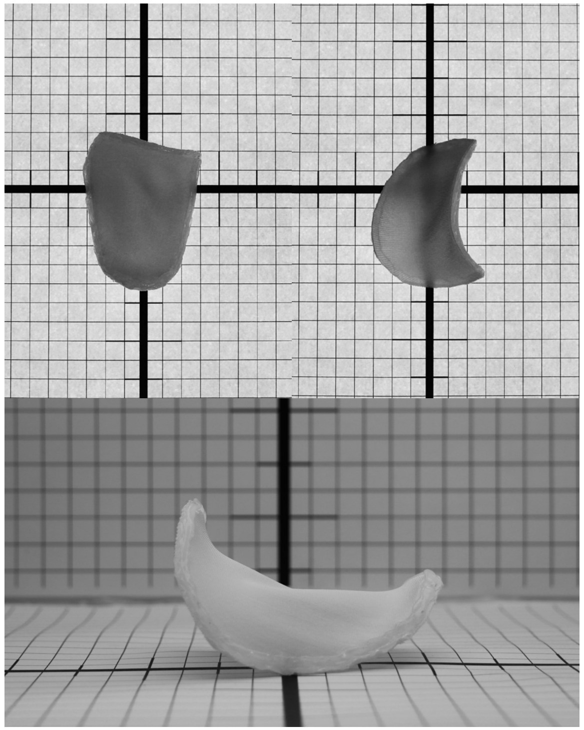
.4.0.7.

Digital/ Physical Evaluation

Comparing Studies

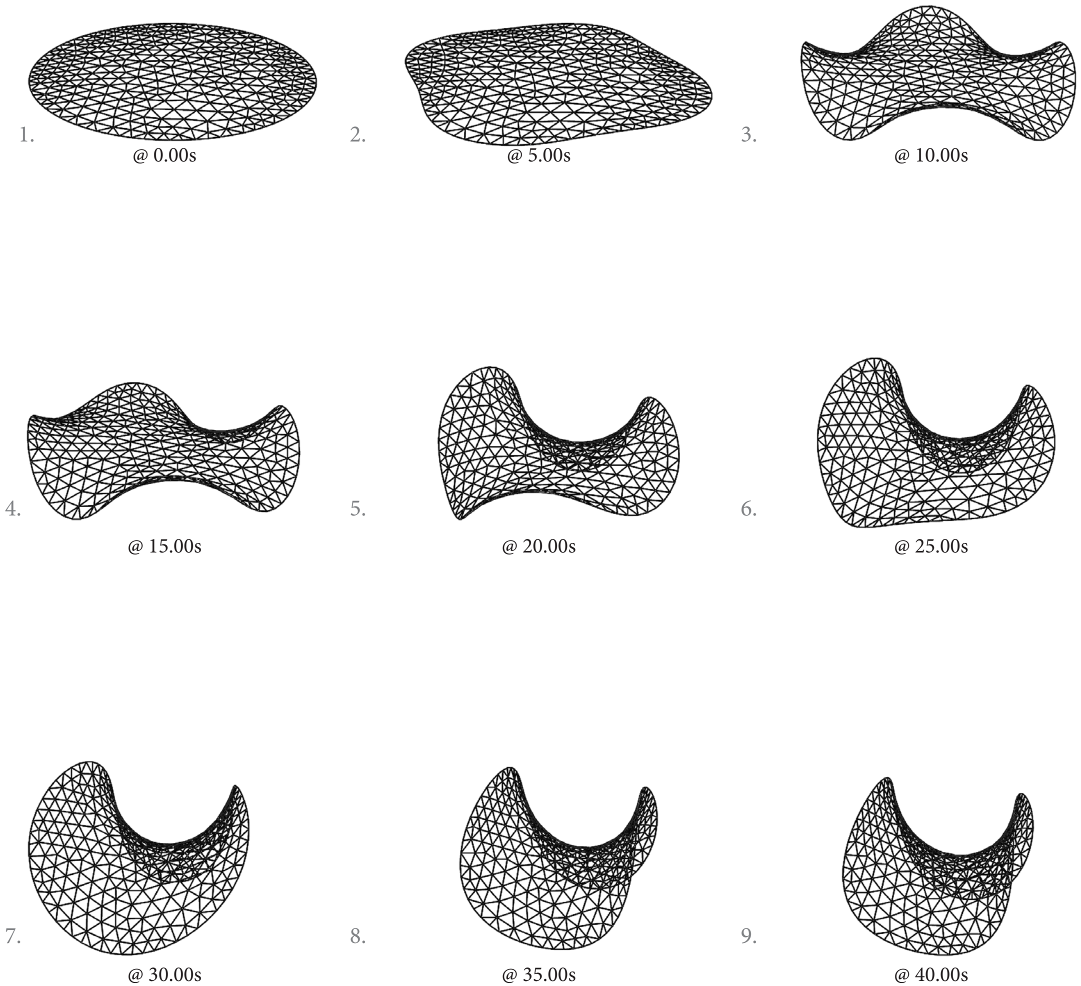
The developed definition is tested to study its accurateness at predicting the patterns effect on the emergent tensegrity form. This is done through comparing them against the previously completed physical models.

Goal Surface



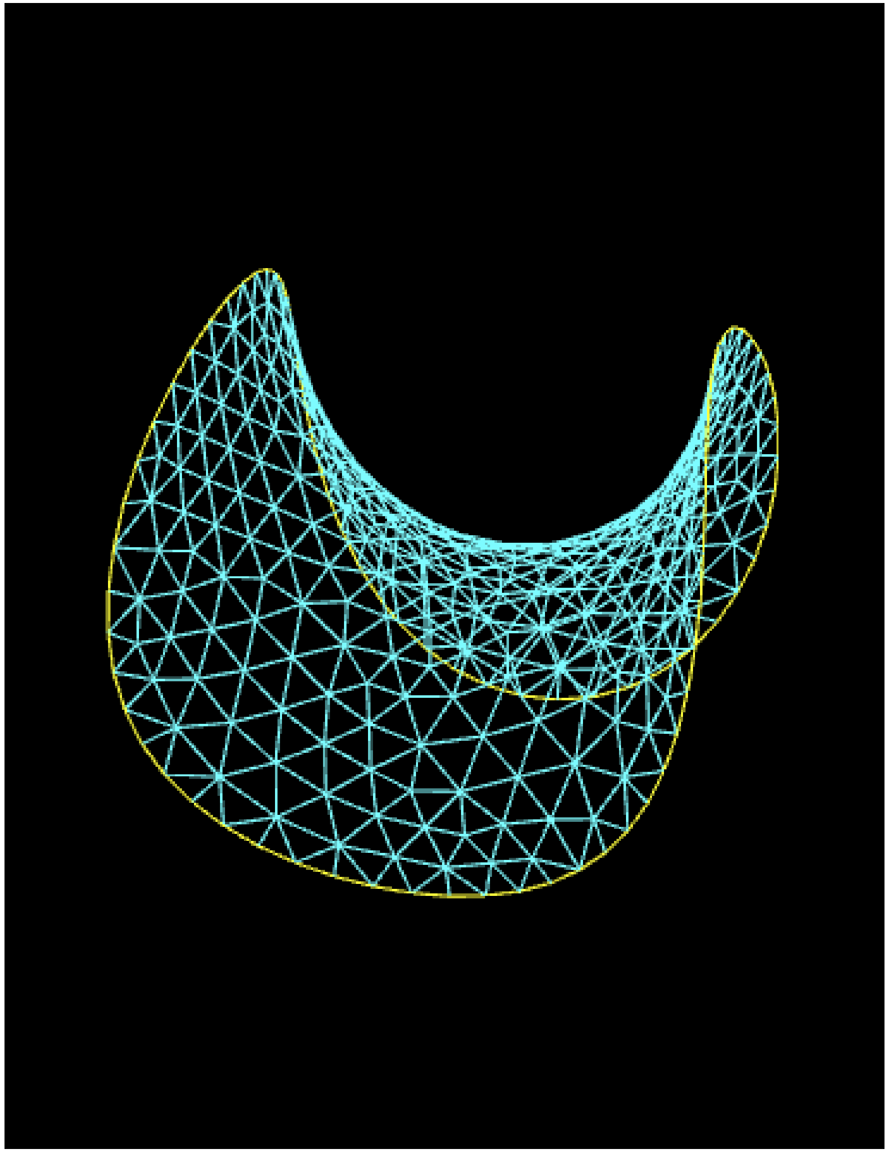
< Fig. 106. 'Goal' Surface Geometry (Author)

Simulation Frames



^ Fig. 107. Simulation Frames (Author)

Final Simulation Result



< Fig. 108. Final equilibrium simulated surface (Author)

Analysis

The simulation proved to be reasonably accurate and true to the real material performance, although multiple limitations were made apparent through the definitions development and simulation attempts. These include:

1. Computational Requirements: simulations can take more than 10 minutes each due to the large number of iterative calculation happening each time step, this can even lead to the simulation crashing.

2. Overlapping geometries: In some simulations, the surface would self-intersect to find an equilibrium, this could be solved through further technical development of the definition but would further the computational cost.

3. Sticking: in some cases, the spring mesh would self-tangle and lock when the surface exhibited a decrease in tension. This became problematic if the surface was still in the process of finding equilibrium, leading to false emergent forms. Once again this could be resolved through creating a thicker mass spring mesh at the cost of computational power.

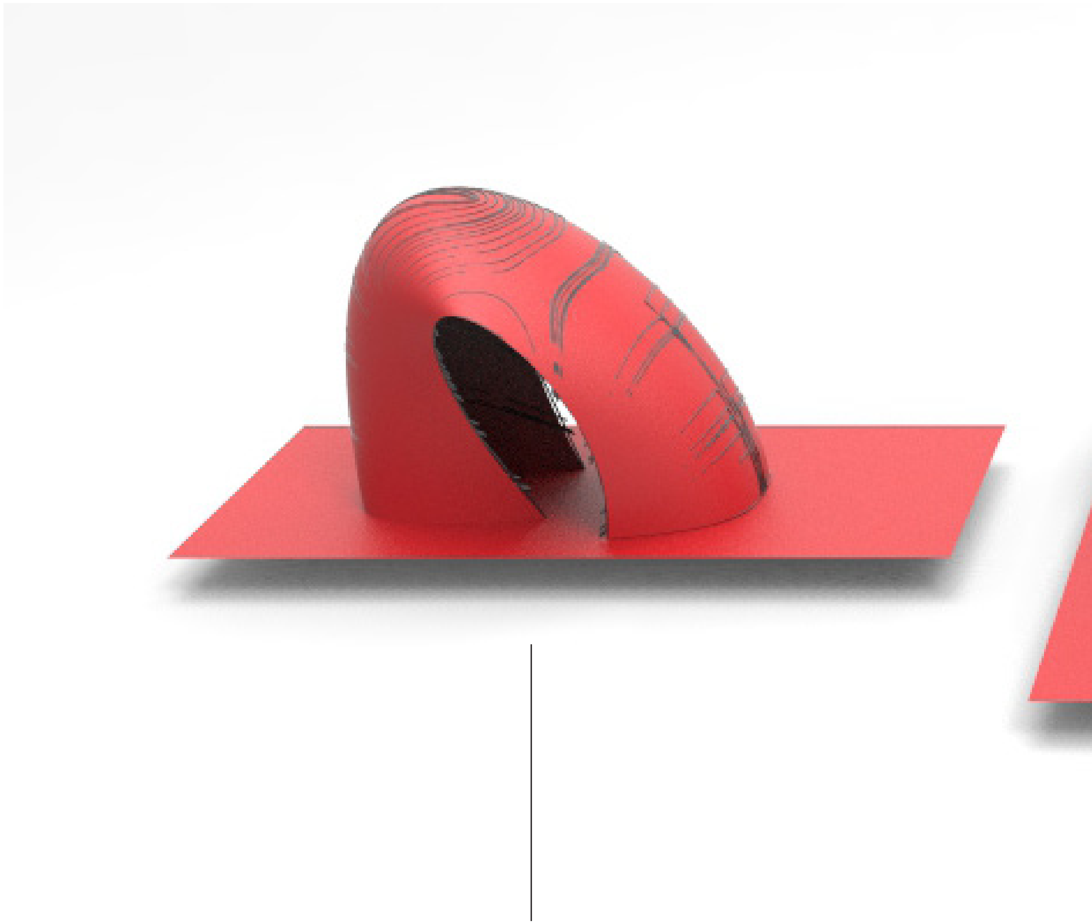
.4.0.8.

Architectural Implementation

The ultimate goal of developing this method of 4D printing, was to examine the potential for it to disrupt conventional CAD/CAM workflows, through testing its ability to be implemented at an architectural scale.

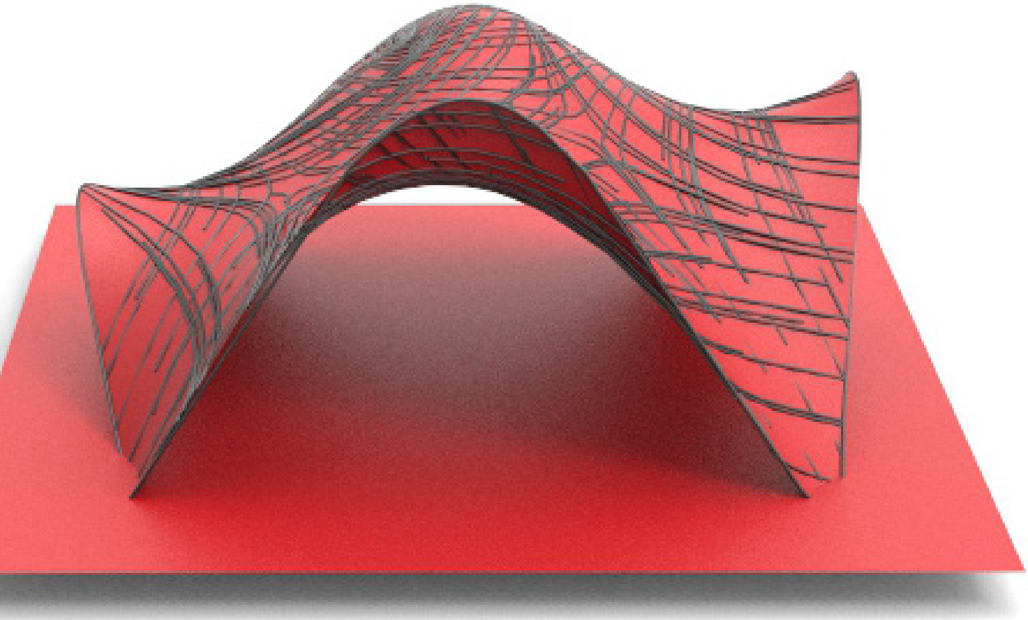
Here, this research provides a conceptual application for this method of fabrication within non-conventional construction environments, through the design of a rapidly deployable, self-assembling tensegrity surface structures from controlled pattern deposition.

Principal curvature patterns are derived from the goal target surfaces, and mapped upon the unrolled fabric. representing the required printing resin paths. The release of the print is then simulated within Grasshopper to check the patterns successfulness in achieving the goal surface.

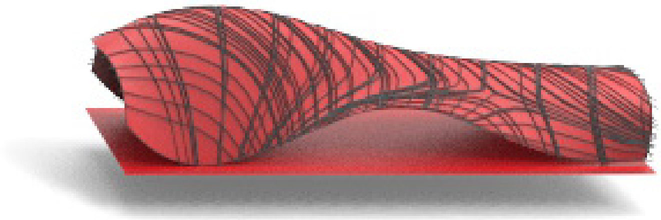


1. Private Shelter

^ Fig. 109. Series of Concept Printed Surface Structures (Author)



1. Pavilion

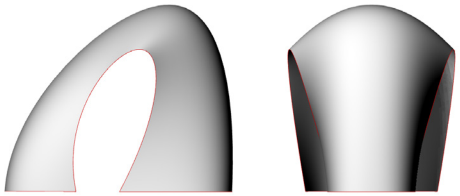


3. Sleeping Shelter

.4.0.9.

1. Privacy Structure

Target Geometry



Print Pattern

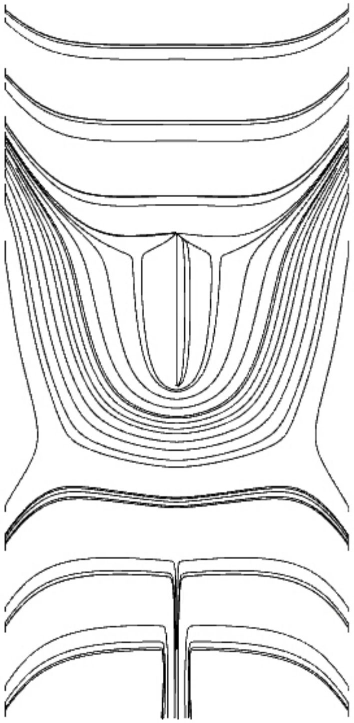


Fig. 110. Goal Surface (Above) Derived Pattern (Below) >

Release Simulation

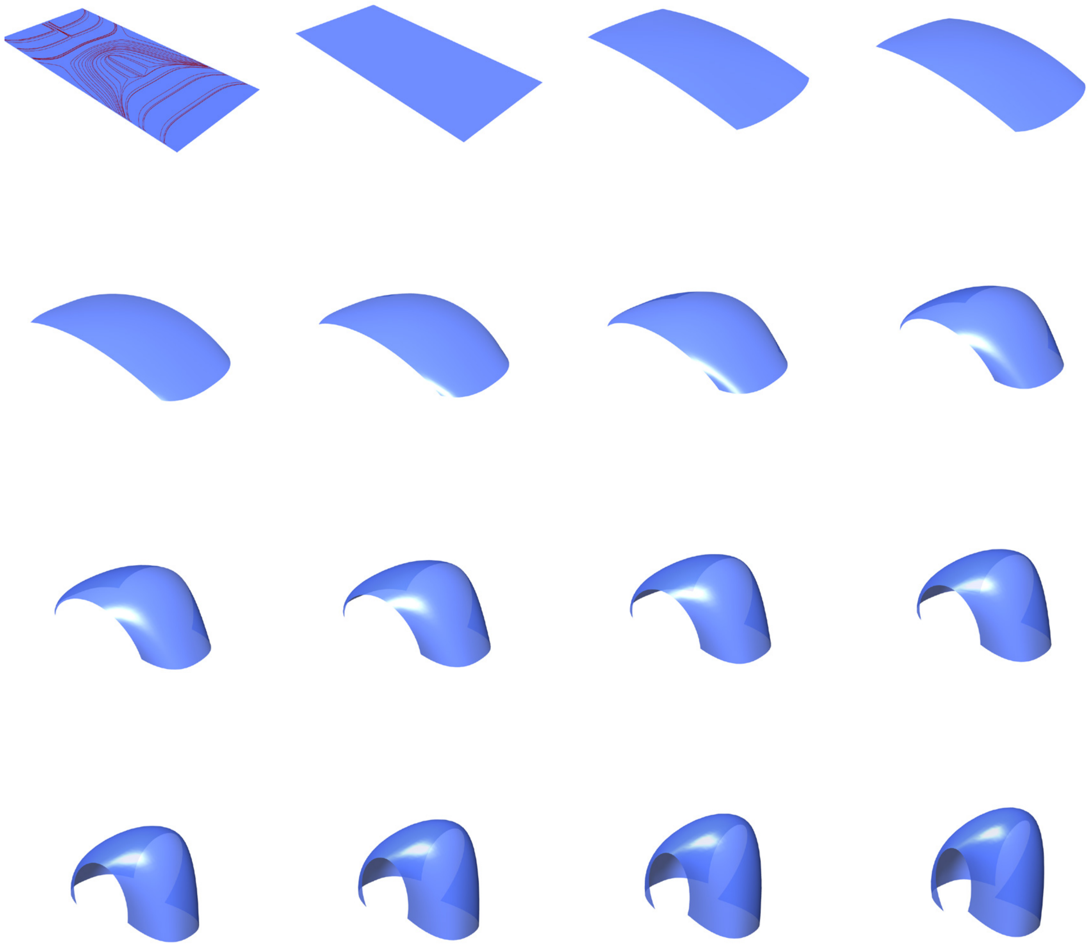


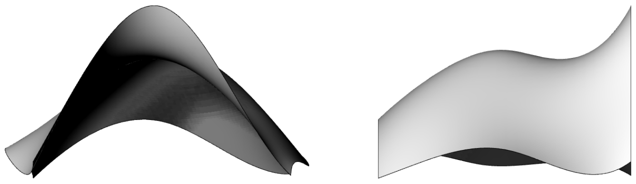
Fig. 111. Fabric Release Simulation ^

Fig. 112. Private Shelter Structure Render (Author) >>


Lee

2. Pavillion

Target Geometry



Print Pattern

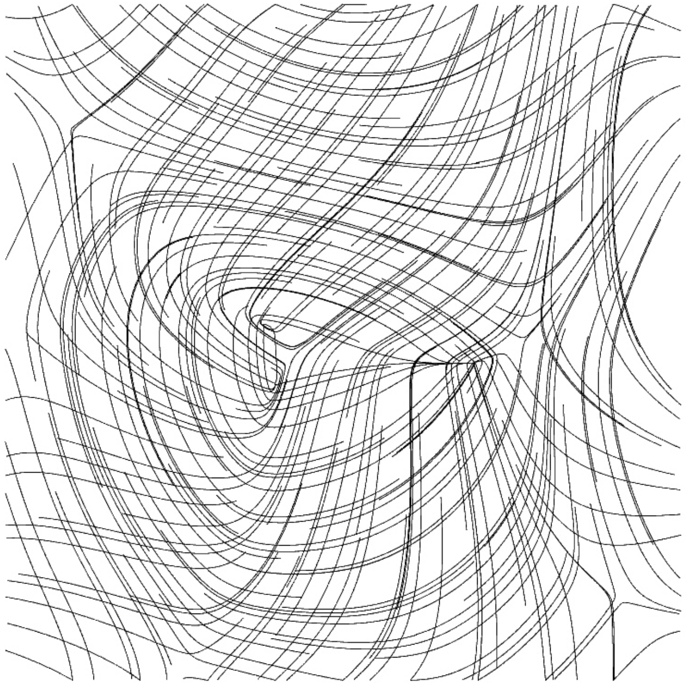


Fig. 113. Goal Surface (Above) (Author) Derived Pattern (Below) (Author) ^

Release Simulation

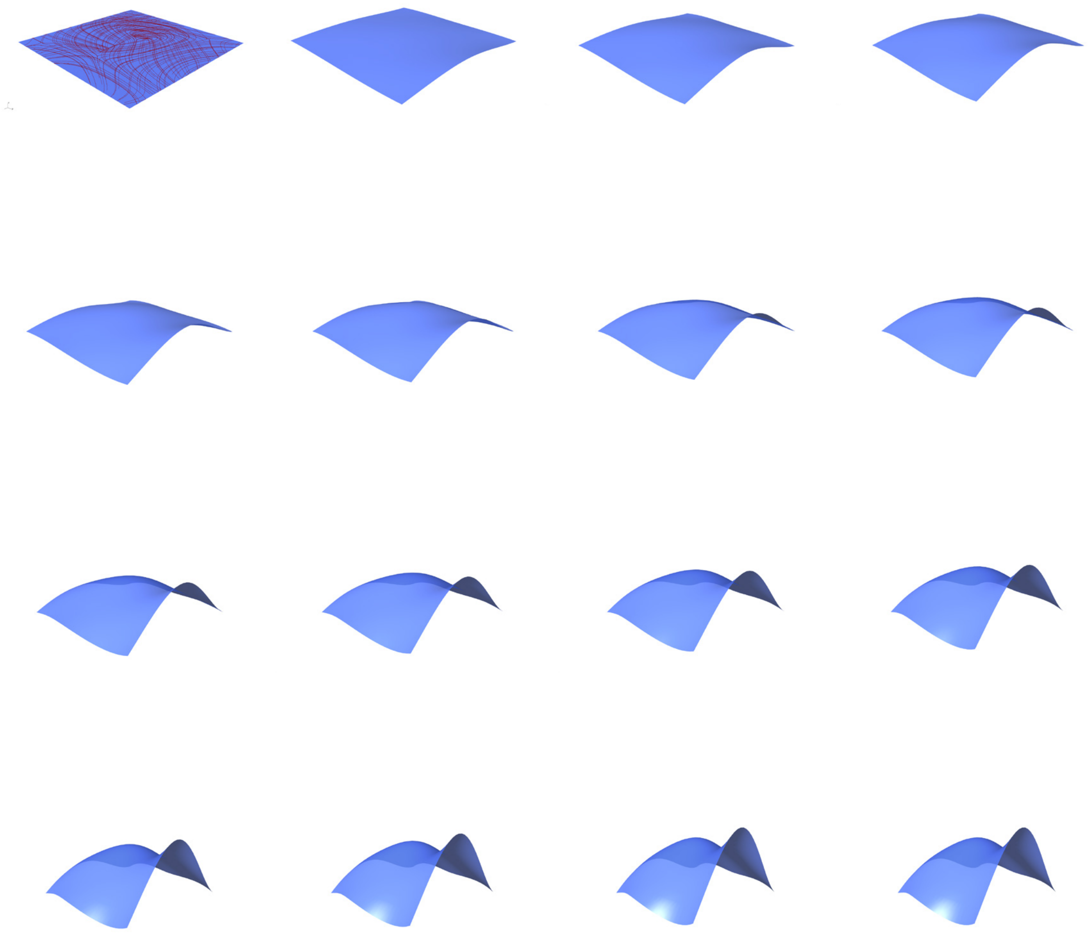


Fig. 114. Fabric Release Simulation (Author) ^

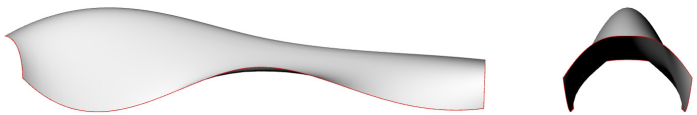
Fig. 115. Pavilion Shelter Structure Render (Author) >>

. 4 . 0 . 11 .

2. Pavillion

Release Simulation

Target Geometry



Print Pattern

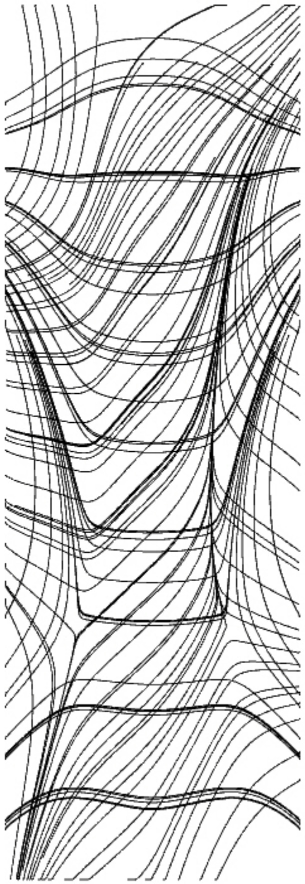


Fig. 116. Goal Surface (Above) (Author) Derived Pattern (Below) (Author) >

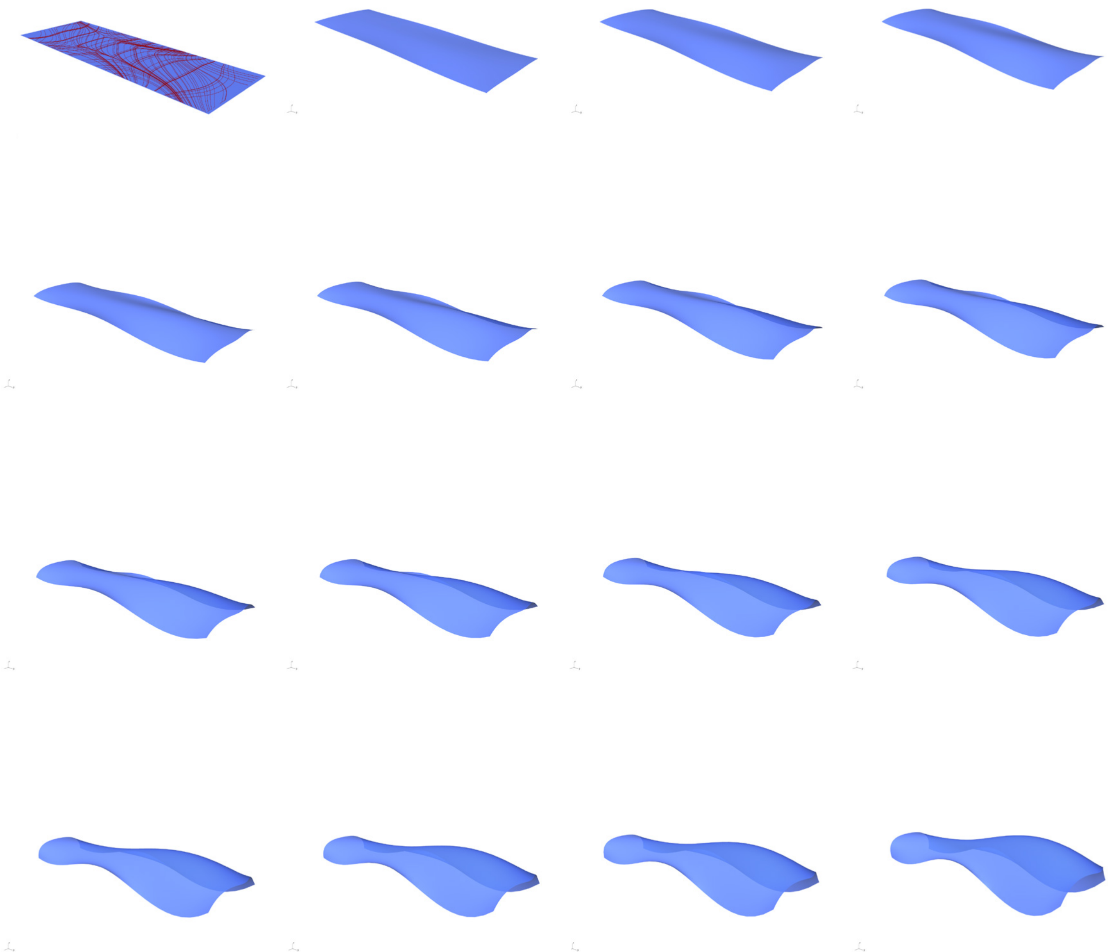


Fig. 117. Fabric Release Simulation (Author) ^

Fig. 118. Sleeping Shelter Structure Render >>

. 4 . 0 . 12 .

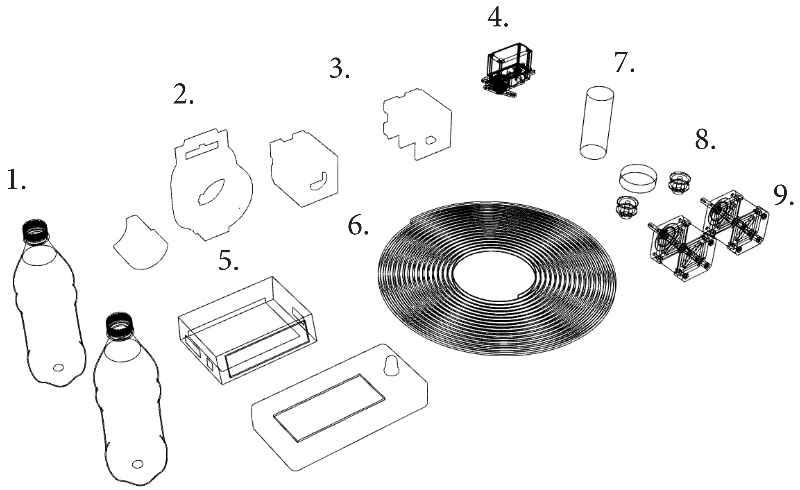
Prototype 4 D Printer

A New Fabrication Method

A prototype 4-D Printer was designed and assembled as a 'proof of concept' for the proposed, large scale 4D printing. The printer consists of a pulley 'spider-cam' nozzle system driven by two vstepper motors that receive g-code (coordinate instructions) by a RAMPS 1.4 stepper driver on an Arduino Mega motherboard.

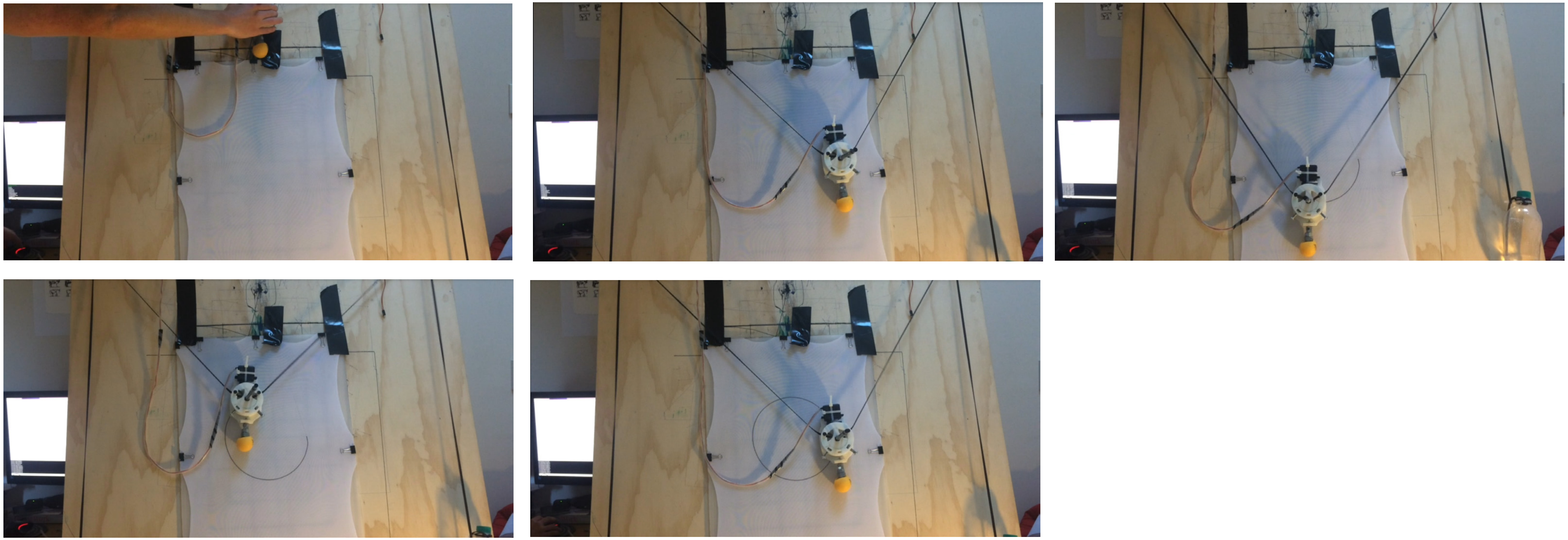
The printer was designed to be setup up on any erect surface, via either suction cups or motor mounts so that rapid prototyping could be constructed at large scale onsite. The printer can run from either USB connection, or via SD card, meaning g-code files can be sent and uploaded freely.

Fig. 119. 3D Model of Printer Design >



1. Bottle Weights
2. Gondola
3. Motor Mounts
4. Servo Lift Motor
5. Motherboard
6. Belt
7. Resin Capsule
8. Pulleys
9. Stepper Motors

Fig. 120. Printer Components (Author) >



^ Fig. 121. Printer Tool
Pathing (Author)

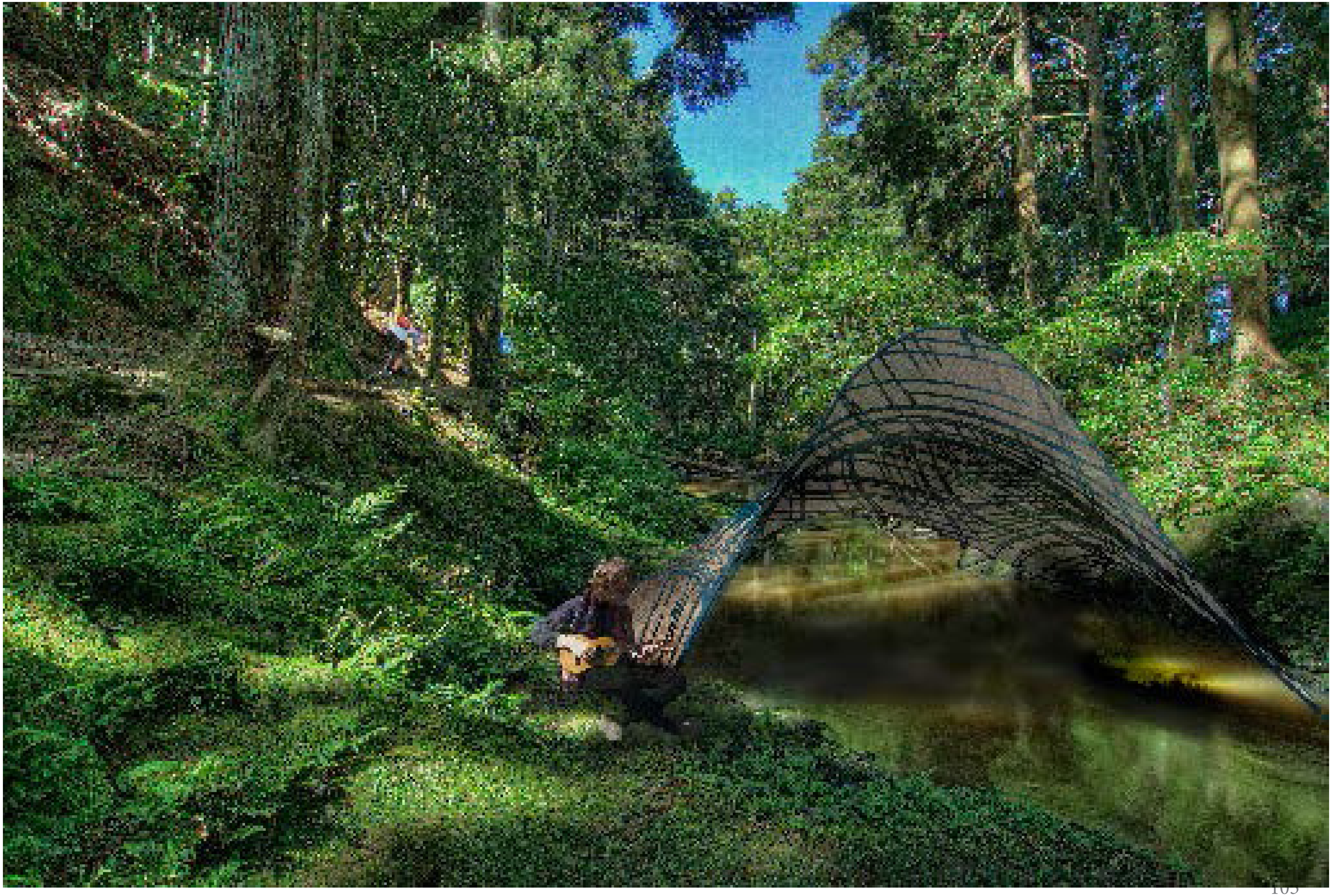
Reflection

Although speculative, this novel fabrication method targets greater efficiencies in the production of geometrically complex shell structures.

The cost of construction is greatly diminished, both due to optimized material efficiencies, and the reduction of shipping material to site. These surface structures necessitate no previous construction knowledge and a rapidly deployable once the resin has dried.

Additionally, the resultant geometry could be further stiffened through the application of a secondary resin coat once the new structures equilibrium is found. In doing so will effectively freeze the surfaces state whilst and also providing further protection from the external elements.

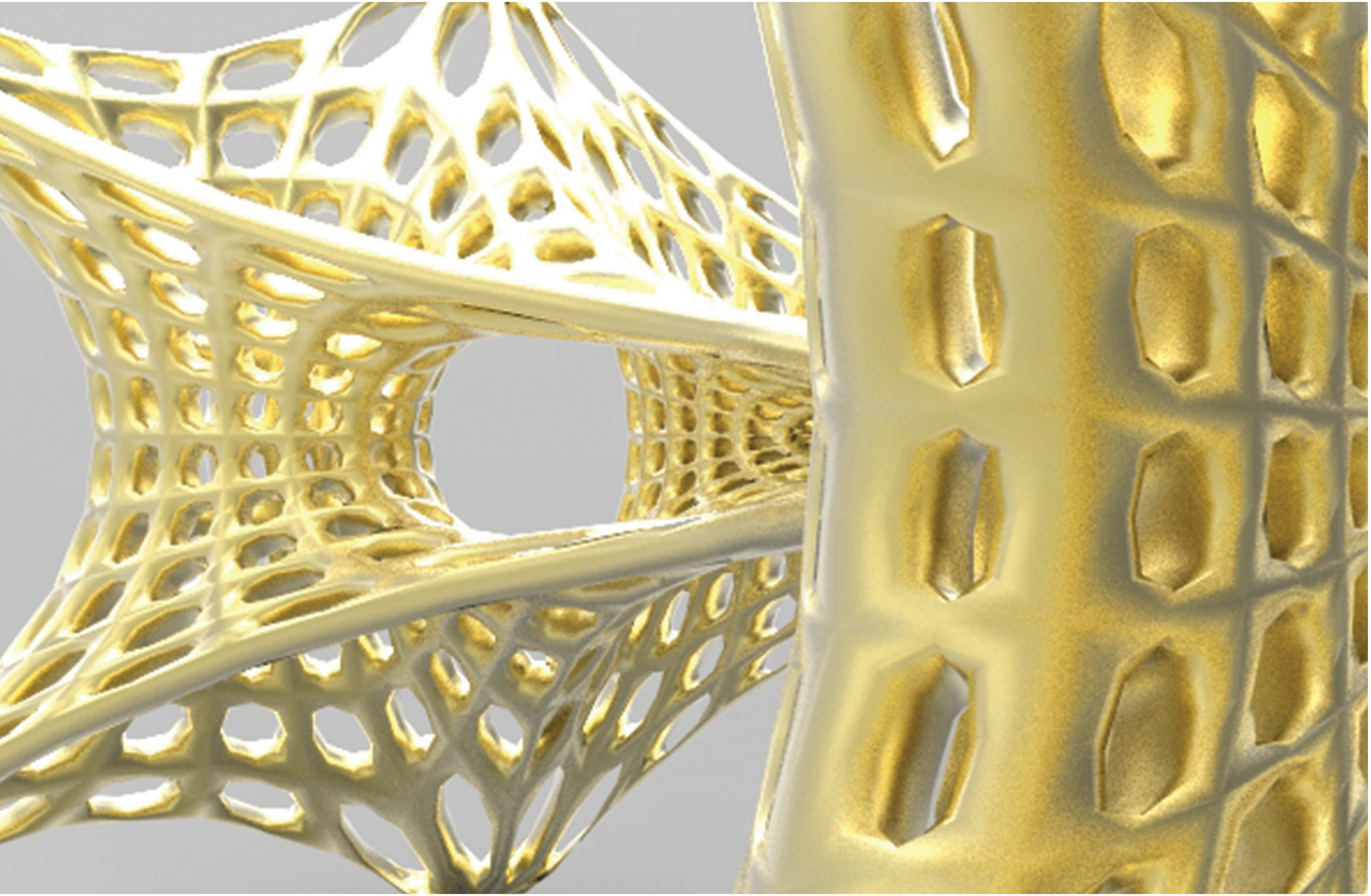
Fig. 122. Shelter Render (Author)
>>



.5.0.0.

Critical Reflection

Fig. 123. Surface Exploration (Author) >



.5.0.1. Conclusion

This design research seeks to answer the question "How can biological theories on growth disrupt the inert material perception within the current discourse of 3D-printing architecture?" This research looks to reinterpret the application of additive manufacturing technologies to the architectural field through a biomimetic lens. It looks to nature and asks how it achieves structures with far more complexity, information capacity and assembly efficiencies, than even the most advanced forms of fabrication technology available today.

The application of additive manufacturing workflows to the architectural industry holds a lot of potential to provide a fabrication solution for the fluid, complex geometrical forms, that are synonymous with computational design. Unfortunately, most contemporary attempts of mass fabrication of computer generated design have thus far resulted in both money and time expensive forms – forms that require the complex assemblage of a massive array of materialistically homogenous, inert components by construction specialists. This research looks not to the machine, but to the material for opportunities to further democratize 3D printing within architecture. It asks 'how does material perform?' 'Can the performance of material be predicted?' And more holistically, 'How do we 'find' material form?'

This design research aimed to develop a synergetic approach to design, whereby material organization and behavior, as they may appear in the digital world, are integrated into the digital design workflow as generative contributors. It has accomplished this through the 'translation' of traditional material form-finding studies, to the digital realm, and exploits the affordances of computation, to extend their design capacity beyond what would otherwise be physically or practically possible.

A key objective of this research was to speculate a novel approach to the fabrication of geometrically complex architectural components. The final design project of this research extends from the findings of the initial translational study of material form finding, to develop a new methodology of 4D printing architecture. This is achieved through the development of a deep understanding of the micromechanics within the material system of pre-stretched fabrics. Through this understanding, the effect of generating conflicting capacities within the fabrics fibers through resin impregnation is studied, and the relationship between pattern and form decoded for reverse engineering.

Overall, this thesis successfully speculates on the capacity of a biomimetic approach to disrupt and further democratize CAD/CAM methods within architecture. By exploring a deeper understanding of physical-digital design workflows, this research fulfills the objectives it had set out to achieve, and contributes to the body of knowledge surrounding additive manufacturing in architecture. Although speculative, the concluding design system exercises a New Materialism based design methodology, providing one example on how in which form can be found.

.5.0.2. Critical Reflection

Throughout the literature review and design exercises, this research examined the works and material perceptions of the great form-finding architects of the 1950s and 60s, and attempted to apply them using contemporary digital design tools. This multi-discipline design methodology provided the advantage of a parallel feedback loop of design and critique. When momentum became stagnated in one realm, there was always an exploration to be conducted in the other. The synergetic relationship between the two realms of design inherently builds a meticulous understanding of the micromechanics of a material, and their effects on the global system, leading to a new perception of material as an active, generative contributor to the design process.

The research and methodology stipulated here contributes to a larger theory of material computation, and it's through a biomimetic lens that practical outcomes are found in response to the issues surrounding additive manufacturing in architecture.

The outputs of this thesis substantiate the results of a sincere attempt to apply notions of form-finding to the digital design environment, and truly exploit the capacities and tendencies that lay dormant within current design and production workflows. Although this research provides a new framework in which complex architecture can be produced, it remains largely untested at the 1:1 scale. This leaves exciting prospects for the future implementation of similar design research, and the fabrication of a truly biomimetic, 4D architecture.

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