Designing Parametric Matter:

Exploring adaptive material scale self-assembly through tuneable environments.

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To my Mam, Dad, Andrew, Tom and Kay

Declaration

This thesis has not been submitted in support of an application for another degree at this or any other university. It is the result of my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated. Many of the ideas in this thesis were the product of discussion with my supervisor Proff. Nick Dunn and Dr Jason Alexander.

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Abstract

3D designs can be created using generative processes, which can be transformed and adapted almost infinitely if they remain within their digital design software. For example, it is easy to alter a 3D object's colour, size, transparency, topology and geometry by adjusting values associated with those attributes. Significantly, these design processes can be seen as morphogenetic, where form is grown out of bottom-up logic's and processes. However, when the designs created using these processes are fabricated using traditional manufacturing processes and materials they lose all of these abilities. For example, even the basic ability to change a shapes' size or colour is lost. This is partly because the relationships that govern the changes of a digital design are no longer present once fabricated. The motivating aim is: *how can structures be grown and adapted throughout the fabrication processes using programmable self-assembly?*

In comparison the highly desirable attribute of physical adaptation and change is universally present within animals and biological processes. Various biological organisms and their systems (muscular or skeletal) can continually adapt to the world around them to meet changing demands across different ranges of time and to varying degrees. For example, a cuttlefish changes its skin colour and texture almost immediately to hide from predators. Muscles grow in response to exercise, and over longer time periods bones remodel and heal when broken, meaning biological structures can adapt to become more efficient at meeting regularly imposed demands. Emerging research is rethinking how digital designs are fabricated and the materials they are made from, leading to physically responsive and reconfigurable structures.

This research establishes an interdisciplinary and novel methodology for building towards an adaptive design and fabrication system when utilising material scale computation process (e.g. self-assembly) within the fabrication process, which are guided by stimuli. In this context, adaption is the ability of a physical design (shape, pattern) to change its local material and or global properties, such as: shape, composition, texture and volume. Any changes to these properties are not predefined or constrained to set limits when subjected to environmental stimulus, (temperature, pH, magnetism, electrical current). Here, the stimulus is the fabrication mechanisms, which are governed and monitored by digital design tools. In doing so digital design tools will guide processes of material scale self-assembly and the resultant physical properties.

The fabrication system is created through multiple experiments based on various material processes and platforms, from paint and additives, to ink diffusion and the mineral accretion process. A research through design methodology is used to develop

the experiments, although the experiments by nature are explorative and incremental. Collectively they are a mixture of analogue and digital explorations, which establish principles and a method of how to grow physical designs, which can adapt based on digital augmentations by guiding material scale self-assembly.

The results demonstrate that it is possible to grow physical 2D and 3D designs (shapes and patterns) that could have their properties tuned and adapted by creating tuneable environments to guide the mineral accretion process. Meaning, the desirable and dynamic traits of digital computational designs can be leveraged and extended the as they are made physical. Tuneable environments are developed and defined thought the series experiments within this thesis. Tuneable environments are not restricted to the mineral accretion process, as it is demonstrated how they can manipulate ink cloud patterns (liquid diffusion), which are less constrained in comparison to the mineral accretion process. This is possible due to the use of support mediums that dissipate energy and also contrast materially (they do not diffuse). Combining contrasting conditions (support mediums, resultant material effects) with the idea of tuneable environments reveals how: 1) material growth and properties can be monitored and 2) the possibilities of growing 3D designs using material scale self-assembly, which is not confined to a scaffold framework.

The results and methodology highlight how tuneable environments can be applied to advance other areas of emerging research, such as altering environmental conditions during methods of additive manufacturing, such as, suspended deposition, rapid liquid printing, computed axial lithography or even some strategies of bioprinting. During the process, deposited materials and global properties could adapt because of changing conditions. Going further and combining it with the idea of contrasting mediums, this could lead to new types 3D holographic displays, which are grown and not restricted to scaffold frameworks. The results also point towards a potential future where buildings and infrastructure are part of a material ecosystem, which can share resources to meet fluctuating demands, such as, solar shading, traffic congestion, live loading.

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1 Introduction

"Gone is the Aristotelian view that matter is an inert receptacle for forms that come from the outside (transcendent essences)."

(DeLanda, 2015)

Physical adaptation and change is universally present within animals and biological processes. Within biology, adaption enables a structure to meet regularly imposed demands more efficiently by altering its properties across its length scales (Oxman, 2012), global to local. Global properties could include: shape, orientation, porosity and local material properties may include: composition, location, volume, orientation, as such they have discourse and interrelationships with one another. Biological processes of fabrication are generated from bottom up strategies, which integrate form, materials and the demands that are subjected upon the materials, meaning each of them act as an active design agent / driver (Oxman, 2010a) and establishes relationships between them. Resulting in shape being interlinked with the forces that act upon them (Vogel, 2003), which enables external forces to inform adaption of the microstructures properties overtime (Vincent, 1982). Currently, these types of interrelationships and adaptive abilities have yet to be fully realised within manufacturing processes or in physical manmade structures, from product scale through to architectural scale, especially across their length scales, from material unit scale, such as molecules, to the global shapes they make-up. In comparison, these shape changing and adaptive abilities have been attained within 3D digital design processes. For example, it is easy to alter a 3D object's colour, size, transparency, topology and geometry by adjusting values associated with those attributes. These transformations are more observable within digital parametric design processes (Jabi, 2013, Burry, 2011, Woodbury, 2010, Schumacher, 2009a, Schumacher, 2009b, Bhooshan, 2017), which manipulates the geometric components of a design and more recently in material based computational processes (Richards and Amos, 2015), where local material properties effect global properties and vice versa, but both can be performance orientated in relation to fluctuating demands, such as, live loading informing: material location, rigidity, volume and global shape (Oxman, 2010b). Significantly, 3D digital design models are almost infinitely flexible if they remain within their digital design software and this raises the question; *how can the digital designs' adaptive abilities be instilled within a corresponding physical representation?* In order to address this challenge this thesis re-imagines manufacturing processes and establishes a methodology for building towards an adaptive design and fabrication system.

The question is broken down in relation to the several predominant components that makeup the proposed adaptive design and fabrication system, the components are: digital design, fabrication and material properties. Each component is narrowed down into research areas that can potentially enable physically adaptive designs, but in order to create discourse and relationships between them material platforms, process and mechanisms must be identified.

Design

As mentioned previously advancements in computer aided-design (CAD) software and methods have produced adaptive models, which is primarily and more efficiently achieved if its components (geometries or materials) have a relationship between their attributes (shape, size, colour, texture, location) and relevant values and or demands, such as, structural, environmental, aesthetic. For this reason, the three main relationship based design processes that will be disused are: 1) (Burry, 2003, Woodbury, 2010), 2) material based design computation (Oxman and Rosenberg, 2007a, Oxman, 2010a) and 3) gradient based designs (Oxman, 2011b, Richards and Amos, 2016). These processes of design generation have been chosen because: A) they create models which can change their attributes (size, texture, colour, density among many others) on the fly, by generally altering: numerical values, data sets or criteria constraints. B) They enable adaptation across dimensions and scales. Meaning, the 3D global shape can adapt based on its local material properties as demands fluctuate. C) Generating solutions based on relationships between multiple design demands, a model's attributes and material properties creates integrated (meet multiple demands) (Wiscombe, 2012), heterogeneous (multiple material properties) (Oxman, 2010b) and or anisotropic (mechanical properties vary along axes / material orientation) (Oxman et al., 2012) designs. The digital design strategies surveyed increase in resolution sequentially, which provides insight into what types of physical material properties could be guided by digital design tools when physically growing an object, shape or pattern.

Fabrication

A primary reason for the adaptive inabilities of the artificial is due to traditional design and fabrication processes, where inert materials are used (Spiller and Armstrong, 2011a) and traditionally form is imposed upon them (Armstrong, 2014). As a result, the relationships between design, fabrication and materials become separated into linear stages. Conversely, biological processes demonstrate this does not have to be the case. Biological structures can tune and adapt material properties and shapes physically. Cuttlefish and octopus notably demonstrate this ability. They can change both their skin colour and texture, to avoid detection from predators (Panetta et al., 2017). DeLanda's 'new materiality' also conceptualises how material states and behaviours can vary as they are interacted with or reach threshold conditions (DeLanda, 2015). Understanding that materials are not truly homogeneous and can compute forms when subjected to varying conditions, for example, loading or tension, enables their dynamic and shape changing capacities to be leveraged. With these notions of materiality and precedent of biological processes in mind design and fabrication processes are remained, in regards to how materials can be interacted with by engaging with material processes, to achieve: 1) a discourse between digital design tools and materials and 2) physical adaptation.

Materials

In order to begin to engage with, manipulate and guide material processes to achieve physical adaption, a suitable material process must be identified. Material self-assembly (here after SA) is chosen because: a) it is scalable and can be witnessed from molecular scale to planetary weather system (Whitesides and Grzybowski, 2002). B) The global properties a design are based on its local material interactions, which give rise to emergent properties (De Wolf and Holvoet, 2004) that could be highly desirable. C) Occurs within multiple material platforms, which will be explored within the experiments. Reimagining design and fabrication processes by incorporating SA materials raises the question; *how can physically adaptive 3D designs' be created, which could adapt their local and global properties (shape, pattern, texture, volume) by guiding SA material interactions via digital design augmentations?*

The rethinking of design and fabrication processes aligns with an emerging area of research, Active Matter. Active Matter focuses on creating physical materials, at various scales (from nano to meso), which can "self-assembly, transform autonomously, and sense, react, or compute based on internal and external information...", resulting in 'programmable matter', which is; "a material that has the ability to perform information processing much like digital electronics" (Tibbits, 2017a). Active matter focuses on the phenomena and mechanisms of SA, which provide a means of collaboration between diverse fields of research, from material science, micro robotics to biochemistry and meteorology.

Current research in the area of design and self-assembly has established multiple methods, material types and a recipe for the required ingredients to achieve objects and structures that can SA. The defined ingredients are: *"I - Materials and Geometry; II - Mechanics and Interactions; III - Energy and Entropy* (Tibbits, 2016). The resultant structures leverage desirable abilities such as: scalability (Tibbits, 2012b), reconfiguration (Papadopoulou et al., 2017) and responsiveness (Tibbits, 2014a). The two main strategies used here are: A) individual material components having predefined geometries and interfaces to govern self-assembling interactions. B) Units with defined composite materials and or material orientations are fabricated by depositing them during additive manufacturing processes and has led to the term 4D printing. Both of these strategies address challenges of creating a robust fabrication process by self-error correcting when subjected to noise, by predefining the material components properties, i.e. geometries and interfaces or material location, orientation and composition. They are robust as these processes have multiple assembly possibilities but can still fabricate objects with defined functions (deterministic). On the other hand, the defined components only afford a degree of flexibility when exploring shapes that have not been defined (non-deterministic) (Tibbits and Flavello, 2013).

Energy in these systems is used as a way to alter environmental conditions, which enables varying conditions to initiate SA. However, the parameters of the various energy types used (magnitude, direction, intensity, duration) is not governed or varied throughout the assembly process, it as random in essence. As it is a defined ingredient within this system it has a significant impact on SA processes. As such, the experiments carried out in this research explore how varying properties of energy within these SA systems can be achieved so it becomes an informed material stimulus that guides interactions. The two primary reasons for exploring how varying environmental conditions, so they can act as a stimulus are: 1) its abilities to generate both random patterns and desired crystal shapes and 2) its ability to link digital design tools with fabrication and materials in an iterative system is established by Ayres (Ayres, 2011).

The first point can be witnessed in several examples that range from art, meteorology and micro-crystal growth. Artist Hall asks how can a painting be grown and creates 2D dynamic paintings, which are generated from multiple paint mediums and how stimulus impacts their interactions (Hall, 2014). Meteorological behaviours can also be witnessed in self-assembling 3D ink patterns in Illari's 'weather in a tank' experiments (Illari et al., 2009). These first two examples are more random patterns. However, deliberate micro-crystal shapes (from vase-like to coral-like) can be grown by varying conditions over time (Grinthal et al., 2016, Kaplan et al., 2017). These material platforms demonstrate high degrees of freedom for possible designs at various scales and dimensions without using predefined geometries or locations of material compositions but they are not governed or manipulated by digital design tool amendments. The second point is established by Ayers *persistent modelling* strategy (Ayres, 2012b), where predefined metal components are physically deformed by inflation, which is governed by a digital design representation that controls and monitors the internal pressure the sheets are is subjected to.

By employing physical stimulus as the method to guide material scale SA the notion of tuneable environments is explored and developed in order to build towards an adaptive design and fabrication system. In doing so, it is possible to grow 3D shapes and patterns from SA materials that can also be adapted. The thesis defines 'tuneable environments' as a set of physical stimuli (e.g. temperature, pH) that are adjusted by digital design tools to alter the conditions of a volumetric space that contain self-assembling materials. The stimuli define the fabrication process and effect material interactions and properties. The use of stimulus allows engagement with material scale SA, raising new challenges, such as accuracy. However, material scale SA also affords highly desirable potentials, such as the ability to adapt and tune both the global and local properties of a display, object or structure (e.g. shape, location, volume and composition). Tuneable environments are used to establish and develop interrelationships between design, fabrication and materials. Meaning digital augmentations can now be physically produced. The methodology is explored across two material platforms, via multiple explorative experiments. Principally, the mineral accretion process (Hilbertz, 1979), which is the electrolysis of seawater. Here material aggregation is used to grow materials on 2D and 3D cathode scaffolds. Secondly, 2D and 3D liquid diffusion are employed to understand how to guide material scale self-assembly without being globally constrained to 2D and 3D scaffolds.

The thesis contributes towards rethinking design and fabrication processes, in order to begin to create physical designs which can leverage adaptive abilities. This will lay foundations for a range of applications, such as physically growing new types of 3D holographic displays, medical procedures where splints are directly grown onto a patient's broken limb, or even a material ecosystem where buildings can adapt and share resources.

1.1 Aim

Currently there is a separation between the feedback of digital design models and the final physical objects or structures created from them, i.e. any augmentations to the digital design models are not reflected, or materialised in the final physical design once they have been fabricated. The loss of feedback and the inability of physical objects to update their properties (shape, colour, texture, composition) is particularity evident in relationship based digital design models / processes. For example, digital parametric models can be easily altered by changing values assigned to attributes of the design. The attributes and parameters can also be interlinked, meaning they have relationships. Significantly, these easy to make digital manipulations and relationships are completely lost or significantly reduced in the physical objects because of traditional fabrication processes.

The overarching aim of this thesis is to connect and instil the dynamic properties of digital design tools back into the materials that makeup the corresponding physical shapes and patterns, so any digital augmentations are iteratively fabricated. In order to achieve this, a design and fabrication strategy is established, which enables feedback between digital design tools and material scale SA, so designs' can be physically grown and manipulated in 2D and 3D. As a result, design and fabrication processes are tightly linked, which enables physical objects to tune and adapt their properties across scales and dimensions. Developing these processes will further an understanding of how digital design tools can be used to monitor, guide and manipulate the interactions of self-assembling materials, so digital augmentations are physically produced.

In order to begin and address the overall aim, a series of sub questions are defined that will be explored by surveying current literature and by carrying out multiple design experiments. The literature reviewed will help to identify design and fabrication strategies, mechanisms and material processes to base and develop initial experiments upon. The experiments are iterative and informed by a continued review of literature, which will help establish a process and material platforms capable of maintaining interrelationships between digital design, fabrication and material scale SA. The aim and series of objectives are:

Aim

How can structures be grown and adapted throughout the fabrication processes using programmable self-assembly?

Objectives

1*) To understand how digital design tools can guide material scale self-assembly.*

2) To identify material platforms that can grow 2D and 3D shapes or patterns and adapt them.

3) *To establish a design and fabrication methodology that creates interrelationships between properties of design, fabrication and material scale self-assembly*

1.2 Thesis Overview

The thesis contributes towards establishing a novel methodology, which is used to govern material scale SA, informed by digital design augmentations. The thesis relates to and extends research carried out in architectural SA (Tibbits, 2016). This is achieved by understanding how design, fabrication processes and materials can have a discourse with one another by initially surveying the analogue parametric experiments carried out by Frei Otto. The literature review then goes on to document advancements within these respective areas to determine synergies, potentials and a framework for developing an adaptive design and fabrication system. Taking principles from Otto's experiments enables digital design tools to engage directly with materials by via the mechanism of manipulating environmental stimulus. The literature review forms a sound theoretical basis for developing and carrying out informed experiments, which explore potentials highlighted within the literature. The experiments are used to establish a methodology for creating an adaptive design and fabrication system based on material scale SA processes, in particular the mineral accretion process, by addressing challenges that emerge. Finally, potentials and applications are highlighted based on the overall discoveries.

1.3 Chapter Summaries

To provide a more detailed overview, this section provides a brief summary of each chapter in this thesis.

Chapter 1: Introduction

Chapter 1 introduces the main components of the thesis along with the aim and objectives of this thesis. It also provides an overview of the research and experiments carried out.

Chapter 2: *Foundations for Adaptation*

The chapter examines analogue and *Computer Aided Design* (CAD) processes, which are capable of generating and altering material properties, shapes, patterns, organisations and structures. The analogue models examined are those of Otto's form finding experiments. These analogue models are able to respond and reconfigure based on stimulus and initial conditions, which help to understand material computational abilities, relationships and how they are sensitive to stimuli. Comparatively, the CAD models can respond or adapt to associated numerical values or performance criteria. The CAD strategies examined increase in resolution as the initial strategies examined are based on geometric (boundary representation) compared to the later strategies, which are able to programme the designs matter. Significantly, through the abstraction of the digital processes they are removed and separated from the physical materials, meaning any changes that occur to the digital representation post production are not physically reflected. This chapter highlights how properties of digital tools could be reconnected with physical materials.

Chapter 3: *Fabrication Processes & Searching for Material Computation*

The chapter examines a range of *Computer Aided Manufacturing* (CAM) processes, from 3D printing to robotic fabrication. CAM processes are capable of fabricating design changes on the fly. Meaning, digital design changes can be accommodated and physically reproduced in real-time. However, the materials are typically treated as inert and do not leverage or engage material computational abilities. Meaning the materials themselves cannot self-assembly or self-heal when conditions are imposed upon them. For this reason various CAM process that begin to engage with material computation processes are examined to understand how fabrication processes can guide and or monitor material interactions.

Chapter 4: *Linking the Digital & Physical*

Ayers demonstrate how *'Persistent Modelling'* maintains relationships between digital representations and physical representations, where digital design models can be used to deform the physical model / structure. This strategy establishes that inducing stimuli (e.g. water pressure, temperature) can link digital design tools with physical materials. For example, the stimuli is controlled, monitored and represented by the design tool, which manipulates physical components properties / material properties. However, design tools based on boundary representations cannot account for actual physical material generated as the design model treats materials as homogeneous. Additional digital tools and strategies are reviewed to understand how they can engage with and guide physical material interactions by basing the design tools on physical material properties and processes.

Chapter 5: *Searching For Material Platforms*

This chapter examines a range of approaches to self-assembly, from self-sensing robotic units to programmable matter. Typically, these self-assembly strategies are based on either: 1) defining the material components properties (geometries and interface connections) or 2) *'programming matter'*, where the structures material properties are defined through 3D printing processes or composite laminates, which enable structures to respond to conditions. Both these strategies predefine the structures material properties, which can lead to restricted resolution in the material system, recursive patterns and predefined responses. In order to address these issues alternative material platforms, which perform self-assembly are reviewed. In particular, generative painting processes by Perry Hall, ink diffusion and the mineral accretion process. All of which perform material computational process on the material scale when subjected to stimuli and do not have properties of their material units predefined. For these reasons these material platforms are used within experiments carried out in this research as they can be used to develop and adaptive fabrication system.

Chapter 6: *Methodologies*

Chapter 6 discusses why a *Research through Design* (hereafter RtD) methodology has been employed and how it facilitates the exploration and developments of an adaptive design and fabrication through iterative practice based prototyping. A strategy of exploration commonly employed within the field of architectural research. Importantly, the limitations of RtD are also discussed in the context of the prototypes developed but these limitations can be addressed through interdisciplinary collaboration, which is enabled due to the nature of physical prototyping acting as artefacts / boundary objects. Additionally, methods of material analysis and why they have been chosen are discussed.

Chapter 7: *Design Experiments, Results & Conclusions: Buildings Towards an Adaptive Design and Fabrication System Using Mineral Accretion.*

The iterative development, results and key findings from the series of mineral accretion experiments are presented and discussed within this chapter. Critically, this chapter documents the development towards an adaptive design and fabrication system. Significantly, the system is developed by inducing a stimulus (voltage), which results in a design and fabrication process based on interrelationships. Monitoring these resultant effects highlights feedback mechanisms. Examining the experiments parameters and interrelationships gives rise to the notion of growing, tuning and adapting structures using *'tuneable environments'*. Although feedback is achieved within the system, a key limitation is that the structures are constrained to the shape of the cathode scaffolds. It is questioned if tuneable environments can be used to guide material computational processes / self-assembly without the need for predefined scaffold structures.

Chapter 8: ***Contrasting Materials: Moving Away From Scaffolds***

This chapter explores how tuneable environments can be used to guide material computational processes / self-assembly without the need for predefined scaffold structures. The results and key findings from a series of 2D generative paint and 3D ink diffusion experiments are presented and discussed. Significantly, the results establish tuneable environments can manipulate generative 2D and 3D patterns. However, it is also established that contrasting material are needed as they can act as a semi-rigid scaffold, which highlight how reproducible patterns and properties can be generated. Additionally, within the 3D ink diffusion experiments the material properties (e.g. density and viscosity) of the contrasting materials not only facilitate more subtle material manipulations but also simultaneously generates; gradient-based, multi-dimension, multi-scale, multi-material properties. These material abilities re-imagine 3D printing processes, which are no longer based on layer-by-layer form generation but instead, a rapid volumetric fabrication process.

Chapter 9: ***Conclusions and Key Discoveries***

Chapter 9 reflects on the series of experiments as a whole as specific conclusions are discussed following each individual experiment. The chapter discusses the research contributions, the key findings and finally how it explored the research aim by employing a *research through design* methodology, which highlights new approaches an benefits of a design and fabrication process based on interrelationships, which are created through '*tuneable environments'* and understood through feedback mechanisms.

1.4 Experiments and Mapping Strategies

The literature surveyed combined with the experiments carried out within the thesis are used to answer the above questions. The experiments have been explored and carried out under a research through design methodology. The experiments are also explorative and iterative by nature as they require an understanding of how physical parameters (e.g. temperature, pH, diffusion rates, agitation) of the material platform can be used to guide material scale SA, it's interactions as well as local and global material properties e.g. volume, texture, lactation, shape or pattern. However, the experiments are created by combining multiple strategies and methods from various fields of research, in particular: design, computer science, additive manufacturing, electrical engineering and chemistry. As a result, the design and fabrication methodology developed throughout this thesis is only possible from carrying out interdisciplinary research. Figure 1 documents, at a higher level, the various material platforms used and the mechanisms (stimulus) used to engage with the material platforms processes of self-assembly. It helps to clearly map the series of experiments, which develop a range of stimulus based fabrication systems. Figure 1 is structured on the fabrications systems components, which are: 1) material *ingredients* 2) design *instructions* and 3) fabrication *stimulus*. Finally, figure 1 highlights the degree of feedback within each of the experiments as they develop and build towards an adaptive fabrication system.

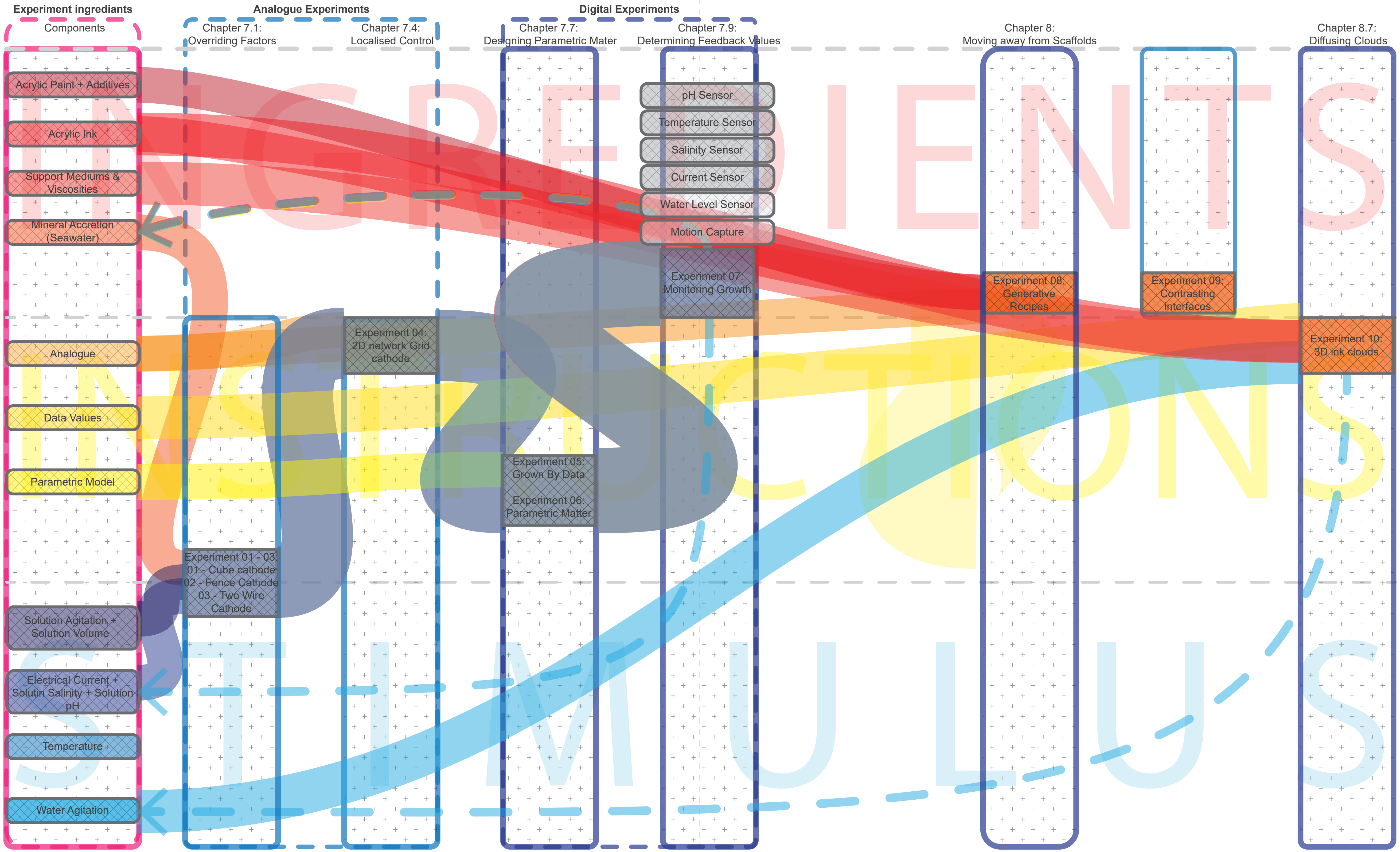


Figure 1: Experiment flow diagram highlighting the predominant components of each experiment, the chapter structure, the experiments development and if feedback is present within the experiment.

1.5 Clarifying terms

As the research sits between multiple boundaries, which have established terminologies, it is worth clarifying some of the key terms defined within the context of this thesis in relation to the experiments and system developed.

- **Self-assembly;** *"is the autonomous organization of components into patterns or structures without human intervention"* (Whitesides and Grzybowski, 2002). The components employed in this methodology are the materials themselves so self-assembly can occur at the material scale, in this case of the experiments the molecular scale. Initiating how the materials assemble is achieved by manipulating environmental stimulus via digital design tools and hardware. The materials (components) used do not have pre-design global or local geometries.
- **Tuneable environments**; are comprised of a set of physical stimuli (temperature, pH, agitation, electrical current) that are adjusted via digital design platforms to alter the conditions of a contained volumetric space, which contain the materials that self-assemble. The stimuli are the mechanisms of the fabrication process, which guide material interactions so desired properties can be grown, such as: shapes (2D & 3D), global patterns (2D & 3D), textures, volumes, densities, compositions.
- **Material computation**; is the materials ability to self-organise when imposed forces or conditions are induced upon them based on the materials inherent properties, which can create global 2D and 3D patterns, shapes or structures based on individual component or material interactions (Leach, 2009, Menges, 2012b, Menges, 2016). An example of these abilities being used to generate designs can be witnessed in the numerous analogue models developed by Frei Otto (Vrachliotis, 2016).
- **Mineral accretion**; is the electrolysis of seawater. *"By establishing a direct electrical current between electrodes in an electrolyte like seawater, calcium carbonates, magnesium hydroxides, and hydrogen are precipitated at the cathode, while at the anode, oxygen and chlorine are produced. The electro deposition of minerals is utilized to construct large surface area (i.e. greater than 100 square feet) structures, building components and elements of a hard, strong material (i.e. 1000-8000 P.S.I. compression strength)"* (Hilbertz, 1981). Significantly, the material growth self-assembles on the material scale and can be predominantly controlled by the supply and duration of electrical current amongst other parameters (Goreau, 2012). It is possible to monitor varying numbers of these parameters and conditions depending if the system is closed or open (Hilbertz et al., 1977). Here, a system is classified as open if the electrolyte solution (seawater) is replenished within the container from an external source, fresh seawater from various locations. The system is closed if the water is not replenished.
- **Open loop control system (OLCS)**; is where the physical stimulus (electrical current, pH, time) are the control actions, which are independent from and have no feedback

with the process variables. The ability to alter the material properties (volume, type, location, texture, patterns, shapes) throughout the self-assembly process are process variables. Meaning, the physical stimulus induced are not monitored or regulated via the digital design tool to determine if a desired property (such as material volume) has been physically fabricated or grown. The corresponding stimulus and resultant material property will be clarified within each experiment.

- **Closed loop control system (CLCS)**; conversely to open loop control systems, the physical stimulus (control actions) do have feedback with the resultant material properties (process variables) as they grow. Meaning, resultant environmental effects are monitored and used to determine if material properties (volume, location, shape / pattern) can been associations can be made between the two and design parameters. As a result, interrelationships can be created between resultant environmental effects, resultant material growth / properties and controlled stimulus, which require the design tool to act as the feedback controller, to determine if environmental conditions within the tuneable environments need altered or maintained to fabricate desired material properties, when utilising the mineral accretion process.
  Both OLCS and CLSC are defined here in relation to the mineral accretion experiments carried out within this thesis.
- **Interrelationships**; in the context of the mineral accretion experiments; are the relationships between: A) the governed physical conditions (material resources, alkalinity, pH, temperature, agitation, electrical current, time) and B) the resultant physical conditions (material resources, alkalinity, pH) and material properties (local volume, location, type or composition, texture and global 3D shape or pattern). The interrelationships are monitored and governed via digital design tools, which creates interrelationships and iterative relationships between digital design, fabrication and self-assembling materials.
- **Adaption**; is the ability of a physical design to change its properties (composition, shape, texture) without it having a predefined material response (bending, shape, texture) when it is subjected to fluctuating environmental conditions (humidity, pressure, water, electrical current, heat). Instead, the physical change is induced by augmentations occurring within digital tools and the resultant physical change is monitored (via sensors) to provide feedback between design, fabrication and material properties.

2 Foundations for Adaptation

Fabricating 2D and 3D designs' that can physically adapt across scales (molecular to global) is challenging and requires rethinking both design and fabrication relationships, processes and methodologies. A sound starting point is to survey literature carried out within architectural design and fabrication research, this is because it provides a rich and ongoing account of design strategies based on relationships and materials both in analogue (Otto and Rasch, 1995, Huerta, 2006) and digital mediums (Oxman and Rosenberg, 2007b, Schumacher, 2009b, Colletti, 2010, Oxman, 2010b, Oxman, 2010a, Wiscombe, 2012, Menges, 2012a, Richards and Amos, 2015, Block, 2016, Schumacher, 2016, Richards and Amos, 2016, Bhooshan, 2017). Architectural research also explores the incorporation and development of new fabrication technologies that provide a wide range of processes and enable the increasingly complex digital models to be fabricated with incredible accuracy (Kolarevic, 2001, Kolarevic, 2004a, Glynn and Sheil, 2011, Dunn, 2012, Willmann et al., 2012, Kolarevic and Klinger, 2013, Iwamoto, 2013, Augugliaro et al., 2014, Gramazio and Kohler, 2014, Gramazio et al., 2014a, Gramazio et al., 2014b, Doubrovski et al., 2015, Stuart-Smith, 2016, Brugnaro et al., 2016, Menges et al., 2017, Keating et al., 2017). Collaborative research into materials has also enable an ever increasing palette (Soldevila et al., 2014, Correa et al., 2015, Reichert et al., 2015, Soldevila and Oxman, 2015, Soldevila et al., 2015, Hu et al., 2016, Menges, 2015, Wood et al., 2016), which can also be employed as the fabrication agents with explorations into chemical systems (Hilbertz, 1970, Hilbertz et al., 1977, Hilbertz, 1981, Hilbertz, 1991, Hanczyc and Ikegami, 2009, Armstrong and Spiller, 2010, Spiller and Armstrong, 2011b, Cejkova et al., 2014, Armstrong, 2014, Hanczyc, 2014, Barge et al., 2015, Cejkova et al., 2016, Kaplan et al., 2017), bio chemistry (Ginsberg et al., 2014, Dade-Robertson et al., 2015, Bader et al., 2016b, Dade-Robertson et al., 2016b, Dade-Robertson et al., 2017a, Dade-Robertson et al., 2017c, Dade-Robertson et al., 2018a, Bader et al., 2018b) and material units that can self-assemble (Tibbits, 2011, Tibbits, 2012a, Tibbits, 2012b, Tibbits and Flavello, 2013, Tibbits, 2014a, Tibbits, 2014b, Tibbits, 2016, Papadopoulou et al., 2017) as well as self-sense (Frazer, 1995, White, 2005, Gilpin et al., 2010, Levi et al., 2014, Soldevila et al., 2015, Reichert et al., 2015, Gershenfeld et al., 2015, Sadeghi et al., 2017). However, exploring the challenge of physical adaptation across the designs' length scales, which are governed by digital augmentations, has yet to be fully realised within this field as design and fabrication processes typically remain separated. Typically design, fabrication and materials do not have iterative interrelationships to guide and physically grow a digital design from self-assembling materials (here after SA materials). In order to understand and create designs' that can physically adapt based on digital augmentations literature is surveyed across a wide range of areas, such as: digital design and fabrication, computer science, cybernetics, biology, chemistry, biochemistry, material science and artistic practices.

It is important to first define what physical adaption is in the context of the thesis. Here adaptation is;
The ability to alter and tune multiple physical properties (shape, composition, texture, volume) of a 2D and or 3D physical design (shape or pattern), which are linked to digital augmentations and have not been pre-determined in response to changing environmental conditions or stimulus (temperature, humidity, light, loading).

Meaning, the global transformation of a shape or pattern is not predefined (Tibbits, 2012b, Papadopoulou et al., 2017), recursive (Tibbits, 2014b) or set between states when subject to a force or stimulus (Tibbits et al., 2014, Menges and Reichert, 2015, Reichert et al., 2015, Correa et al., 2015, Yao et al., 2015b, Guttag and Boyce, 2015, Wood et al., 2016, Hu et al., 2016, Wang et al., 2016, Ou et al., 2014a). Within biology this is not the case as material can be tuned and adapted. The adapted features of an organism are a result of selection forces (environmental demands specific to a trait of the organism), which also inform local internal adjustments (physiological adaption's). The organism's adapted forms enable them to become more efficient or desirable at meeting the demands of the selection forces (Bock, 1980). The interesting aspect of biology here is; how external forces or stressors (physical activity, mechanical loading, malnutrition, sleep duration and type) can impact and inform the internal conditions of an organisms' systems (circulatory, cardiovascular, endocrine), which result material properties adapting (composition, shape, density) to demands. An example of biology's ability to tune and adapt material properties in relation to stress and biomechanical forces can be witnessed in the bone remodelling process (Frost, 1990, Pearson and Lieberman, 2004, Hadjidakis and Androulakis, 2006, AMGEN, 2012). The bone remodelling process will be examined briefly in chapter 5 to understand the mechanisms that achieve material adaptations and determine how conditions and mechanisms could be used to guide self-assembling material interactions, and properties.

Taking inspiration from how forces and conditions act as a means to interact with materials within biology can also be witnessed in the many form finding experiments of Frei Otto. Otto's

Woollen thread and *Occupation with Distancing* experiments are used as the starting point examining related work, which highlights: A) a diverging lineage that maps the focus of form generation of current research compared to ours, which is form and material adaption. Current research within architectural design has predominantly focused on advancing digital design and digital fabrication strategies. Significantly, these sophisticated digital design and fabrication strategies are predominantly still separated from materials post production. B) Otto's experiments provide insights for fostering our diverging path and how the two paths can be linked together by exploiting the computing abilities of materials when subjected to forces or conditions (see figure 3).

Reviewing Otto's experiments helps develop a methodology for creating an adaptive design and fabrication system, based on three consistent parameters: **1) forces or stimulus, 2) conditions or frameworks** and **3) materials and their properties**. These parameters are interrelated and brought to light from further examination of the material processes within the experiments, compared to a focus on their form generating abilities. Understanding what these parameters may consist of is refined throughout the literature review and investigated within our own experiments. These parameters provide scope and common ground, which can link back to and extend current research within digital design and fabrication.

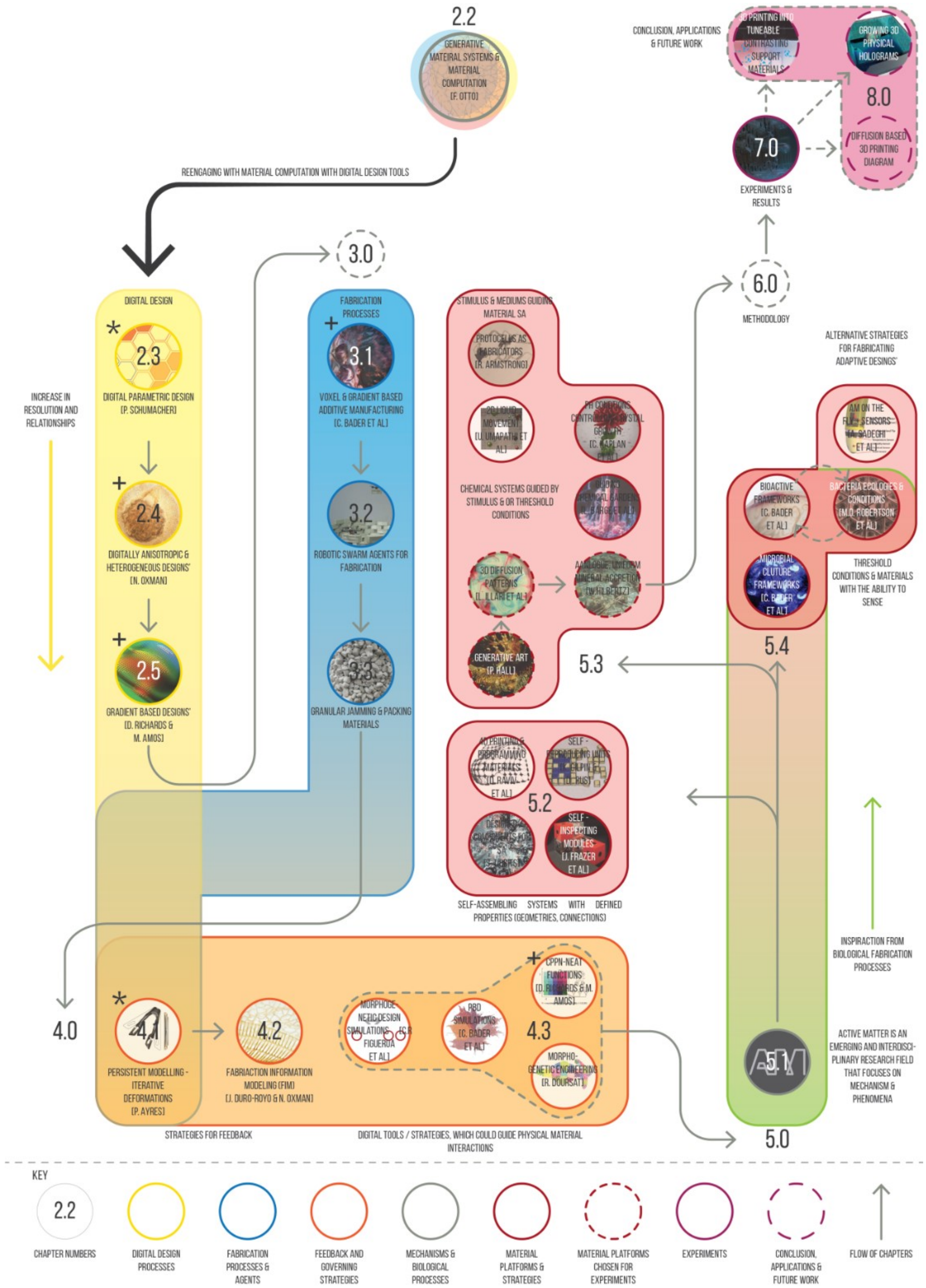
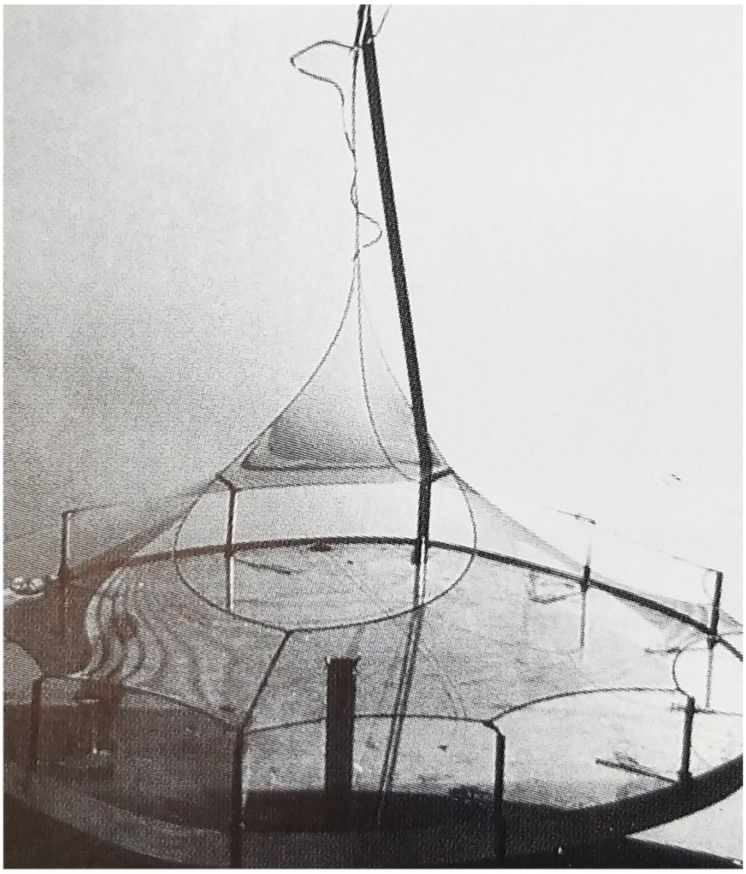
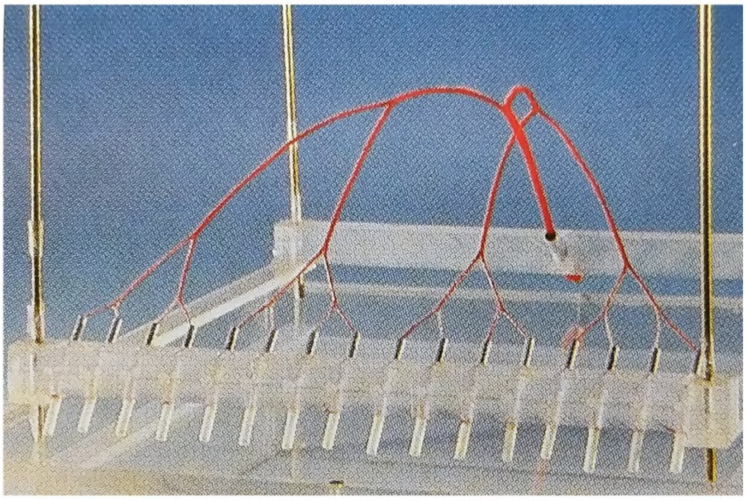


Figure 2: Literature examined and mapped based on a starting point of Frei Otto's form finding experiments due to their material computational abilities. Diverse research areas are also mapped, which are surveyed to determine how they can be connected into a design and fabrication system by employing fabrication parameters based on multiple stimulus and create a tuneable environment within a volume to guide self-assembling materials interactions and properties.

2.1 Analogue Parametric Models & Material Computation



A



B

Figure 3: Various Form Finding models by Frei Otto. The models represent a variety of material computation processes based on different material types which generated 2D and 3D forms. A) Soap films within frameworks create 3D minimal surfaces. Source: Otto, F., & Rasch. B., Year: 1995. B) Woollen threads located at points of support generate 3D branching column systems. Source: Otto, F., & Rasch. B., Year: 1995.

The analogue parametric models of Otto establish how materials (soap bubbles, woollen threads and polystyrene chips) combined with imposed forces (surface tension, agitation, magnetism) can generate sophisticated 2D patterns as well as 3D architectural scale forms (Burry, 2016) (see figure 4). The resultant forms embody the interlinked relationships between materials and forces. The experiments allow conditions to be setup within a physical framework, enabling materials to generate shapes that have a degree of flexibility based on imposed and resultant forces, such as; attraction of polystyrene chips to magnetic needles, which repel and displace one another due to magnetic fields. Notably, the shapes generated can be altered by varying parameters of: A) the imposed forces (magnitude, location). B) The properties of the framework (dimensions, connections) and C) the properties of the materials and mediums used (amount, dimensions, composition, viscosity).

The various models developed by Otto reveal multiple material abilities, which enable 2D and 3D form finding. The models and certain material type are able to address a range of design challenges at multiple scales. For example, the soap bubble experiments were used to 'form find' minimal surfaces for 3D architectural structures and can be seen in the tension canopies of Munich's Olympic stadium. Sophisticated material abilities can also be witnessed in both the Woollen thread experiments, which produced complex 2D patters to determine optimal detour path networks and the 2D cluster formations created in the Occupation with simultaneous distancing and attracting forces models (Schumacher, 2009b).

Otto's 2D models are examined in greater detail, which provide insights and a context for creating a diverging path of focus for developing an adaptive design and fabrication system. In doing so, an understanding is developed that helps to determine: A) what can be constituted as a framework to guide material interactions. B) How forces can be utilised as the mechanism for material SA. C) How material SA properties can be manipulate. D) How the main focus and development of form generation within digital design research (shape, integrated, adaptable, self-organising, material resolution) can be reconnected back to physical material scale self-assembly.

2.1.1 A Framework Form Threads

> *Frei Otto's form-finding models bring a large number of components into a simultaneous organising force-field so that any variation of the parametric profile of any of the elements elicits a natural response from all the other elements within the system. Such quantitative adaptations often cross thresholds into emergent qualities.*
> *(Schumacher, 2009b)*

The woollen thread models were used to determine 2D optimal detour path networks; "Depending on the adjustable parameter of the thread's sur-length, the apparatus – through the fusion of threads – computes a solution that significantly reduces the overall length of the path system while maintaining a low average detour factor" (Kolodziejczyk, 1991). The threads are confined within a fixed circular wooden framework and are able to move with greater degrees of freedom the further away they are from the framework. Meaning, the dimensions of the framework or slack provided to the threads has a direct relationship to their degree of flexibility, i.e. the amount the threads can move. Spuybroek discusses the setup and process in more detail with a focus on how the material system is used as a 'form finder' (Spuybroek, 2005).

The threads have an amount of flexibility from slack provided to them, allowing the threads to move. Meaning the materials become agents within the design process. The threads interact with other local neighbouring threads and converge, but do so based on global and local conditions and interactions. The emergent 2D pattern is informed by interactions across multiple scales due to the neighbouring interactions of the threads, which occur based on local and global forces. Meaning, the strings are able to compute 2D path networks based on the imposed conditions. The conditions are a combination of the forces (tension, gravity, agitation, friction) imparted upon the materials. The materials themselves, in this case wool and their properties (slack, diameter, smoothness) and the properties of the mediums or liquid mixtures (liquid surface tension, viscosities) the materials are submerged within. These aspects impact on the final forms generated and can be strictly controlled in the initial setup of the system. However, it is possible to alter these conditions throughout, which enable shape changing abilities of the forms created. These are the parameters of interest and will be explored as to how they can be manipulated using digital design tools. This raises the question; *what material platforms are based on and create local and global conditions and how can these conditions can be monitored and manipulated to adapt 2D or 3D shapes and patterns?*

Another feature of the patterns worth mentioning is how the void spaces are created during these material processes of convergence and bifurcating. The positive spaces are created by the threads, which contrast with the negative void spaces created between them as a result of material convergence (see figure 4C). The pathways and void spaces created reveal multiple forces at play in the experiment, which contrast one another and are also inherent within the materials used. For example, the initial shaking of the framework that holds the threads when submerged in water (or other mixtures) displaces and overlaps them; this begins to bunch threads together. The displacement is aided by the water as it provides bouncy, allowing the threads to move more freely. Conversely, more viscous mediums used, such as; a glue and syrup mixture (Spuybroek, 2004) would inhibit or reduce the amount of displacement caused by the initial shaking as viscous force is greater and energy is not transferred to the threads as efficiently, which highlights how the liquid mixtures act as support mediums and a type of less rigid framework. As the set-up is removed from the water, the water's surface tension and gravity attract the threads together forming a collection of thicker pathways. From this the threads begin to converge and bifurcate. Contrasting with the forces of gravity and tension would be the friction and tension between neighbouring woollen threads, which prevents areas and sections from joining, creating the void spaces. The forces of friction and tension are inherent within the materials used, but become activated and more prominent during the patterns generation.

The woollen thread experiment raises two points of interest: firstly, the idea of how contrasting forces that are inherent within single materials (e.g. initially fine wool fibres binding to neighbouring ones, which lead to whole threads being entangles) and the material system can be used as a tactic to guide material interactions, which can be exploited to fabricate or leverage opposite qualities (shapes: positive or negative, textures: rough or smooth, compositions: hard or soft, orientations: horizontal or vertical). Secondly, the possibility of using liquid mixtures as a framework, which is less rigid than the physical wooden ring, which fixes the end positions of the threads. The possibility of a liquid framework is demonstrated as the various liquid mixtures support the threads when they are submerged within it. Altering properties of the mixture (temperature, pH, viscosity) means they can also be used as a way to further control the magnitude and types of forces imparted on to the materials within them, such as liquids with greater viscosity dampening the energy supplied to the threads during agitation. The use of support mediums provides another avenue to explore ways of guiding interactions and processes of material SA; *How or what material process can be exploited by altering a support liquids' properties to create a less rigid framework and environment for the materials to self-assemble and adapt their properties?*

Two instances of Otto's occupation and distribution experiment are examined next as it uses more granular type materials and engages with fields of force (magnetism). They will serve as another precedent and vehicle to determine what other possible physical mechanisms and principles can be developed for guiding local and global material interactions, which can be related back to properties within digital design tools and strategies.

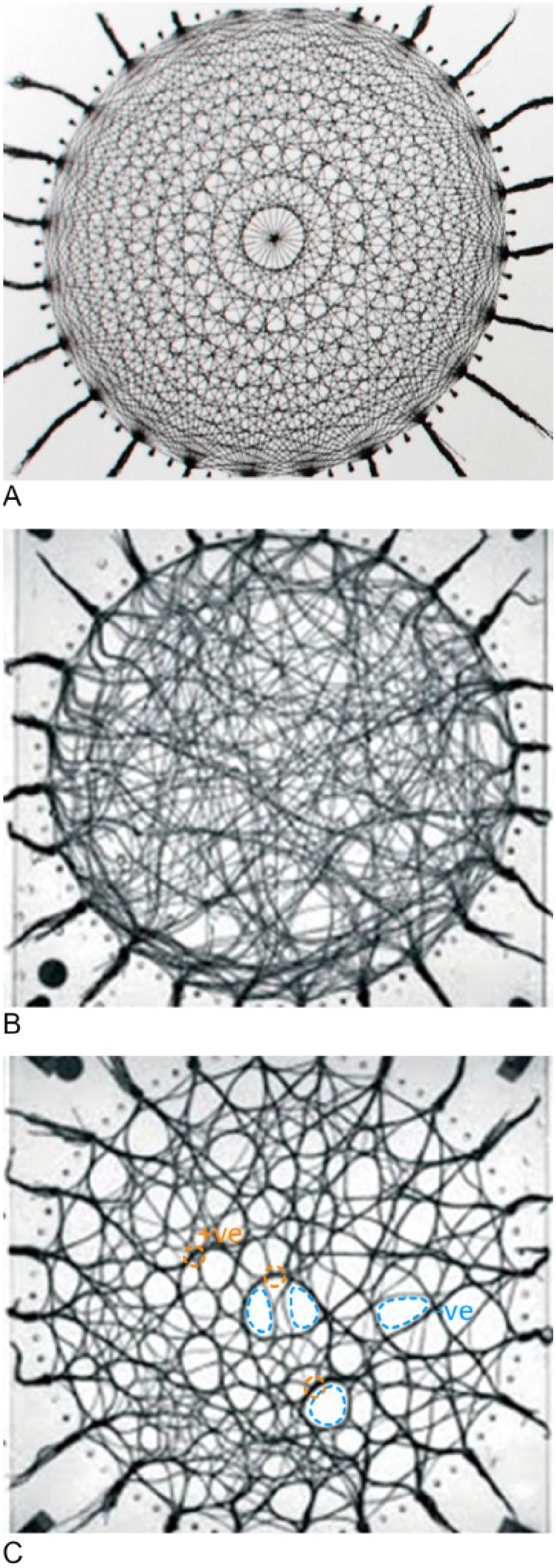


Figure 4: Three stages of Otto's woollen-thread model. C) Highlights the positive and negative spaces created from the conditions and resultant forces within the material system. Source: Otto, F., & Rasch. B., Year: 1995. Annotations: Author.

2.1.2 Granular materials & and framework of forces

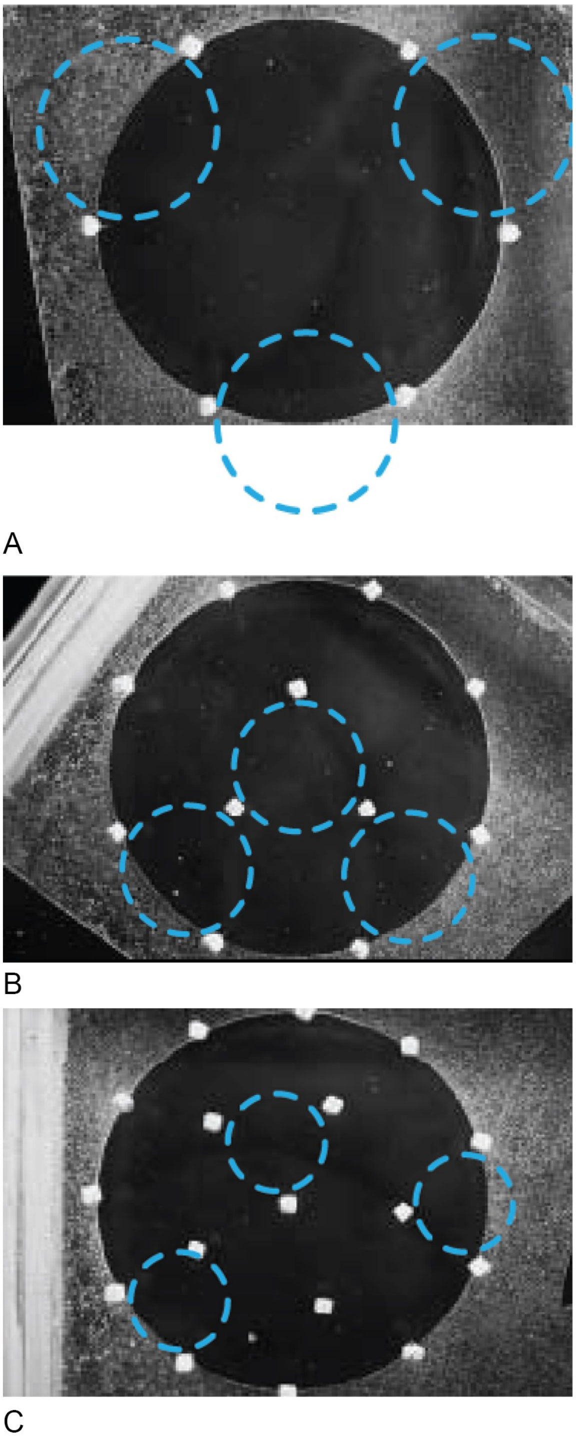


Figure 5: Otto's Occupation with distancing models. A - C) a sequence of images that depict varying organisational patterns as more needles are added. The patterns are created from neighbouring magnetic repulsion and have almost uniform distancing, highlighted by the dashed circles. Source: Otto, F. Year: 2003. Annotations: Author.

The first instance of Otto's *Occupation and Distribution* models that uses only magnetised needles is now described and examined. Here, a series of needles are placed on the surface of water, which are within a defined boundary of a shape or area. The needles float as they have within cork floats. The ability to float allows the needles to move. As needles are added to the shape, they distribute themselves via magnetic repulsion between local neighbouring needles, creating global 2D patterns.

The distributed 2D patterns explored how shapes, spatial areas and urban territories could be internally organised (see figure 6A - C). Otto describes the setup and other details of this experiment in greater detail and begins to allude to the abilities and benefits of using forces as a fabrication mechanism; *"Once they (needles) reach their position, the magnets remain there as if held by invisible threads, even when violently disturbed. They can remain in this position for days"* (Otto, 2003).

The aspect of interest is the magnetic forces and how they can be manipulated to initiate fabrication and pattern transformation, which self-distributes. The use of magnetic forces in this setup reveals and reinforces several interesting potentials: A) the organisation of patterns (local distances) are resistant to inadvertent disturbances (severe shaking) as the distances are not mechanically fixed. B) The benefits of contrasting forces (magnetic attraction and repulsion) are revealed again. In this case as a way of creating and organising patterns with approximately equal distancing. C) The patterns created are a scalable process and are also adaptable because they self-organise and change shape when needles are added or removed. The scalability in this system is due to the materials neighbouring interactions, which inform the global patterns. However, the limit of scalability is dictated by the material resolution, as well as the size of the area they are placed within *"One can place any number of points, up to about a hundred, on any surface"* (Otto, 2003). D) Gradient fields can be created by varying the magnetic strength of a node, which would enable greater variation in the 2D patterns; "*In addition, varying the magnetic field strength can alter the distances, thereby increasing and reducing the associated territories. When carrying out the experiments, changes in field strength are very easily achieved by placing two or more needles on a buoy"* (Otto, 2003).

The use of gradients in this system would allow for more sophisticated material computation, as 'weightings' can be assigned to individual needles. Meaning a hierarchy of order of logic could be assigned to individual nodes, due to localised variation in magnetic strength. The use of weighting's is a strategy employed in Random Boolean Networks (Weaver et al., 1999) (here after RBNs). RBNs were defined by Kauffman (Kauffman, 1969, Kauffman, 1993) and are used to help represent and understand complex cellular activity. An example of assigning weightings to nodes could be used to organise urban areas. For example, district areas which require more space such as cities would be represented by a more powerful magnet. The needles that represent smaller surrounding towns would be displaced further away (providing more space) for the city node and closer to neighbouring needles with the same magnetic strength. The magnetic strengths and gradient variations enable complex spatial organisation to be created from material computation processes. The potential similarities between Otto's experiment and RBNs demonstrate how material computation can perform sophisticated computational processes. However, it would be difficult to attain or determine the attributes of the nodes if their properties and neighbouring relationships fluctuated because it is analogue. For this reason, digital design tools are incorporated as a means monitor conditions and relationships.

Now the second instance of this experiment is reviewed with a focus on how the magnetic needles act as a flexible framework of nodes, which attract granular materials and form cluster patterns.

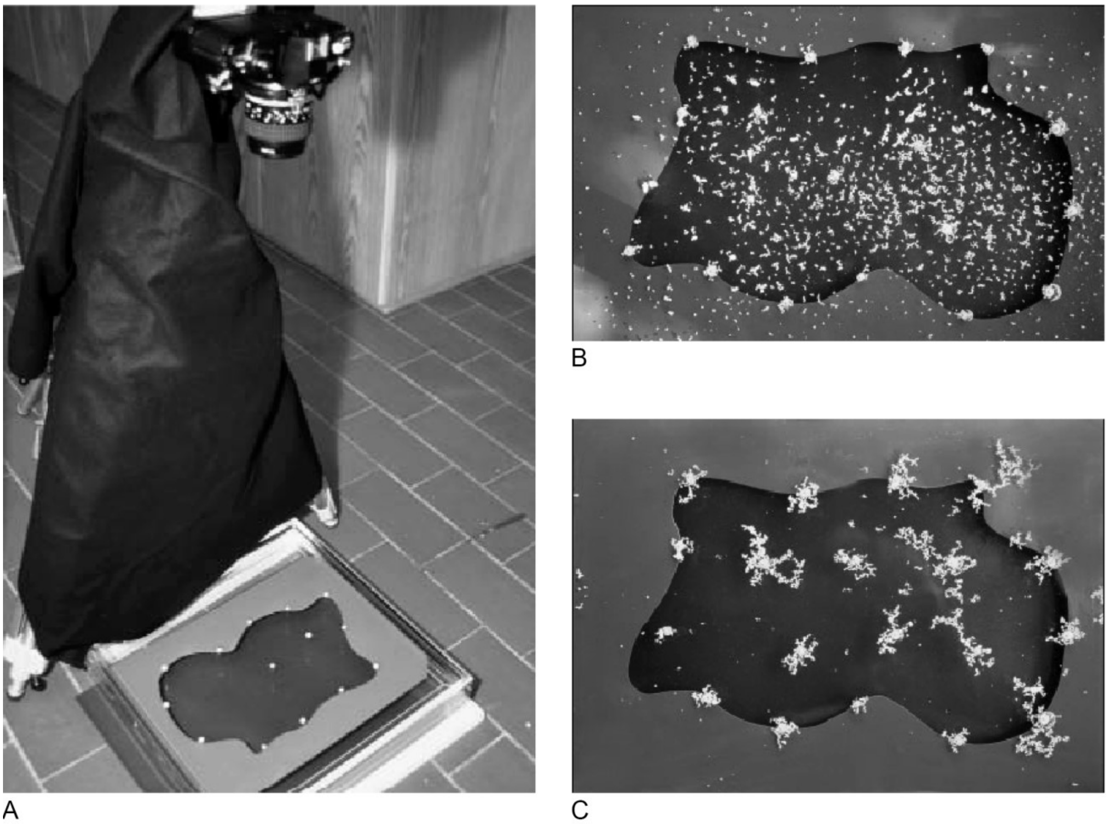


Figure 6: Otto's occupation with simultaneous distancing and attractive forces model. A) Experiment setup with framework of needles self-distributed within irregular area. Source: Otto, F., Year: 1992. B) Framework of magnetic needles and unorganised polystyrene chips. Source: Otto, F., Year: 1992. C) Needles acting as nodes, which attract polystyrene chips to form clusters. Source: Otto, F., Year: 1992.

A second instance of the occupation experiment introduces polystyrene chips (see figure 6). The chips are attracted to the needle locations and form cluster patterns around them. The points of focus here are: A) the needles acting as a flexible framework and the relative cluster patterns formed around them. B) The use of forces as a way to self-organise granular materials. C) The self-organising cluster patterns are created without predefining the properties (geometries, connections, interfaces) of the granular materials.

As mentioned previously in Otto's first iteration of the occupation experiment, it is possible to alter the needles pattern by varying their properties (amount, magnitude, location), which results in a flexible framework. Meaning, it is possible to influence certain properties (amount, location) more easily of the polystyrene chips than others (cluster patterns). This demonstrates how analogue control over forces can be used to alter and guide properties of the 2D patters created from self-assembling materials.

These experiments are used as a vehicle to speculate on the potentials of being able to develop programmable self-assembly strategies without defining the geometries or interfaces of the material components. Instead imagine continuously being able to manipulate the conditions the materials are placed within, in this case the needles magnetic magnitude and location. However the conditions are altered based on transformations that occur to a digital design that represents the network of needle, which in turn alter granular material configurations. Developing this strategy can create a discourse between, design, fabrication and granular materials, where the fabrication process is non-deterministic allowing for potentially desirable properties (shapes, organisations, distributions) to arise. Conversely, design and fabrication process are typically deterministic, where the physical outcome in known prior to the fabrication process (Tibbits and Flavello, 2013). Highlighting properties and mechanisms of material interactions and computation within Otto's experiments and intending to guide them via digital design tools raises new challenges but exciting potentials.

Firstly, the polystyrene patterns created are heterogeneous i.e. they are not uniform (homogenous) in shape, location or amount. However, if the forces can be tuned or further refined to effect more material properties (orientation, composition, type) then it may be possible to create patterns or structures that are materially heterogeneous and or anisotropic. Biology demonstrates the ability to organise (Neville, 1993, Vogel, 2003) and adapt (Vincent, 1982) material based on forces acting upon it, resulting in material efficiencies (material strength vs. amount).

Secondly, as magnetic fields have a dissipating field of force, i.e. a gradient effect, it may also be possible to organise different types of materials to desired locations within areas of the gradient force. However, this would require a material or multiple materials, which have varying affinities and sensitive's. Ultimately, this would enable structures with gradated properties (flexible to hard) to be created using gradient forces as the fabrication strategy. An example of a gradated material in nature is the jumbo squid beak (Tan et al., 2015), which goes from soft to extremely hard. How this is achieved will be examined to help understand what future potentials could be achieved by varying conditions and forces in a continuous fabrication process.

Thirdly, the transformative potentials of the magnetic forces can have on material qualities. For example, imagine being able to alter the polystyrene cluster patterns size or shape and even migrate them around the network of nodes by demagnetising certain nodes and or changing the magnetic strength of individual nodes. Using forces as a means of fabrication raises two main challenges: 1) how can physical forces produced by each node be controlled and monitored based on augmentations that occur within digital design platforms. 2) How to determine if the desired material properties they effect, in this case the clusters (amount, size location, global or local patterns) have been achieved. These two challenges open up an array of possible material platforms that have the capability to monitor or respond to varying conditions, which will be discussed in chapter 6. In order to address the second challenge, a possible avenue to explore is the mutual relationship between forces used and the contrasting material properties fabricated, so relationships between material effects on conditions can be measured.

The diverging path of predominant research is now mapped and discussed, which has typically focused on digital form generation, by recapturing the relationships and material abilities of Otto's experiments digitally. Significantly, this path still produces a linear process, which separates digital design, fabrication and materials but current research is now beginning to integrate them together. Understanding the incredible advances in *Computer Aided Design* (hereafter CAD) and *Computer Aided Manufacturing* (hereafter CAM) enables us to establish how these recent developments can be utilised and guide processes of material SA.

2.1.3 Shifting focus

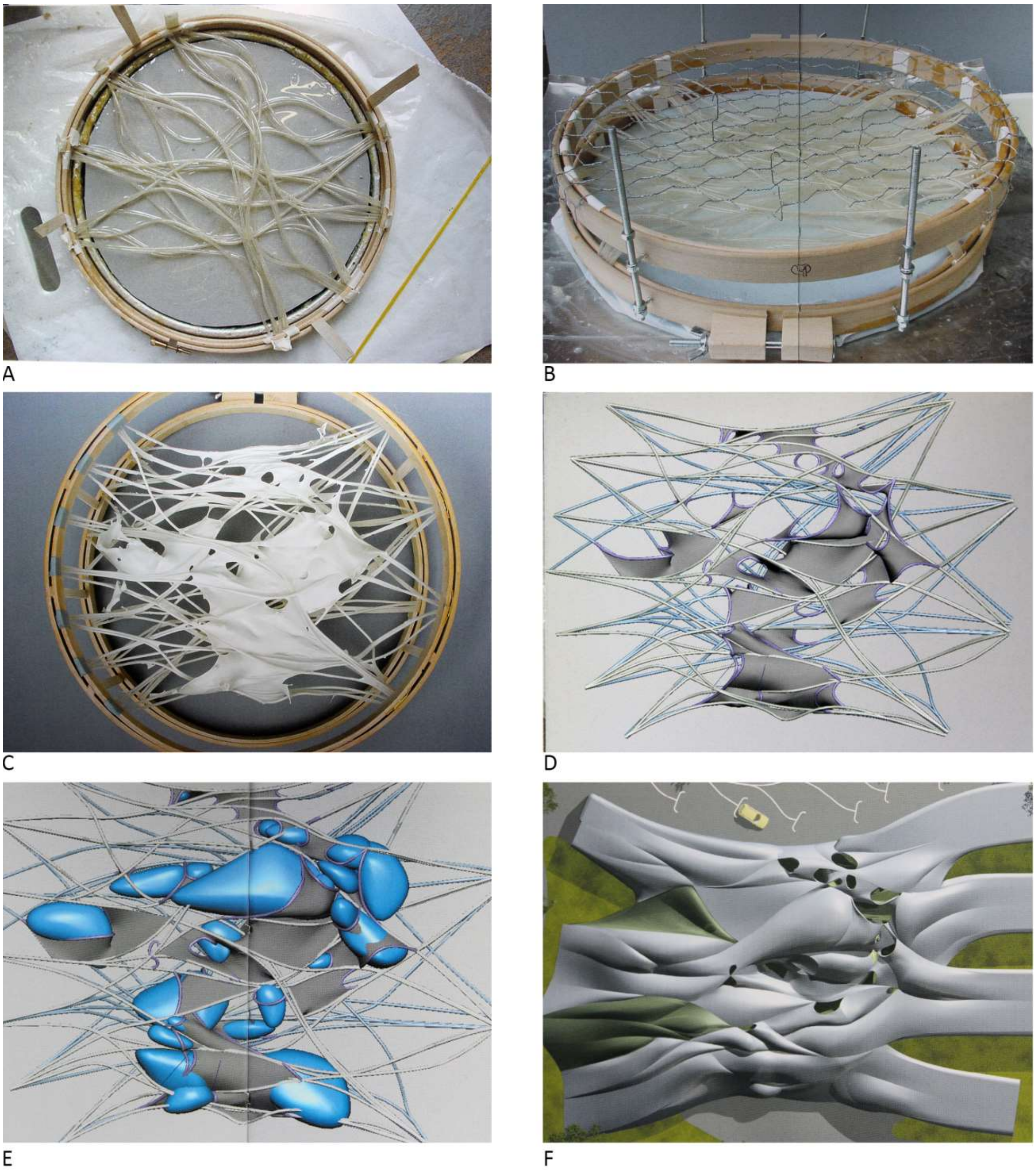


Figure 7: NOX Soft Office. A - C) Analogue experiment setup which creates 3D spaces from silicone tubes and lacquer within a wooden framework. As the lacquer cures, changing state the frameworks are separated within 3D space, creating forms and surface connections. D - F) the forms created within the analogue model are digitised and altered to create a conceptual architectural design. Images A - F: Source: Spuybroek, L. Year: 2004.

Soft Office is a conceptual architectural project by NOX architects (Spuybroek, 2004). The initial stage of the design process is an experiment, which generates 3D forms inspired Otto's form finding experiments. Here silicone tubes and lacquer are used and suspended in 3D space from two circular wooden frameworks (figure 7 A - C). The lacquer goes through different states and as it dries it creates 3D curved surfaces between the silicone tubes. Again the materials are computing forms and producing 3D shapes and properties based on the conditions they are placed within. Significantly, it is the models 3D forms are digitised and then refined to create architectural spaces (figure 7 D - F)

The trade-off of digitally capturing only the physical forms means the resultant digital model and physical model have become separated i.e. any digital manipulations are not physical reproduced. The method of digitising the physical shapes is not mentioned, but this could an alternative methodology for iteratively linking physical material adaptations to digital representations. The project provides a good case study for: 1) abilities present within the physical model being significantly reduced or removed when chiefly focusing on form generation and digitally capturing the forms generated, not the processes. 2) The digital and physical model is separated as the digital shapes are not created based on the material relationships or conditions. Meaning any digital augmentations could not be related back to the physical as the processes have no common intermediary to connect them.

Conversely, digital designs created using computational design processes are of greater interest because of their generative and transformative abilities, but they can also have an intuitive discourse with physical materials by relating similar attributes present between digital and physical. Peters discusses computation and its benefits compared to how they are more traditional used within the context of architectural design; *"But what do we mean by computation? Most architects now use computers, but usually to simply digitise existing procedures with entities or processes that are preconceived in the mind of the designer. For example, architects use the computer as a virtual drafting board making it easier to edit, copy and increase the precision of drawings. This mode of working has been termed ‘computerisation’* (Terzidis, 2006). *‘Computation’, on the other hand, allows designers to extend their abilities to deal with highly complex situations"* (Peters, 2013). Ahlquist and Menges also provide a definition of computation which resonates with how it could manipulate material interactions, here computation is; *"the processing of information and interactions between elements which constitute a specific environment; it provides a framework for negotiating and influencing the interrelation of datasets of information, with the capacity to generate complex order, form, and structure"* (Menges and Ahlquist, 2011).

As witnessed in Otto's experiments, the materials have the abilities to perform computation based on various interactions. A primary aim of this research is to extend digital computational processes by instilling them within physical material interactions of self-assembling processes. The marriage of both digital and physical simulations has been taken advantage of within evolutionary robotics, as the physical robot is directly engaging with real-world parameters, which more accurately informs the corresponding digital simulation (Lipson and Pollack, 2000, Pollack et al., 2001, Zykov et al., 2004, Lipson et al., 2006, Bongard et al., 2006, Cheney et al., 2013). In doing so, the digital design models will be used to output instructions to guide SA processes and link the two. The next three sections review three methods of computational design. They can all dynamically change properties of a digital design (shape, colour, texture, composition). Significantly, each section also increase in the resolution sequentially, which reveals how these digital design strategies can potentially engage with more intricate physical material properties and provides rich grounds for future collaboration.

2.2 Design Instructions

The order of the following topics places digital design strategies first because: 1) it is intended to be the platform the physical augmentations are based up on. 2) They will be used to determine if a physical adaption has been produced during the experiments e.g. a desired volume of material growth has occurred at a defined location within 3D space. 3) Provides an understanding of the possible resolution a digital design can be generated upon; from global geometries to local material composition and if an increase in digital resolution enables control over less defined physical properties of a self-assembling material platform. Less defined meaning properties, such as surface texture, porosity that are not directly linked to a specific stimulus but potentially the overall conditions. 4) Their potential use for governing and revealing relationships as a system becomes increasingly complex.

Three types of design strategies are surveyed. *Firstly*, parametric design, *secondly*, material based computation and *thirdly*, gradient based designs. They are examined because of the digital shape changing abilities they afford, which become increasingly extensive in regards to what properties they can adapt, from geometric boundary representations to global adoptions based on local material compositions. A primary challenge is to map what digital parameters and relationships have a relevant or mutual discourse with a certain material property or process when a physical SA material platform is chosen. For example, imagine inducing changes in temperature along with liquid agitation to move volumes of molten wax around a 3D volume to desired locations to create larger volumes of wax. Here, the control over volume and x, y, z co-ordinates of the digital model would be related to temperature and agitation. As previously mentioned based on examining Otto's experiments, how can it be verifying if the desired qualities of a digital design (pattern, shape, surface texture, colour) have been physically reproduced when alternating environmental conditions as the means of fabrication.

2.3 Parametric Design

"In parametric design, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be created."
(Kolarevic, 2004b)

Parametric design is a design process that creates geometric forms and organisations by defining their parameters and the relationships between them to make up an overall global design. The heritage of parametric design and its process is discussed by Carpo, who argues it can be traced back to procedural rules found in antiquity and gothic architecture. Carpo highlights how the written descriptions of Vitruvius from 25BC are procedural instructions which create formal relationships and is an early form of parametric design. A consequence of the written descriptions results in variation (Carpo, 2016) as they are interpreted by the fabricator. Gibbs developed these rules by creating visual documentation of the relationships between geometric components and ratios that determined certain column typologies (Gibbs, 1753). Additionally, Frazer used genetic algorithms to evolve these formal relationships and generate new column typologies (Frazer, 1995).

With the advent of computers and development of various *Computer Aided Design* (CAD) software packages it is also possible to generate digital designs parametrically, this process is termed associative modelling. The advantages of combing a computers processing abilities with parametric design processes (procedural logics and geometric interrelationships) allows: 1) the digital geometries and organisations can be transformed constantly and in real-time by altering multiple parameter values (typically by changing values of a number slider), which are directly mapped to the attributes of geometries. 2) Digital geometries that can be changed with multiple degrees of freedom. However, this is dictated by the number of parameters associated to the geometries and can limit scalability of resolution (Richards and Amos, 2015). 3) Increasingly sophisticated digital models as an increased number of geometric components and interrelationships can be defined and handled with greater ease, creating an enhanced scalability to this design process (see figure 8D & E). 4) Description of increasingly complex geometric structures which can be structurally efficient and ornate (Block, 2016). 5) Digital fabrication instructions / processes that can be produced directly from the models data (Stuart-Smith, 2016).

The main point of interest afforded by a digital parametric platform is the first point and how it can be instilled within physical materials. In order to do so digital parametric models are thought of in relation with self-organising properties present in Otto's experiments, so digital and physical materials can be reconnected. However, limitations become apparent when reconnecting digital simulations back to physical materials because of: A) digitisation and B) how typical CAD software represents the materials.

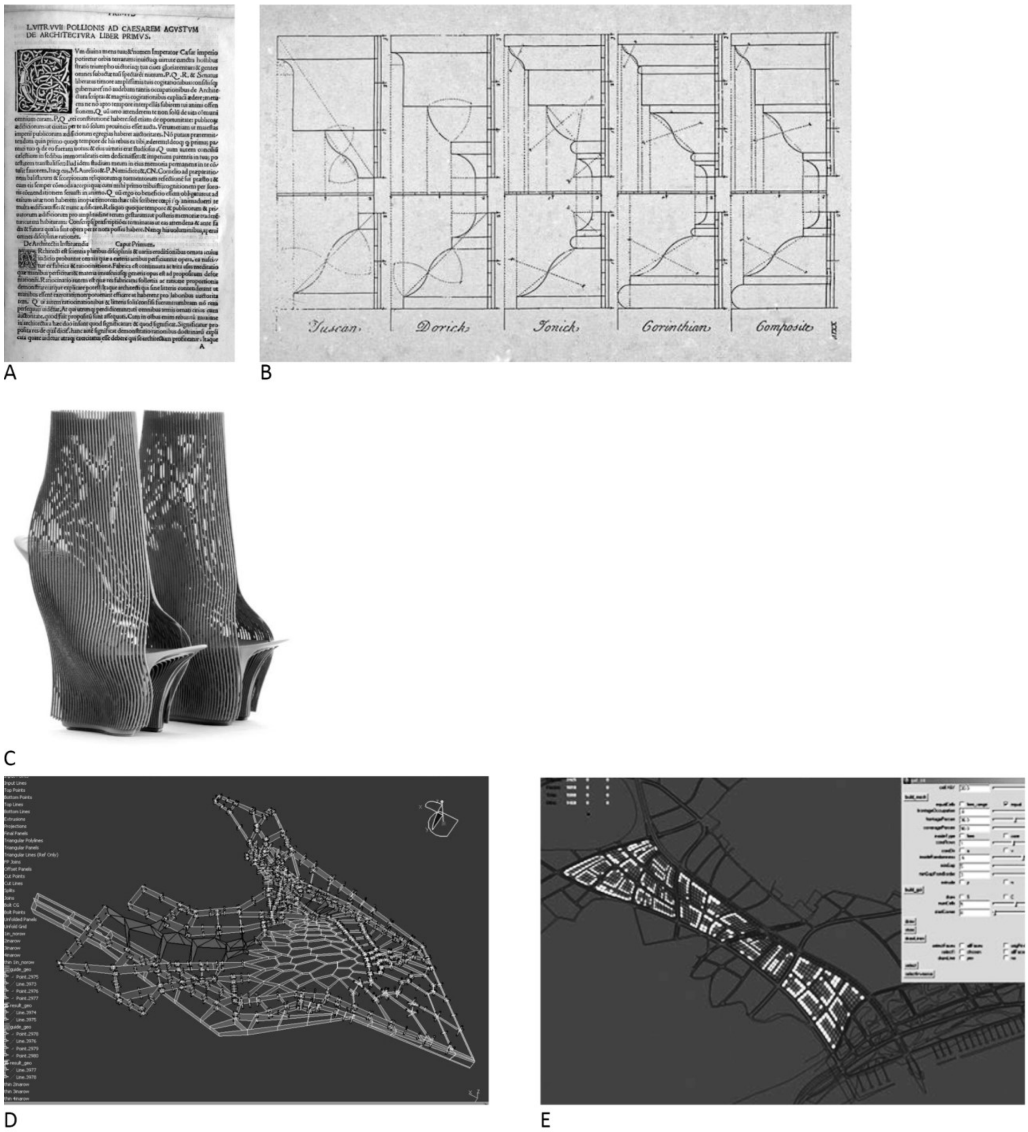


Figure 8: Parametric design process, both analogue and digital. A) Vitruvius describes procedural rules and formal relationships for creating architecture. Source: Vitruvius. Year: 25BC. B) Sequence of images that depict how to produce mouldings to make up the geometric components and relationships for classic column typologies (Image B: Gibbs, J., Rules for Drawing the several Parts of Architecture, 1732). Digital design tools enable parametric processes to create geometries of a design that can be dynamically manipulated, typically via value sliders which are related to attributes of the geometry. C) The digital processes enable degrees of scalability and application, ranging from product (Image C: Lovegrove, R., Ilabo, 2015) to D) 1:1 structural canopy installations (Image D: Wiscombe, T., & EMERGENT, Dragonfly, 2007) and D) the organisation and formal logics of urban scale planning for Kartal-Penkik Master plan, Istanbul, Turkey (Image F: Zaha Hadid Architects, Kartal-Penkik Master plan, 2006).

The ability to set-up conditions to generate designs via material computation was witnessed and discussed in Otto's form finding experiments. The conditions become somewhat fixed during these experiments as they (gravity, tension, liquid viscosities, framework dimensions, material properties) are not easily or discreetly manipulated over their duration. Comparatively, developments in CAD software have enabled Otto's experiments to be reproduced digitally by digitising aspects of the analogue setup; the materials, forces, geometries and frameworks (see figure 9). Digitisation is the conversion of physical properties into digital. Significantly, the digital versions enable an increase in speed in regards to easy of set-up, multiple properties can be explored by manipulating conditions (gravity, node distances, wool sur-length) on the fly, allowing for greater degrees of flexibility in the system.

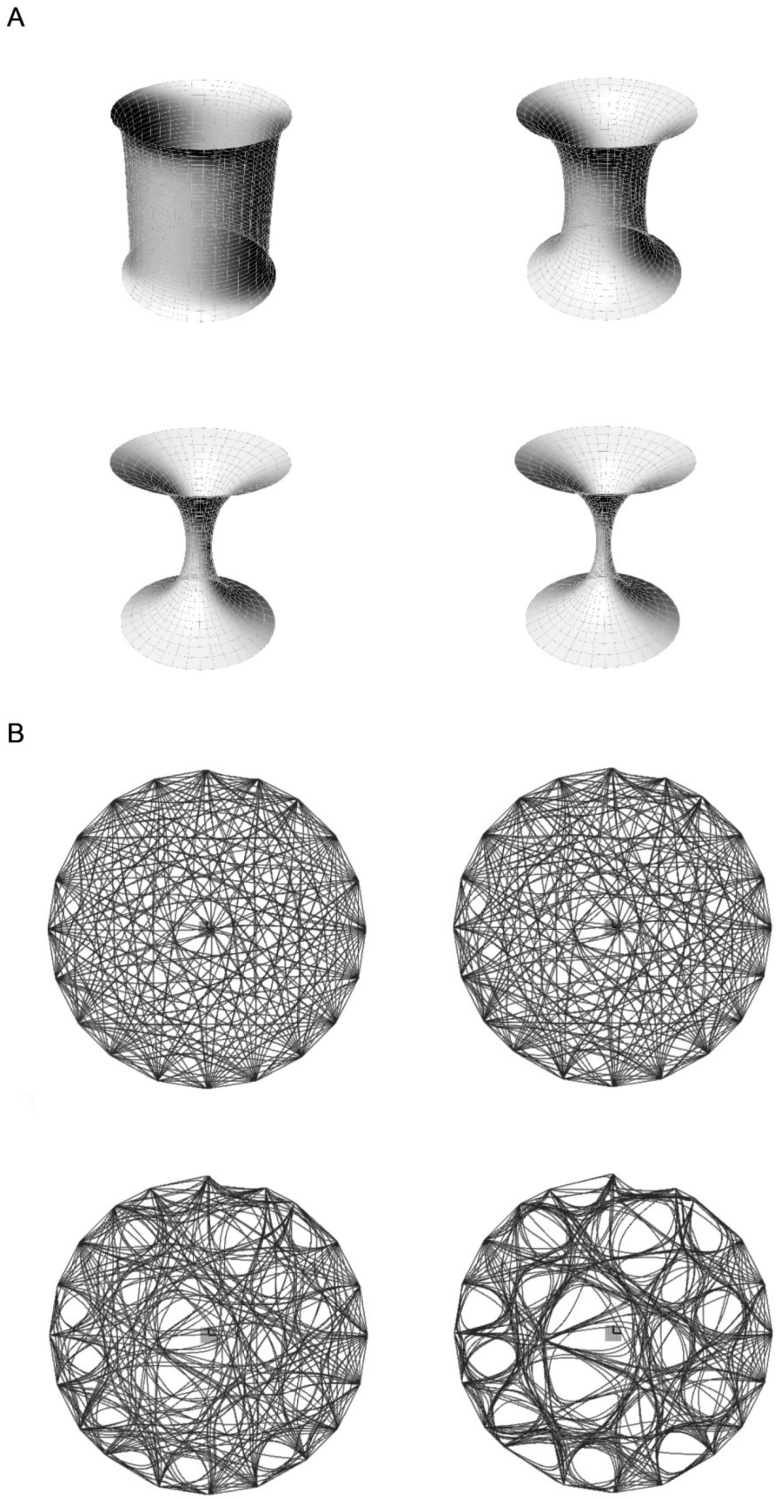


Figure 9: Digital simulations of Otto's experiments shown as a sequence of screen shots to highlight dynamic geometric behaviours when subjected to simulated forces. A) Minimal surface model (Image A: Leung, N., surface tension simulation, 2018). B) Optimal detour path network model (Image B: Hristov, T., wool-thread simulation, 2015). Both are created in Grasshopper and use the incorporated physics library kangaroo. Grasshopper is a parametric visual interface plug-in for the 3D modelling software Rhino.

However, digitisation results in the abstraction of actual physical processes. As such, the digital version has comparatively reduced processing power compared to the physical system (Kwinter, 2011). The digitisation process combined with how typical CAD tools represent materials reveals challenges and limitations when reconnecting the digital with physical materials, with the intention of using digital augmentations to guide SA material processes.

Firstly, due to digitisation, it will be necessary to map digital design parameters to relevant stimulus that can affect corresponding SA material processes so as to create a discourse between the two platforms. For example, simply altering a digital circles location via a numerical slider could be used to directly control properties of a physical stimulus like liquid agitation (duration and flow-rate), which causes a material unit to move within a corresponding liquid volume, like tuning the energy supplied to the units of the fluid crystallisation project (Tibbits, 2014b). This would represent an open loop control system (OLCS here after) as the control action (agitation) does not have feedback to determine if the process variable (material location) has been sufficed. Monitoring the physical materials location in this example and providing feedback to the design tool would create a closed loop control system (OLCS here after). Ayres demonstrates how stimulus is used to establish this connection between digital representations and physical artefact to achieve iterative physical deformations (Ayres, 2011) and the strategy will be discussed in Chapter 4.

Secondly, typical CAD software represents the components and objects of a design as boundary representations (B-reps), meaning they are not suited for internal material spatial variations (Michalatos and Payne, 2013, Richards and Amos, 2016). A consequence of this is that the internal volumes of the digital model are materially totally homogenous. As a result any digital manipulations are geometrically driven and not based on how material properties could compute form based on demands or conditions.

Thirdly, The result of combing the first two point's means all of the nuances present in the physical system such as materials variations are not represented digitally (Ahlquist and Menges, 2012). A significant result of this is the typically linear behaviours exhibited by deformations to digital models / material, a factor not present within physical materials especially when threshold conditions are surpassed, which display non-linear behaviours and can achieve new capacities (DeLanda, 2015). These discrepancies between behaviours will become more prevalent when attempting to guide SA materials as they are granular in nature and create heterogeneous, non-uniform material compositions.

Fourthly, accurately uncovering, determining and further understanding nuanced interrelationships within the proposed adaptive fabrication system between digital augmentations, induced stimulus and resultant material properties and environmental conditions could become limited if it is based on strict cause and effect single relationships, predefined within the parametric design tool. A consequence of this would potentially limit how reliable the fabrication of physical designs' are compared to the digital model. A strict cause and effect strategy could also inhibit the discovery of novel and robust fabrication logics and process, which could arise from combining multiple stimuli, these fabrication abilities have been demonstrated within existing strategies of SA, where the geometries and connections of the material components are predefine (Tibbits, 2011, Tibbits and Cheung, 2012).

2.4 Material Based Design Computation

The next two sections of this chapter focus on the synergies between digital computational designs strategies based on materiality and physical material scale SA. The digital design strategies examined are A) material based design computations (here after MBDC) and B) gradient based designs, both of these computational design strategies can generate digital forms based on a granular level. These strategies could extend and enhance the discourse and control over the manipulation of material properties when subject to stimulus compared to B-rep simulations (Ayres, 2012a) as digital materials are not represented as homogeneous and more accurately represent real world materials. The intention is be to utilise these strategies so as to determine relationships between conditions and material properties of a chosen SA material platform that are not directly linked to a certain stimulus, such as surface texture.

Oxman established MBDC, which takes inspiration from biological form generation and generates designs that are not geometrically driven (Oxman, 2010b), instead, form, structure and material properties become integrated wholes for generating 3D design models based on a digital material unit resolution. The digital material units used here are voxels. A voxel is a volumetric pixel and can be assigned information (colour, rigidity, softness) based on its location in relation to multiple environmental conditions (structural, environmental, corporeal, sound), making the materiality, structure and global geometry performance driven (Oxman, 2007). This integrated, multi scalar design approach also enables desirable properties (structural and material efficiencies) to be replicated that are universally present within biological structures at multiple length scales (Ortiz and Boyce, 2008), such as: anisotropy (Oxman et al., 2012), integration (Wiscombe, 2010, Oxman, 2010b), materially heterogeneous with variable material types (Oxman, 2011b) and densities, which can also become functionally graded (Oxman et al., 2011, Richards and Amos, 2015, Richards and Amos, 2016). This ability to digitally inform a designs materiality based on demands enables its matter to be physical programmed at a granular level (Oxman, 2012). While models generated with this methodology remain digital they can also mimic biological processes, such as remodelling, by tuning and adapting its material properties (Oxman, 2011a). The experiments intend to explore how these highly desirable properties and digital abilities, such as variable compositions and remodelling could be achieved physically and more intuitively if similar material based computation strategies were employed to inform interactions of material scale self-assembly.

Generating designs based on material (voxels) gradients is a current research topic that extends MBDC and will be briefly discussed next because of: 1) the possible digital material resolution afforded. 2) The scalability of processing information based on a highly granular digital material resolution. 3) The ability to utilise a gradient based design methodology to determine relationships. Alternative approaches and benefits to digital material computation are also discussed by Menges (Menges, 2012a), which integrates the performative capacities of materials as a design driver (Fleischmann et al., 2012, Menges, 2016) and even produce mechanically responsive abilities from composite wood materials (Menges and Reichert, 2012, Reichert et al., 2015, Menges and Reichert, 2015).

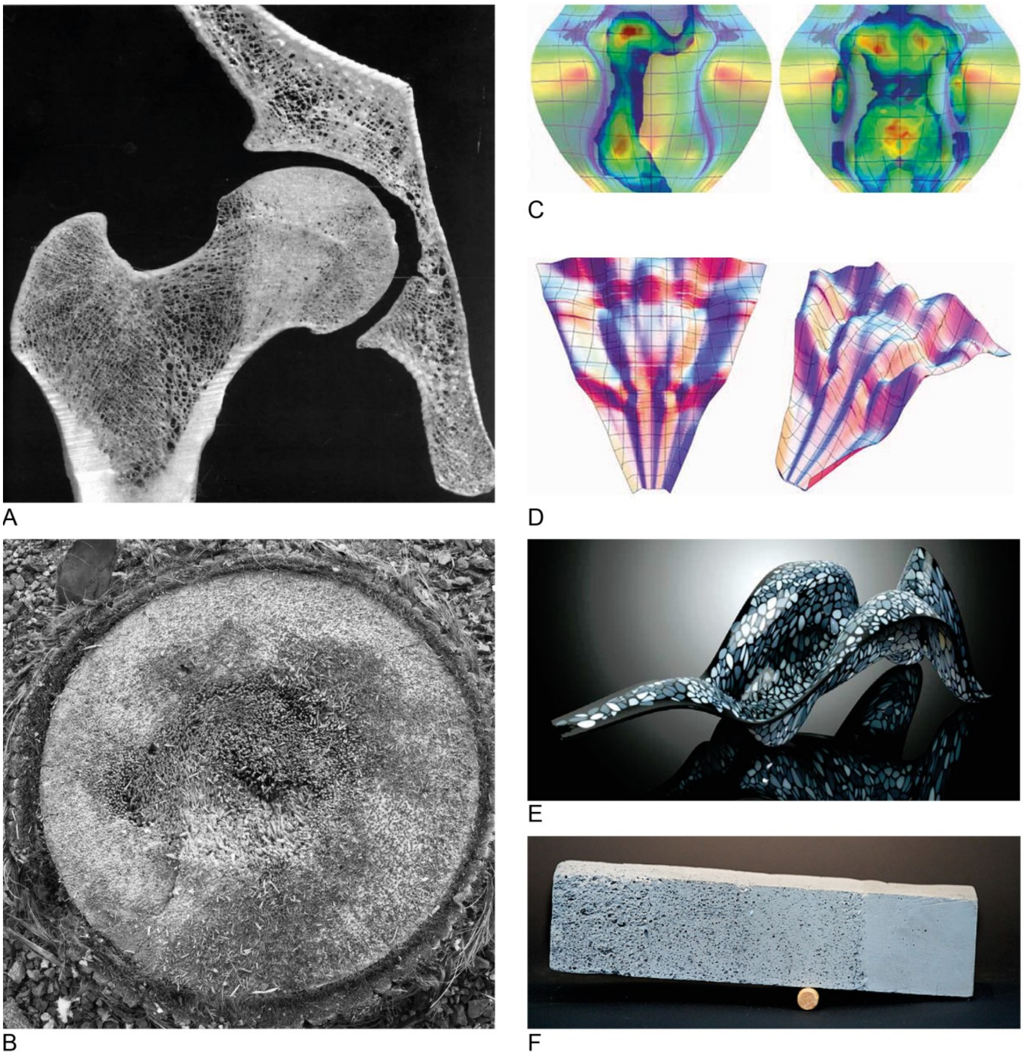


Figure 10: Biological and artificial gradient structures. A) Femur head cross section highlights biological structures achieve varied internal spatial organisations by locating materials and varying their properties in relation to demands they are exposed to, for example, the vaulted structures of trabecular bone located at lines of compression and tension compared to lamellar layers of osteons that make up cortical bone. Source: Nachtigall, W and Blchel, K. Year: 2000). B) Palm tree cross section reveal variable densities in relation to bending stiffness along its height, enabling materials efficiencies. Significantly, the material efficiencies increase over time (Rich, 1987). Source: Highfill, K. Year: 2004. C - D) Pressure map studies informed the analytical stages of MBDC process to generate the form, structure and materiality, for example, a body pressure map is used and the analysis is used to generate a variable material chassis lounge (Oxman, 2009). Source: Oxman, N. Year 2008. E) Prototype chassis lounge 3D printed with variable material properties, creating integrated performance orientated designs. Source Oxman, N. Year: 2008 - 2010. F) Variable linear gradient of concrete achieved by "adding a foaming agent (aluminium powder)" (Oxman et al., 2011). The material reactions here demonstrate the abilities of material computation to generate volumetric and linear gradated materials. Source: Keating S. et al. Year: 2011.

2.5 Gradient Based Designs

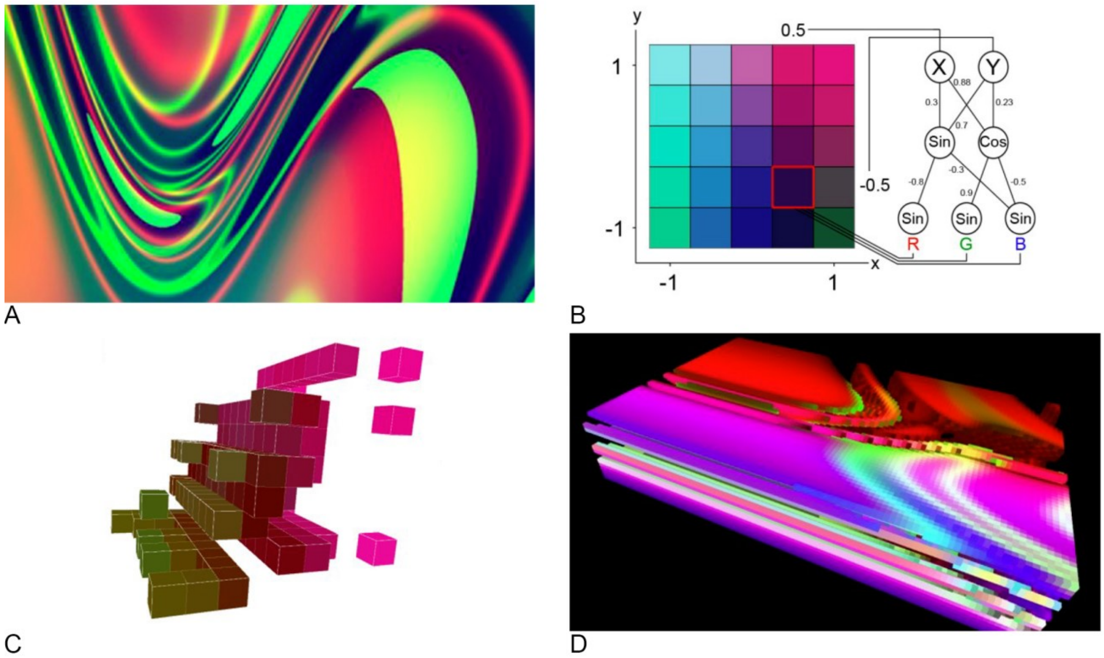


Figure 11: CPPN-NEAT patterns and relationships. A) Infinite voxel pattern resolution is possible as the CPPNs regenerate new colours when zooming into patterns. Source: Richards, D., and Amos, M. Year: 2015. B) RGB colour generated by feeding the nodes co-ordinates into the CPPN and using various mathematical functions. Source: Richards, D., and Amos, M. Year: 2015). C) Issues of buildability as voxels can be located within free space. Source: Richards, D., and Amos, M. Year: 2015). D) 3D volumetric patterns based within Cartesian space. Source: Richards, D., and Amos, M. Year: 2016.

As mentioned previously in MBDC individual voxels can be assigned with various properties: colour, rigidity, transparency among others. As a result volumetric material compositions can be achieved through out a digital designs' geometry as they can be made up of varying voxel patterns or gradients (Michalatos and Payne, 2013). Recent advancements have enabled volumetric patterns to be created from vast numbers of voxel, combining this with the ability to programme the voxels properties in relation to multiple design demands (structural, acoustics, aesthetics, transparency) enables multi-material gradients at a highly granular level that are functional (Bader et al., 2016a, Richards and Amos, 2016) i.e. digital design composed of volumetric functional gradients. In this context function relates to material properties informed by design demands and gradients are the gradual transition from multiple material types to another, for example, from hard to soft and from transparent to multi-coloured, which occur across a volume of space.

Now imagine being able to harness the ability of tuning and adapting all of the digital models' local material properties in conjunction with its complex global geometry and being able to do this physically on the fly. This could lead to totally new artificial material possibilities, such as body armour that repairs itself when damaged or splints that grow and change composition as broken bones heal, . In order to develop the idea further of how these types of design strategies could have a discourse with and potentially benefit from combining with material SA a methodology of particular interest is examined.

The CPPN-NEAT methodology employed and developed by Richards and Amos is examined as it generates highly granular material gradients that are also functional and evolvable. CPPN stands for *Composition Pattern Producing Networks* (Stanley, 2007) and these patterns can be combined and evolved by the evolutionary algorithm NEAT, which stands for *Neuroevolution of Augmented Topologies* (Stanley and Miikkulainen, 2003), the definition and brief non-technical description of this methodology is also provided by Richards and Amos (Richards and Amos, 2015). However, the focus is on the exciting strengths afforded by the CPPN-NEAT strategy and the gradient patterns created and relating them to potentially programming material scale SA throughout a fabrication process by guiding and determining environmental conditions. Figure 11 highlights some of the challenges that arise from voxel based designs, which reveal potential opportunities when combining CPPN-NEAT designs with material self-assembly. The several strengths afforded by this methodology are:

A) Infinite resolution of the functional patterns is possible (Richards and Amos, 2017); imagine patterns within patterns. The benefit of this highly granular digital resolution begins to resemble physical materials at an extremely small scale and can accommodate or generate designs that are not homogenous. Meaning, potential less defined material characteristics could be guided during physical material growth in comparison to typical tools based on B-reps, as the physical and digital materiality and resolutions become similar.

B) Scalability is also afforded by the patterns generated as they are based on local neighbouring voxel relationships. The patterns are also highly flexible and can be easily manipulated in real-time, much like the digital parametric design platform *Grasshopper,* but significantly the volumetric patterns can be easily evolved, even as the material resolution increases (Richards and Amos, 2016). This addresses issues of employing evolutionary algorithms as they become cumbersome when high degrees of freedom are introduced (Richards and Amos, 2016) i.e. increasing the number of parameters to manipulate a designs' properties makes them cumbersome and slow. The benefit of this means multiple digital design options can be explored by steering their parameters (Kilian, 2014), which could become more prominent if physical designs could adapt to demands on the fly.

C) The significance of real-time manipulations and analysis of weighting's between CPPN's relationships to generate the patterns further strengthens the discourse with material computational processes as the time lag or discrepancies are reduced, potentially enabling real-time analysis between digital and physical simulations. As previously mentioned the strengths of linking physical and digital computation are exploited within evolutionary robotics. The time and resolution similarities could possibly facilitate the governance between bond type (mechanical, chemical, electrostatic, surface tension), duration, 2D or 3D location and physical material type in relation to performance demands. Material connection types have been explored at small scale (Hiller and Lipson, 2009), with semi-permanence enabling programmable reconfiguration (White, 2005, Zykov et al., 2007, Gilpin et al., 2010, Levi et al., 2014).

D) They are robust as the CPPNs are not based on predetermined associations, i.e. they are non-linear, which again aligns non-linear material behaviour like plastic deformation witnessed in Hooke's law. The combination of this with the ability to analyse them in real-time lends their abilities to possibly be used to determine what fabrications stimulus or environmental conditions that make up the tuneable environment can suppress or promote more discrete material properties (surface texture, porosity, density) of a SA material platform when needed.

E) 3D digital designs generated from volumetric voxel patterns using CPPNs produce challenges in regards to physical buildabilitiy, as voxels can sometimes be located in space without connection to surrounding voxel networks that connect to a ground plane (Richards and Amos, 2015). A challenge that needs to be addressed as these digital designs are typically fabricated using multi-material additive manufacturing technologies. However, such challenges could be less pertinent if the design tools were used to guide a fabrication method based on material self-assembly. This is because logics of buildability would be inherent within the materials as they are physical and their interactions are governed by physical conditions, such as gravity. However, new challenges would arise by combining the two that are unforeseen without implementing an experiment to combine them both.

Now in relation to the gradients there are two significant points of interest highlighted by these digital material gradients: 1) designs based on global and local features can be programmed and reprogrammed across the designs length scales as demands change, which not only begins to mimic biological process where materials can be tuned but could go beyond them as materials could completely change their properties if demands radically change, if they are made out of materials that could be re-programmed. *2)* They provide a transition between various material types (stiff to soft) that do not have an abrupt boundary or interface, an incredible example of this can be found biologically in the jumbo squid's beak (Tan et al., 2015). However, physically dissolving these material boundaries depends on how the design is fabricated and the mechanism that enables material transitions. Understanding ways this is achieved could lead to physical gradient patterns that can be iteratively re-programmed over time. A mechanism that achieves this will be highlighted in the following chapter which examines fabrication processes.

2.6 Chapter Summaries

The main points of interest from design processes examined in this chapter are briefly summarised below.

- Otto demonstrates that various material types can compute forms and organisations. These forms are governed by initial, resultant and contrasting conditions and material properties. However, forms become static as conditions are not deliberately manipulated on the fly, nor are interrelationships discovered as resultant conditions or material interactions are monitored.
- Digital parametric design platforms can create digital designs as well as represent Otto's experiments that can be augmented on the fly. This is possible by manipulating variables of parameters associated to the design's geometries. However, linear geometric interactions are predefined, and B-reps treat materiality as homogenous, resulting in scalability issues, abstractions and inaccuracies from real world material interactions.
- Both MBC and CPPN-NEAT strategies address the issues homogeneous and linear materiality behaviour of B-reps as models are generated from voxels, which enables performance driven adaption, material remodelling and multi-materiality and has synergy with material scale self-assembly. Significantly these abilities are not fully realised within physical materials.
- The CPPN-NEAT strategy also affords scalability in regard to volumetric voxel resolution and time taken to analyse pattern relationships as they are represented as mathematical functions. Critically, the analytical abilities of CPPN-NEAT could be used to derive and govern nuanced interrelationships between stimulus and less defined material properties, such as material texture.

The following chapter will examine a variety of fabrication processes to understand how they are related to the design process, which informs how they fabrication process interacts with material components and determines material properties, i.e. how deterministic is the fabrication process. Additionally, logics and mechanism are highlighted to understand how and at what scale material computation occurs or could occur in these processes and how it is guided.

3 Fabrication Processes & Searching for Material Computation

"It is increasingly understood that – in its broader definition – computation is not limited to processes that operate only in the digital domain. Instead, it has been recognised that material processes also obtain a computational capacity – the ability to physically compute form" (Menges, 2016).

Typically a linear design and fabrication process still predominates within *Computer Aided Design* (CAD) and *Computer Aided Manufacturing* (CAM). Meaning any design changes (augmentations) that occur to the digital model post fabrication are not typically updated in the final artefact or materials i.e. there is a separation between design and fabrication processes because of the linear nature. There is no feedback between the two. CAD/CAM processes are also typically deterministic i.e. the shapes created in CAD software are specifically fabricated using a CAM process where there is no intended deviation (due to technology tolerances) from design concept to physical product. CAM processes are not typically employed to guide material computational processes, they impose form upon materials. A ramification of these deterministic processes could limit potentially highly desirable properties from emerging or new typologies to be revealed within the fabrication process not previously conceived with the design process (Tibbits and Flavello, 2013).

A methodology that addresses the challenge of linear fabrication processes is *'Persistent modelling'* (Ayres, 2012b) and will be discussed in greater detail in the next chapter. In order to unpack the typical linear and deterministic processes further this chapter examines multiple fabrication processes, from: various additive manufacturing methods, robotic agents, biological agents and granular jamming. In each approach the fabrication process becomes somewhat less deterministic and reveals other potentials afforded as a result. In order to draw parallels between the fabrication processes examined and understand how incorporating self-assembling within these strategies could potentially enrich their abilities they will be discussed in regards to: logics, material properties, and mechanisms between material components that highlight where material computation is performed or not. Significantly, it is the role of material computation in these processes that is of particular interest and more specifically; where it can or does occur, the mechanisms that enable it and how they can be manipulated to understand how fabrication processes based upon them and how they can be guided via digital tools. It is also important to highlight the fabrication technologies and processes (and later material platforms) mentioned above as they could also lead to adaptive structures. However, their inherent implications of how they interact with materials will be discussed.

Otto's form finding experiments established how designs can be generated by engaging with material computations. A primary benefit was; how setting up conditions and how these conditions can be varied (inducing stimulus) throughout the 'form finding' process can manipulate both the material properties (local) and the designs 3D shapes (global) simultaneously. The experiments reveal how maintaining, changing and tuning stimulus can be used as the fabrication mechanism for guiding material scale SA and emergent properties, which helps to envision a design and fabrication system based on tuning stimulus. By tuning and adapting stimulus throughout a fabrication process could enable a structure to adapt its shape and properties across is length scale, e.g. a buildings global shape change would also be related to alterations occurring to internal architectures to become denser or more rigid if the building became larger, leading to greater material efficiencies. A main challenge that is prominent in the analogue models of Otto was the lack of feedback between material computational processes, material formations and design information, which became especially apparent in the more granular experiments (Otto, 2003, Schumacher, 2009b). The limited feedback opens up challenges associated with material behaviour under certain or variable conditions, which are a factor not particularly evident within deterministic modes of fabrication. The big issue of engaging with material behaviours in the fabrication process is that they can be non-linear when subjected to forces or fluctuating conditions (DeLanda, 2015) and can be compounded with an increasing number of material units or granular materials as the interactions become more complex (De Wolf and Holvoet, 2004). Meaning it can become increasingly difficult to predict material behaviour or determine if a desired or potentially desirable material property (shape, composition, volume) has been fabricated when a form of feedback is not present. Systems can become increasingly complex based on simple rules (Kelly, 1994, Doursat et al., 2013). The challenges of increasing complexity and non-linear material behaviour are issues to bear in mind with the intention of developing an adaptive design and fabrication system based on material computational processes of SA materials that do not have the capacity to self-sense or intuitively provide feedback when subject to varying stimuli in order to guide them.

The intent of this chapter is to discuss the benefits of advancements in CAM processes but also understand alternative means of how fabrication processes can interact with materials so form does not have to be imposed upon them but can come from within the materials (DeLanda, 2004). The chapter will highlight alternative means by examining where material computation can or does occur within CAM technologies, how it is initiated and how it can be guided. Finally, the chapter will also form a foundation for selecting material platforms discussed in chapter 5 that will be employed within the design experiments.

3.1 Searching for Mechanisms in Additive Manufacturing

The focus of this section is on current additive manufacturing process (AM), which have recently enabled a manufacturing process that produces materials with variable properties (Oxman, 2011b) and functional gradients (Oxman et al., 2011, Richards et al., 2017). Meaning material compositions and or internal architectures do not have to be homogeneous, leading to less material waste and higher degrees of customisations (Doubrovski et al., 2015). This ability to manufacture designs by discreetly controlling where material is located has allowed for physical materials to be programmed, which leads to multi-functional structures (Oxman, 2010b, Oxman, 2012). The three types of AM of particular interest are: multi-material AM (Richards et al., 2017, Bader et al., 2018a), C*omputed Axial Lithography* (CAL) (Kelly et al., 2017a, Kelly et al., 2019) and *Rapid Liquid Printing* (RLP) (Hajash et al., 2017). The aim of examining multiple strategies of AM will be to determine how material computation occurs and how the various AM strategies could be combined or extended by further utilising stimulus as the fabrication mechanism.

There are several forms of AM reviewed: *firstly,* multi-material layer-by-layer approaches, which uses light (e.g. ultra violet) as a stimulus to change that state of the material being deposited (per layer), from liquid to solid, that makes up the product being fabricated but additionally reveals where material and the type of material computation that occurs. *Secondly,* Computed Axial Lithography (CAL) highlights how AM processes do not have to be restricted to layer-by-layer logics by orientating materials around continuously updated stimulus (light projections). *Thirdly,* Rapid Liquid Printing (RLP) demonstrates how contrasting materials can be used as a support medium to suspend and maintain a materials 3D position throughout fabrication, which alleviates layer-by-layer restrictions. Examining these AM strategies reveal how material computational processes within them could potentially be further exploited by combining aspects of all three strategies, providing a basis for experiments that could create an adaptive AM design and fabrication system.

3.1.1 Heterogeneous AM: layer-by-layer

Figure 12: 'Lazarus' is a product scale, contemporary death mask fabricated using layer-by-layer AM technologies, which can deposit multiple materials at high precision. The geometric forms and material composition was generated using the Data-driven Material Modeling (DdMM) strategy (Bader et al., 2016a). The various colours highlight the extremely high resolution and multi-material properties achieved from advancements in AM. Advancements have enabled 300-600 ink droplets per inch to be controlled in a build volume of 500x400x200mm enabling 929 billion voxels to be addressed (Bader et al., 2018a). The printers' ink droplets properties are controlled by digital models typically created from voxels i.e. digital voxels represent the physical ink droplets. Source: Bader, et al and the Mediated Matter Group MIT. Year: 2016. Photograph: Reshef, Y.

Typically to design and fabricate physical structures composed of multiple materials (as described in section 2.4 material based design computation and section 2.5 gradient based design) a designer digitally defines where the selection of discrete materials are within the designs' volume and either assembles the parts, or more often fabricated in one piece using layer-by-layer additive manufacturing technologies (Oxman, 2011b, Oxman et al., 2011, Michalatos and Payne, 2013, Bader et al., 2016a, Richards et al., 2017, Bader et al., 2018a). The various resin materials deposited by the print head in each layer are cured by exposing them to the stimulus of light (of a certain wave length), which changes them from liquid to solid. Again, overall this fabrication approach is highly deterministic, however, before the light cures (solidifies) the various resin materials, the extremely small droplets of resin perform a material computation process in the form of diffusion, where neighbouring liquid droplets of resin diffuse and mix with one another (Bader et al., 2018a). Diffusion enhances the material gradients but leads to issues of tolerances regarding visible legibility (Bader et al., 2018a) as the various materials to mix, preventing defined boundaries between them. But because the diffusion occurs on such a small scale it is highly controlled. Meaning all the different materials do not just diffuse and mix with one another and as a result of the controlled diffusion, high degrees of material variation can be achieved at the product and wearable's scale (see figure 12). The interesting factor is that the diffusion amount varies depending on the resin type and colour (Bader et al., 2018a), which opens up parameters for potentially guiding the diffusion process as a means of continuous fabrication in combination with other stimulus, such as: light, surface tension, viscosity, heat. *Functionally graded rapid prototyping* (FGRP) (Oxman et al., 2011) and *water-based fabrication* (WbF) (Soldevila and Oxman, 2015) are another approach to AM that exploits the mechanism of diffusion to achieve continuous material gradients. WbF achieves these gradients by creating a palette of water based material gels with a varying concentration of chitosan. The higher the chitosan concentrations in the mixture the stronger the material is. The various solutions can be combined by extruding them through a connected nozzle to create multiple material compositions throughout the fabricated design. Meaning, the material properties can gradually varied by altering the amount and composition of the mixture extruded so various material rigidities and transparencies can be achieved. The materials diffuse with one another before they cure and achieve less defined material boundaries (Soldevila et al., 2014, Soldevila and Oxman, 2015, Soldevila et al., 2015).

The overall adaptability of the physical artefact is limited using these layer-by-layer fabrication strategies. Overall adaptability meaning the degree in which the physical artefact could change its global and local properties in relation to one another throughout its' volume as well as being able perform material computational processes based on a change in stimulus (e.g. UV light) post fabrication, where additionally, the stimulus could be governed by a digital design tool. These AM fabrication strategies limit physical adaptability because: 1) the material compositions and forms become fixed once fabricated due to the resin materials changing state from liquid to solid. 2) The light stimulus is used to permanently fix the materials state not to guide its potential diffusion abilities. 3) The layer-by-layer logic of this method. For example imagine finishing the fabrication process, then a design demand changes within the digital model, which means the physical internal composition and architectures need to be updated. Due to the fabrication process these required changes cannot be carried out (using the same process) without manufacturing a totally new piece. Comparatively, in Otto's design experiments a change to either local or global properties could be carried out simultaneously, as local and global properties are linked but limited to the properties of the framework they are manipulated within. Now in comparison to the lay-by-layer strategies imagine being able to fabricate structures by guiding the diffusion mechanisms present within them to achieve simultaneous global and local adaptation, which is not restricted to 2D layer build-ups. This is because diffusion can occur throughout 3D volumes, can be prevented by contrasting liquids and at different rates depending on the liquids viscosities, which could potentially result in various surface texture qualities, e.g. high or longer diffusion rates could lead to more delicate, capillary like structures. Whereas slower rates could produce smooth surface textures. The artist Tom Price explored how contrasting materials (tar and resin) can be combined as one to generate contemporary 3D sculptures in the Synthesis 1 and 2 series. The tar and resin contrast visually but they also contrast in material states during the fabrication of the sculptures. The material states contrast as the tar is initially inactive but when combined within the volume of resin, which is curing and heating up (becoming fixed and inactive) the tar becomes active and performs material computational processes. As a result the masses of tar heating up they expand and create a multitude of patterns and properties, from various colours to large dark masses and from fissures fine vapour trails (Price, 2014) (see figure 13). The heat generated by the resin is the stimulus in this system but it is random and not controlled in this process, resulting in random tar patterns, which again become fixed when the heat energy generated by the resin drops below a threshold value needed to active the tars' material computational properties. Again this process demonstrates how material computational processes can generate volumetric, variable patterns that are comparatively difficult to generate digitally. In comparison, the digital models and fabrication methods of AM enable high precision and control over multi-material properties, enabling them to become functional (Oxman, 2011b, Oxman et al., 2011, Doubrovski et al., 2015, Bader et al., 2016a, Richards et al., 2017, Bader et al., 2018a). However, being able to harness and dictate the properties of stimulus (duration, location, magnitude) that impact material computational processes opens up the potential of also being able to create controlled multi-material patterns that are functional and more significantly could be updated based on changes to the properties stimulus.

Figure 13: 'Synthesis I' by Tom Price explores how resin and tar interact with one another. As the resin heats up and cures the tar expands and creates a multitude of emergent shapes and 3D patterns throughout the sculptures volume and at various scales from micro to macro. The patterns reveal stimulus can be used as a generate mechanism albeit random in this context. Additionally, because the resins' state becomes fixed along with the internal patterns, negating the effect the heat stimulus can have on the patterns changing. The approximate dimensions of the sculpture are H: 2000 mm / W: 330 mm / D: 330 mm. Source: Price. T, 'Synthesis I'. Year: 2014. Photograph: Moravec, J.

There are significant challenges to be addressed for developing a diffusion based fabrication system to address issues of the layer-by-layer fabrication process, which have also been alleviated by the following two AM technologies *Computed Axial Lithography* (here after CAL) (Kelly et al., 2017b) and *Rapid Liquid Printing* (here after RLP) (Hajash et al., 2017). These additional methods of AM will be discussed very briefly and then used to speculate on a possible diffusion based fabrication system, which forms the initial concept and early stages for a later design experiment.

3.1.2 CAL and RLP

Overcoming some of the restrictions of a layer-by-layer approach of AM processes has been achieved in two other forms of AM, these are CAL and RLP. Some of the restrictions addressed by CAL are: 1) faster build times as they are not based on incremental fine 2D layer build-ups (Hajash et al., 2017, Kelly et al., 2019). 3) No need for sacrificial support materials, which could increase the range of printable geometries restricted by overhang constraints (Kelly et al., 2017a, Hajash et al., 2017). RLP also achieves the 1st and 3rd point, but additionally RLP can; rapidly change the thicknesses of materials being deposited by changing flow rate or adjusting nozzle dimensions (Hajash et al., 2017).

Typical AM processes where 2D layers of material are deposited in the X, Y and built-up layer-by-layer build-up along the Z plane. Meaning the sequential layers of images used to build-up the object in typical AM processes are orientated along the X and Y axis, making the fabrication process susceptible to gravity i.e. materials cannot be deposited within the 3D printers volume without sacrificial support material below it. Conversely, CAL is a volumetric printing process, where the light (typically ultra violet) is projected into the volume of resin from a series of sources located at different angles. Meaning layers are not built up sequentially but in a single shot solidifying the volume of resin (Kelly et al., 2017b, Kelly et al., 2019). The volume of light is still composed from a series of 2D images (2D sections / slices of the digital 3D model), which significantly are orientated along the Z axis. As the series of images are projected into the volume of resin from multiple sources at various angles a volumetric light stimulus is created, where the series images are serially and continuously updated in the relation to the speed at which the resin tank rotates through the X and Y axis. An added benefit of CAL is that sacrificial support material is negated, as long as the components are connected to one another to some degree (Kelly et al., 2017a, Kelly et al., 2019) (see figure 14). CAL highlights multiple factors in relation to how the effects of stimulus can impact SA material interactions, these are:

- The possible number of stimulus and number of sources that generate stimuli, which additionally can vary over time.
- The ability to combine stimulus from the various sources so they interact with one another. Enabling them to be focused from different orientations and create a volumetric stimulus.

- How the material source being affected can also be continuously orientated (in this case rotated) to subject more of its' volume to the stimuli over time to potentially guide more SA material interactions.

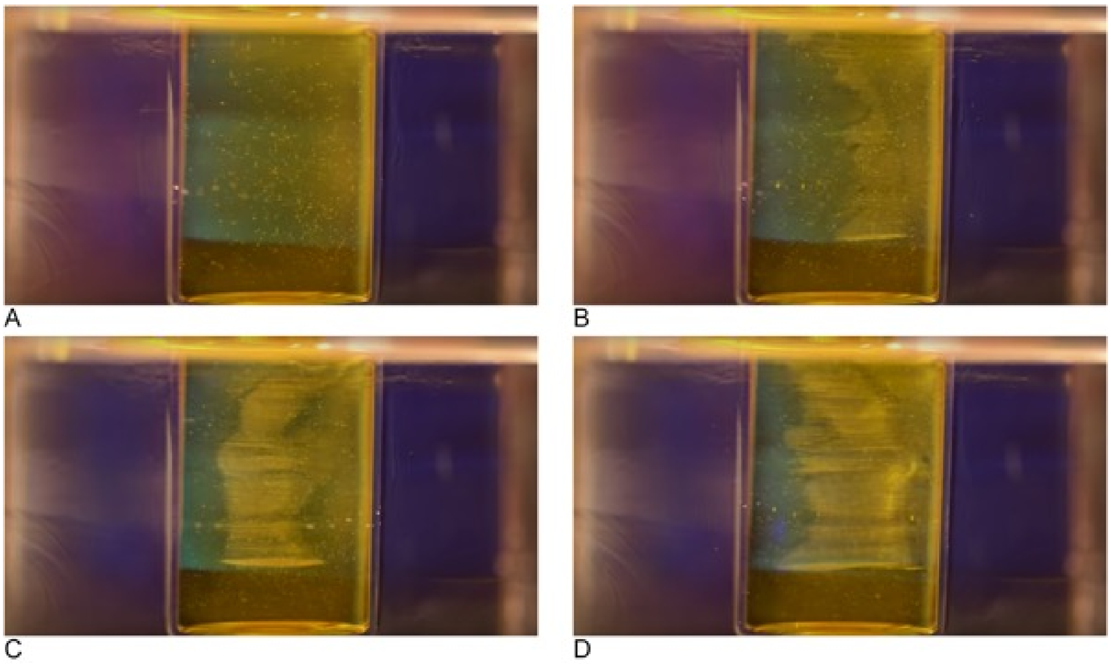


Figure 14: Series of images highlighting the Computed Axial Lithography process, where the objects (in this case 'The Thinker' by Rodin) material volume is manufactured simultaneously unlike typical layer-by-layer approaches of AM. Source: UC Berkley, 2019, Video by Roxanne Makasdjian and Stephen McNally.

RLP achieves the benefits of CAL also but by an alternative means. RLP instead deposits the print material via a nozzle system into volume of gel material, which significantly support the deposited material (see figure 15) (Hajash et al., 2017). This is because the gel and print material contrast materially i.e. they intentionally do not mix or diffuse into one another but the print material can mix with itself. The contrasting support medium is the aspect of real interest as its material abilities could potentially be extended beyond just using it as a support medium by potentially varying its properties via various stimulus (temperature, light, sound, electrical current, pressure) to enable further mechanisms, such as: diffusion rates between support medium and print material, which could enabled multiple surface textures without the need to digitally define them, i.e. they could be material computed and tuned in real-time by changing the stimulus the materials are exposed to. The support material acts as a *tuneable environment* to manipulate material properties. This idea will be speculated upon and imagined in the next section in combination with aspects from the other AM technologies.

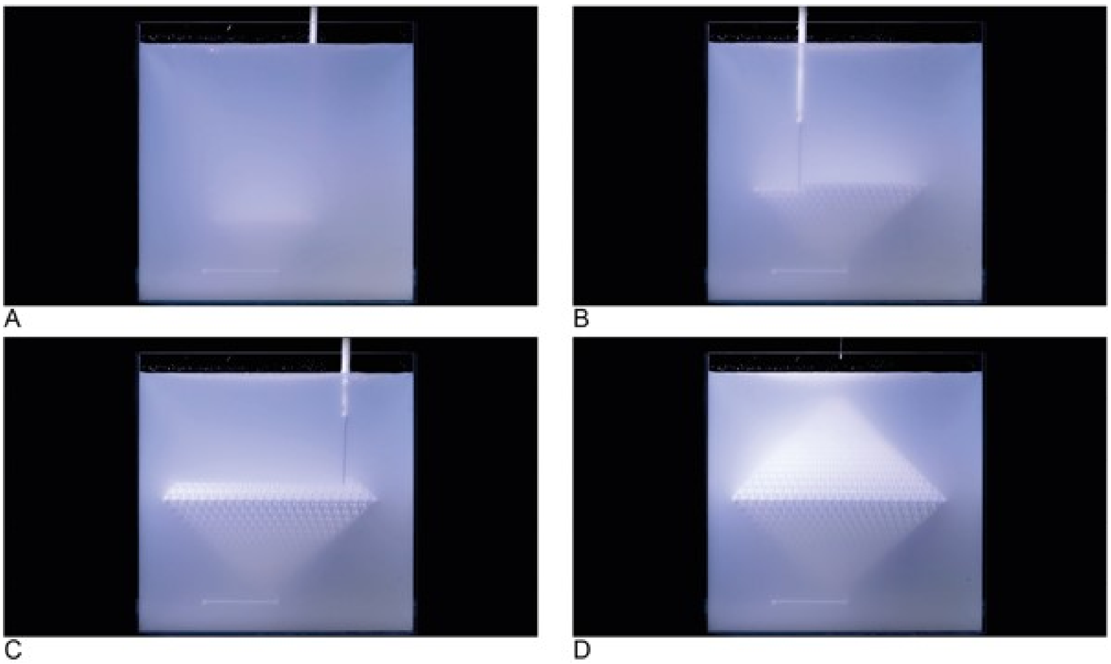


*Figure 15: Series of images highlighting the Rapid Liquid Printing process where material is extruded into a volume of contrasting gel, which supports the material deposited. Enabling rapid fabrication and not limited to layer-by-layer. Source: Self-Assembly Lab MIT, Christophe Guberan & Steelcase. 2017.*There is drawback to these technologies in comparison to the multi-material printers and that is the material palette for these technologies is currently homogeneous, but it could be easy to imagine RLP being combined with the material palettes available within FGRP or WbF to produce designs with variable material properties as the process of deposition is very similar. However, the potential amount the fabrication process and objects being fabricated by them can adapt is limited if subjected to varying stimulus. Perhaps this does not have to be the case; speculating on how aspects of these strategies could be combined and extended by engaging with the mechanism of liquid diffusion present within the multi-material AM process will be briefly discussed next.

3.1.3 Guiding material computational processes in AM

This sub section explores one key factor that has arisen within this section of AM processes; *how material computational processes occurring within AM processes, mainly diffusion, could be guided by stimulus?* The question is explored by 1) combining aspects from the various AM processes reviewed. 2) Examining a stimulus that can create reproducible and reconfigurable patterns in various materials along with potentially combining stimulus to further tune patterns properties. 3) Review additional AM technologies, which utilise or programme materials that can respond to stimulus. 4) Discussing the implications from a possible lack of feedback between material properties and stimulus.

Combining AM processes

The presence of diffusion in the multi-material AM processes revealed material computation occurs within AM but under very controlled conditions (Bader et al., 2018a). Additionally, examining CAL and RLP revealed how collective stimulus and contrasting conditions could be incorporated to guide properties of diffusion or equivalent SA material processes to generate 3D patterns that can be reconfigured in relation to altering parameters of the stimulus that guide material computational processes. For instance, dropping food colouring or ink into water create 3D ink clouds, which have various properties from fine strand like forms to initial masses that ultimately diffuse out into the whole of the waters volume. Imagine being able to alter the properties of the ink clouds diffusion (e.g. rate, location, amount). Expending on this idea of incorporating stimulus and transmitting it through a support medium could begin to generate and guide material patterns of the 3D ink clouds, which could be reconfigured over and begin to leverage new possibilities within a novel process of AM. Being able to manipulate liquid diffusion rates of ink clouds within a 3D volume through stimulus may potentially enable: 1) an AM process not restricted to layer-by-layer logic. 2) Multi-materiality. 3) Adaption that can be achieved across the designs' global and local scale and properties simultaneously. This raises two questions, *how could properties of material diffusion be manipulated? And, what forms of stimulus could be employed to create reconfigurable or repeatable patterns?*

In order to explore the first question and further understand the potential impacts of stimulus on material computational processes, in this case diffusion, the currently inert or potentially underutilised support material in RLP is further examined, as currently it is only used to support deposited material. Instead, imagine being able to use this support material as a tuneable environment that transmits the stimulus (e.g. high frequency vibrations, agitation, light, heat) through it and upon the deposited materials. In doing so it may be possible to guide properties of diffusion to create: multiple textures, colours, patterns, compositions and shapes. The aspects from each respective AM technology that could enable this are:

- ***Multi-Material Printing*** & ***Water based Fabrication*** - The abilities of material to diffuse and mix with one another at various rates and scales.
- ***Computed Axial Lithography*** - Continuous projection of an updated image forming a volumetric light, of various wave lengths (ultra violet to infra-red) into the volume of print material as it rotates to change the state of materials (e.g. viscosities) that could inhibit or enhance diffusion rates.
- ***Rapid Liquid Printing*** - The potential use of the support mediums to manipulate diffusion properties by inducing varying conditions upon the deposited material as environmental stimulus could be transferred to them through the support material, making is a tuneable environment.

Examining Stimulus

Exploring the second question of what stimulus or collection of them could be transferred through a support material to guide and produce reconfigurable, reproducible diffusion patterns could be many. However, the use of various sound frequencies has been demonstrated to create a multitude of 2D patterns, which are reconfigurable and reproducible (Chladni, 1830, Jenny, 2001). Historically, Chladri examined how various sound frequencies produced a multitude of 2D patterns created of sand particles place on a Chladri board (Chladni, 1830) (see figure 16a). The 2D sand particles can be reconfigure in real-time by changing the frequencies induced upon the board, (traditionally by running a violin bow along the Chladri boards' edge, which transfers set values of energy onto the sand particles. The patterns can reconfigure as the sand particles are not physically bonded. Significantly, set frequencies produced certain patterns, meaning, a stimulus can be used to produce repeatable 2D patterns that can be reconfigured in real-time. Jenny extended this research and termed it cymatics by carrying out multiple experiments with various materials, sand, fine powered and liquids with various viscosities (glycerine) (Jenny, 2001). Interestingly, the various material platforms subjected to various frequencies highlighted other properties could be achieved, from regular lattice patterns to 3D patterns as a result powder material jamming and creating 3D sloped formations. Briefly, the main points of interest from these experiments and the various materials used are:

- *Firstly,* the impact the frameworks' (board or liquid container) dimensions and shape has on the patterns created. Meaning the contained could also be used as a means of guiding SA material interactions along with stimulus.
- *Secondly,* Inducing the sound upon glycerine created regular linear and lattice patterns being created on the surface of glycerine liquids (Jenny, 2001). Critically, this highlights being able to change the properties (e.g. viscosities) of the materials being subject the sound frequency stimulus by inducing other stimuli such as light could further leverage other patterns that could be created. For example, maintain a certain liquid viscosity in some areas to produce regular grid patterns and changing its viscosity in other (via heat for example) to create smoother patterns could enable multi-material properties that occur within material computation processes to be tuned with greater control and on the fly.
- *Finally,* it is possible to create 3D patterns by using fine lycopodium powder as the layer on top of one another (see figure 16B-D). Meaning, 3D patterns of sloped formations could be created as higher energy stimulus (sound amplitude) could be used to distribute the power globally and the slopes could be fine-tuned with lower energy supplied as this effects the 'angle of response'(Jaeger et al., 1998) of the powder.
- Additionally, the *Resonantia* exhibition by the artist's Louviere and Vanessa also reveals the complex 2D patterns also possible by inducing sound through water to guide ink diffusion patterns (Louviere and Brown, 2015).

The 2D abilities present within these series of experiments raises the question; *how can these patterns be fabricated and reconfigured throughout a 3D liquid volume?* This is where the use of the support material in RLP could become highly useful in combination with CAL's ability to change the state of material at specific locations by projecting light into a volume. For example, using this CAL ability to change the RLP support materials viscosities and diffusing liquid materials through them. This could result in various surface textures being created as diffusion occurs. Imagine print material diffusing though volumes of liquids with low viscosities creating very fine strands, almost like capillary networks and liquids of high viscosities producing smoother textures. This could open up the possibility of guiding material computational process of diffusion by changing liquid viscosities and additionally moving or generating patterns by inducing sound through the support mediums to guide diffusion patterns. Significantly, these stimuli could be tuned and updated on the fly based on augmentations to a digital design, which enables the physical material to reproduce any digital changes. Meaning, design and fabrication instructions are tightly linked.

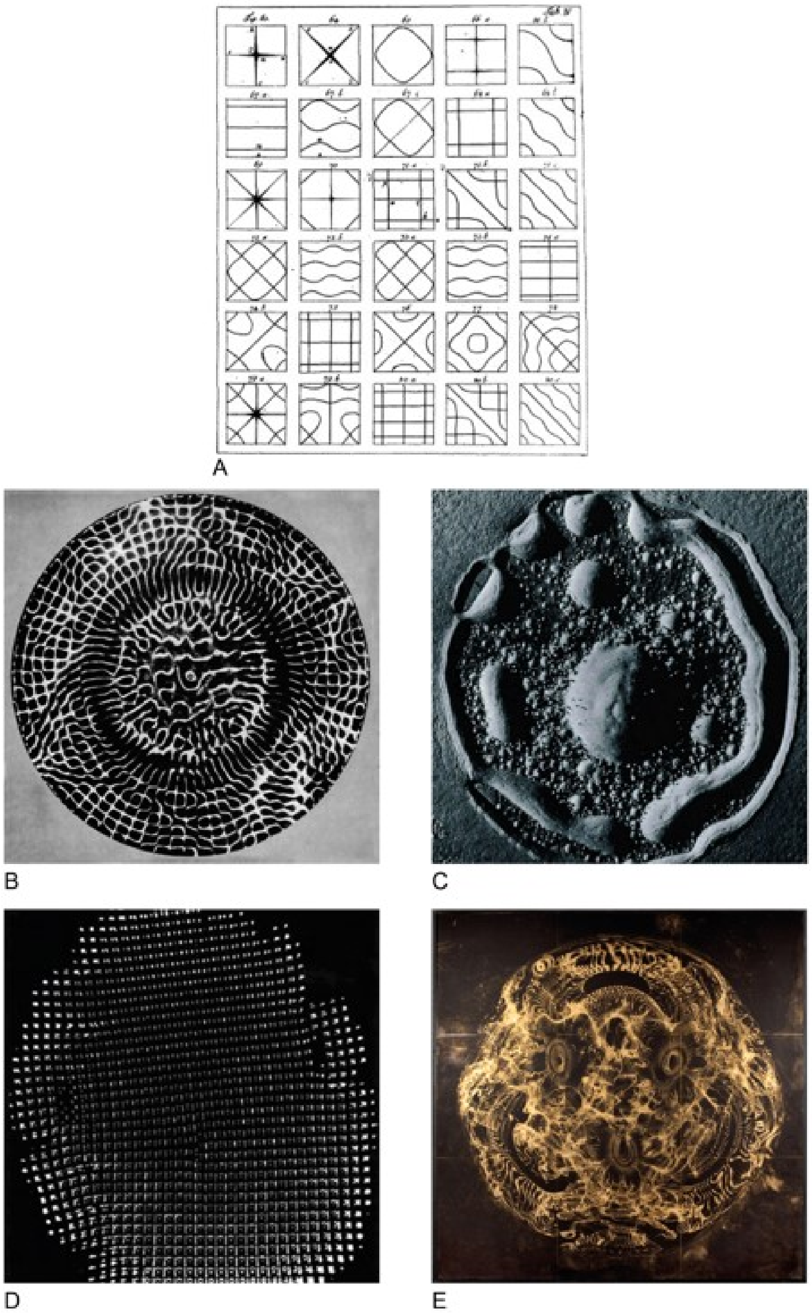


Figure 16: Various frequency / cymatics patterns. A) Various 2D Chladni patterns produce from different sound frequencies on a square Chladni board. Source: Chladni. E, Die Akustic, 1802. B) Hanns Jenny documenting various sound patterns what he called Cymatics. The 2D patterns created by the sand particles are affected by the plate shape. The circles diameter is 500mm. C) 3D Cymatic patterns produce by fine lycopodium powder within a 280mm diameter. D) Regular 2D Cymatic lattice patterns are produced within glycerine, no scale given. Source B-D: Jenny. H, Cymatics: A Study of Wave Phenomena and Vibratio, 2001. E) 1 out of 12 images by artist's Louviere + Vanessa highlighting complex 2D sound patterns produced in water with ink reveals how diffusion can be affected by sound frequencies. 1220 x 1220 mm photograph. Source: Louviere + Vanessa, Resonantia, 2015.

Programming materials in AM processes

Two other research areas that push the boundaries of AM by incorporating materials that can further engage with stimulus as the fabrication mechanism are Cronin's Chemputer™ (Cronin, 2011b) and Grigoryan multi-vascular networks (Grigoryan et al., 2019). *Firstly*, Cronin develops a modularised, inexpensive desktop process to create pharmaceuticals; enabling molecules to be introduced to solutions at controlled times and conditions, which are governed by a digital platform (ChemCAD) (Kitson et al., 2018, Steiner et al., 2019). Additionally, this envisioned the possibility of fabricating designs' within tanks of liquid (BEA, 2016). *Secondly*, Grigoryan achieves highly delicate vascular structures (artificial alveoli) that have functional internal channels, are biocompatible and are monolithic (highly laminated prints, which act as a whole and not layer-by-layer) by incorporating materials (food colouring) into a hydrogel volume (that print material), which inhibit the light stimulus of the AM process (Grigoryan et al., 2019). The fabricated vascular networks are able to have solutions pumped around them as an artificial air sack (within the vascular network) is inflated and deflated. Resulting in pressure changes being transferred through the hyrogel and upon the liquids within the vascular network (as the network structure contracts and expands); causing fluids to circulate throughout the artificial networks. Again, the hydrogel volume acts as its own support material like that in RLP and reveals further potentials of exploring this somewhat secondary and unused space to be able to engage with, guide and leverage material computational processes. The extended benefits of integrating other materials (molecules, bacteria, hardware) into the fabricated components will also be discussed in chapter 5.

Feedback Implications

Tuning and adapting diffusion ink cloud formations within a digital design and fabrication system also raises the issue of feedback between digital design tools being used to govern the stimulus, which affect and generate desirable patterns. This raises the difficult challenge of determining feedback mechanisms between material properties and conditions so they can be mapped to relevant digital design tool parameters so the digital tools can be used to inform stimulus variables, such as, duration and magnitude of vibration frequencies or agitation. The potential lack of feedback between properties of an ink cloud diffusing and design tools is similar to the issue highlighted in Otto's experiments, in particular the *Occupation and Simultaneous Distancing* experiment as the clusters of polystyrene chips are not monitored or used to affect a subsequent condition. For example, within this setup the chips impact on the magnitude of the needles magnetism is not monitored, which could be used to approximate the amount of chips in the cluster patterns. If the chips do not impact the needle’s magnetism then that feedback mechanism is redundant and others must be determined or incorporated.

In order instil and leverage feedback within the developing notion of an adaptive design and fabrication system material platforms will be further examined in chapter 5 to establish what mechanism and resultant effects inherent within the material can be used establish feedback and relationships between material properties, stimulus and parameters of the digital design model. Furthermore, it can also be argued that being able to update material properties by continuously varying stimulus, updated by digital design tool instructions could also be achieved by *Computer Aided Manufacturing* technologies and at very high precision. For this reason several forms of robotic fabrication will be briefly discussed to highlight their logics and relationships with materials.

3.2 Robotic Agents

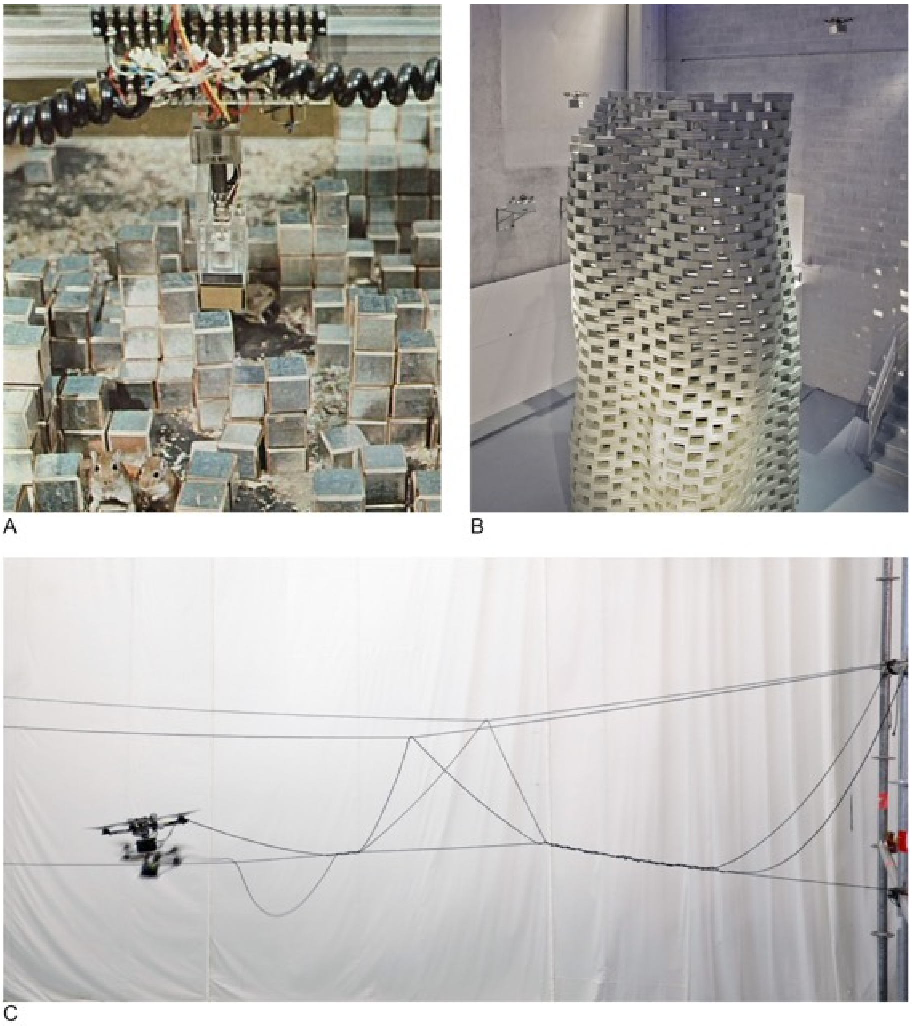


Figure 17: Various robotic fabrication processes. A) SEEK was able to adapt the 3D form of its structures based on gerbil activity with the material units but was constrained by the dimensions of the framework. Source: The Architecture Machine Group (MIT). Year: 1970. B) Flight assembled architecture; uses multiple flying robots as construction agents to place blocks. The unit's mobility means materials can be placed anywhere but work under compression. Source: Gramazio & Kohler and D`Andrea, R., in cooperation with ETH Zurich. Year: 2011-2012. Photograph: Lauginie, F. C) 'Building bridges with flying robots; again uses flying robots but creates tension based structures, meaning, the materials reconfiguration are not limited to layer by layer logics and variable properties can be created by weaving more material. Source: Augugliaro,F. Year: 2012.

CAM processes also enable a continuous fabrication process that can iteratively adapt the global and local properties of a structure based on: 1) digital design augmentations, 2) environmental data and 3) analysing material properties:

- *Firstly,* digital augmentations can be used to update (in real-time) the fabrication instructions of the CAM tool (Malé-Alemany et al., 2011, Oxman et al., 2014, Augugliaro et al., 2014, Peng et al., 2016, Kathrin et al., 2016, Sandy et al., 2016, Keating et al., 2017, Yablonina et al., 2017).
- *Secondly,* varying environmental conditions, such as daylight, can be analysed in real-time to inform the automated fabrication process and properties of deposition (location, amount, time) of granular materials (Angelova, 2015). The role and extended abilities afforded by the granular materials will be discussed in the next section. Additionally, the environmental data in the research project SEEK was gerbil activity and how they disrupted the structures individual material components (small metal cubes). The disruptions were monitored by a camera, which informed a robotic arm / gantry activity and where to reposition the cubes if disrupted, resulting in a self-regulating architecture based on feedback between gerbil activity, material components and global form (Negroponte, 1970, Negroponte, 1975) (see figure 17). Typically feedback within these robotic fabrication systems is achieved via video recording and software evaluating if materials have been disrupted (Helm et al., 2012, Sandy et al., 2016, Giftthaler et al., 2017) or what action to carry out based on orientation (Lussi et al., 2018). The drawback to visual feedback is that only external and global properties can be monitored, not the internal material composition, which could limit the system's sensitives. It is possible to inform AM processes of depositing materials based on sensor information (Sadeghi et al., 2017). Localises sensor information could become more useful for creating a distributed network of information to determine what localised and global properties are needed as design demands fluctuate. However, the sensor values need to be mapped to corresponding material properties, for example, imagine an increase in pressure being detected results in an increase in material rigidity being deposited, which could be driven by alterations to a relevant environmental stimulus.
- *Finally*, it is also possible to scan an object to determine its properties, such as global shape, and carry out fabrication processes, such as AM to add material or computer numerical control (CNC) milling to remove material and update the objects shape in line with user analysis, without the need for completely remaking the initial product (Weichel et al., 2015). Additionally, it is also possible to use robotic units (robotic arms) to construct self-balancing stacks from multiple irregular shaped pieces of rubble by: first, scanning the rubble units, secondly, software determines the stacking order and thirdly, the robotic arm stacking the rubble (Fadri et al., 2017). Understanding what the benefits of CAM fabrication processes and their relationship

with materials will be scoped by how they also bare resemblance to properties a self-assembling material process, which are: 1) a distributed system and 2) the ability to re-configure the material units that compose the structure. For these reasons robotic fabrication processes will be examined, which are made up of multiple robotic units that have mobility and can manipulate and re-position the structure's materials. However, this raises the question of how feedback is achieved so structures can be reconfigured.

It has been demonstrated that prototype structures (towers and bridges) can be fabricated within spatial volumes via multiple robotic agents that can fly (see figure 17) (Ammar et al., 2014, Augugliaro et al., 2014). The multiple robotic units are able to act like swarms, meaning construction and different material processes can occur in different locations and converge (Augugliaro, 2013a, Mirjan et al., 2014, Mirjan et al., 2016b). The significant benefit leveraged by the mobility of robotic units is that structures fabricated by them are not limited to the dimensional constraints of a robotic framework, like that of SEEK. Although this raises the challenge of communication between the multiple agents, which is required between the robotic units so they do not crash into one another and as well as enabling the development and process of fabrication to be monitored (Augugliaro et al., 2014, Mirjan et al., 2014). The material components used within these prototypes structures, which are fabricated using flying robots (see figure 17) raise several interesting issues: 1) the uniform and predefined blocks used in *the flight assembled tower* (see figure 17) (Augugliaro et al., 2014) can be iteratively reconfigured but are constrained to layer-by-layer fabrication logics as the blocks work in compression and are stacked on top of one another. 2) The scale and shape of predefined blocks that make up the tower ultimately restrict the degree and resolution at which the tower can be reconfigured by the flying robots as local material variation is limited to the singular block unit / typology. 3) Comparatively, the bridge structures (see figure 17) are not limited to layer-by-layer logics as they work in tension (Augugliaro, 2013b, Mirjan et al., 2013, Mirjan et al., 2016a) but reconfiguration of these structures is difficult as the structure becomes increasingly interconnected and complex as material is added because it comes from one continuous source. However, localised material properties could be achieved as various knot types (Mirjan et al., 2013, Augugliaro et al., 2015) and weaving / braiding patterns can be fabricated depending on the number of flying robots (Mirjan et al., 2013, Mirjan et al., 2016a). 4) Although the fabrication instructions can be updated to alter the fabrication process, ultimately the process and end result is highly deterministic (Kathrin et al., 2016). Meaning desirable traits and novel typologies that could arise are restricted and not uncovered because no deviation can occur. Primarily this is due to the fact the materials are not active components within the fabrication system as the properties that create form (stacking, weaving, AM or milling) are imposed upon the materials. 5) A major benefit though is that the robotic units can handle materials and fabricate structures in space that humans can simultaneously occupy, which makes them useful for architectural applications unlike the liquid based AM processes. In order to address some of the issues raised above granular jamming will be reviewed next because comparatively, the material components play a more active role in what could be seen as a fabrication process. Research into granular matter (Radjai et al., 1996, Jaeger et al., 1998, de Gennes, 1999, Jaeger, 2015, Murphy et al., 2017a) has revealed parameters (phase / state transition, force chain networks, granule shape / properties) for robotic fabrication processes that can be used to guide the structures properties (global shape, packing densities, volume) composed of granular matter, providing the materials with agency (Keller and Jaeger, 2016).

3.3 Granular Jamming

"Granular matter describes large collections of small grains... The grains can exhibit solid like behaviour and fluid like behaviour".
(de Gennes, 1999)

Granular jamming is reviewed as because it has been employed as a material type within digital fabrication processes, where robotic units pour typically granular material on top of one another to create architectural structures, such as walls and columns. Significantly, the material plays a more active role within the fabrication process, meaning material computation processes occur (e.g. local material flow, variable packing densities) based on materials variables (Dierichs and Menges, 2015, Murphy et al., 2016b) and variables in the fabrication process, such as pouring angle (Dierichs and Menges, 2012, Dierichs and Menges, 2016). These variables impact the effects of gravity, which is the main stimulus in this process but it is not directly tuned. Meaning, altering parameters within the material components themselves along with fabrication processes highlights other potential means of engaging with stimulus and material computational processes to create an adaptive fabrication system. In order to understand properties of granular jamming and how they could be employed into SA processes various aspects will be reviewed:

- *Firstly,* an overview of how granular jamming is created and its inherent benefits.
- *Secondly,* how granular materials can change phases, the interactions between materials (force chain networks) and applications based on phase changing.
- *Thirdly,* how typically sloped / mounded granular structures can become vertical architectural structures by combining a type of physical force chain network with granular matter, enabling structures that rapidly reversible and totally recyclable.
- *Fourthly,* how typically sloped / mounded granular structures can become vertical architectural structures by designing granular morphologies, which effects material computational processes and enables walls to have functional gradients based on light transmittance performance. Meaning feedback between material properties, fabrication processes and environmental conditions is attained.
- *Finally,* how local properties of the jammed architectural structures can be monitored by incorporating localised sensors along with how stimulus can be monitored and

used to effect material computation processes so the physical structure resembles a digital model

3.3.1 Granular jamming overview and mechanisms

Granular matter is a collection of solid material units greater than one micron in size as this threshold makes thermal energies impact on them negligible (de Gennes, 1999). Materials can be composed of granular matter and significantly, the matter interacts with neighbouring units when they contact one another resulting in friction (Murphy et al., 2017a). Granular material types are prominent in nature, for example, snow, soil and sand among many others. The collective granules can interact with one another through their own dead weight because of gravity, which transmits forces through the whole material. Gravity is not the only means of transmitting forces between particles, vacuums can also transmit forces (Brown et al., 2010) among others. The forces transmitted between the collection of granular particles produces the phenomena called, *granular jamming*. For example, pouring sand onto a surface produces piles instead of them all running off. This is due to the forces transmitted between the particles and has scalability as witnessed by vast sand dune type structures. However, simply pouring the materials limits them to creating mounded / sloped forms, which are dictated by their *'angle of response'* (Jaeger et al., 1998). This is the maximum angle at which particles can stay in position before they start to flow over one another at the surface, highlighting the particles are not jammed beyond this angle and behave like a fluid at the materials surface, this makes them marginally stable (Levine, 2001) as light disruptions (effecting angle by tilting or by applying load) can cause them to erode in positions until they jam again. Strategies for harnessing granular jamming abilities that are not confined to sloped mounds include: 1) contain the granules within elastic membranes, 2) contain them within cages, like gabion wall structures, which can be used as retaining walls or architectural walls. For example, the Dominus Winery structure by Hertzog and Demuro. Here rocks are loosely contained within wire cages, which produce variable lighting qualities. 3) Design the material units shape (Keller and Jaeger, 2016). Significantly, granular jamming has the ability to change the materials state based on *'jamming phase transitions'* (Jaeger, 2015). Granular jamming enables materials to change state between solid-like into fluid-like instantly (Song et al., 2008). Meaning granular materials have the ability to act as a liquid, where the granular matter can freely flow over one another locally, to one where the material acts globally as a solid due to the granular matter being fixed in position when subjected to stress. These state changes are dictated by a threshold excitation level and interestingly do not have to occur throughout the whole of the material i.e. material can flow over one another locally at the surface of the material but does not have to occur throughout the material (Jaeger et al., 1998).

Three types of granular matter and processes of granular jamming will be examined: *firstly*, granules within a membrane subjected to vacuums to govern jamming phase transitions (Jaeger, 2015), *secondly*, physical frameworks of *force chain networks* deposited by robots to hold granules (rocks) in place and *thirdly*, designed granule / aggregate components, which informs their jamming properties. Additionally, how feedback and simulation is achieved within these material systems will also be examined and to what degree the materials can self-assemble when subject to stimulus. Briefly, the state changing abilities of granular jamming and how they can be guided by manipulating the mechanisms of jamming transitions open up diverse applications from universal robotic grippers (Brown et al., 2010, Amend et al., 2012) to rapidly deployable / reversible architectural structures (Aejmelaeus-Lindström et al., 2017), rapidly fabricated gradient based structures (Angelova et al., 2015) and even displays with variable stiffness's and surface textures (Follmer et al., 2012, Stanley et al., 2013, Ou et al., 2014b). How these abilities are achieved will be sequentially unpacked and will help to understand the active role materials can play in these fabrication processes and how material interactions, state changes, feedback and simulation can be guided by engaging with mechanisms that dictate properties of granular jamming, from inducing global stimulus to informing packing densities based on designed material components.

3.4 Jamming Transitions and State Changing Materials

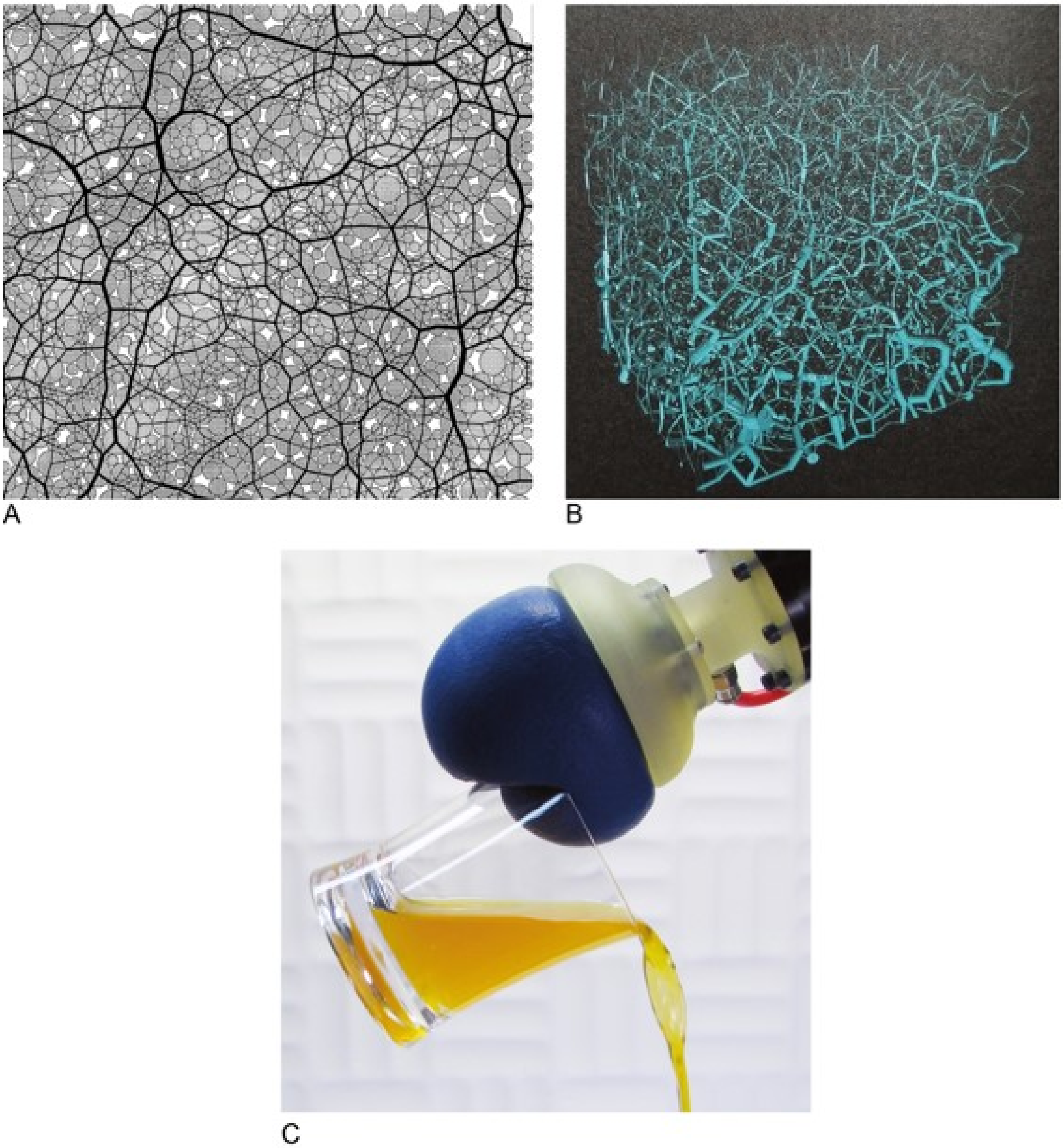


Figure 18: Granular Jamming simulations and universal gripper. A) Computer simulation of a 2D force chain network highlighting path and the network of forces transmitted between neighbouring granules and throughout their entirety, which significantly, can be reconfigured if stress is altered. Additionally, the magnitude is highlighted by the lines thickness, revealing a non-uniform / inherently disordered system. Source: Radjai, F. Year: 1996. B) computer simulation of a 3D force chain network. Source: Murphy, K. Year: 2017. C) Application of granular jamming enables a universal robotic gripping device that can mould over any shape object and grip it when a stress (vacuum) is created within the membrane. Source: Brown, E. Year: 2010.

Granular jamming occurs when neighbouring granules make contact with one another (creating friction) and force is transmitted between them, which results in the state change of the materials properties, from fluid (essentially no force transmitted) to solid. The state change can be termed as a jamming phase transition (Jaeger, 2015). Controlling the jamming transition is typically achieved by inducing a vacuum upon the material units, which are typically contained within a membrane (Aejmelaeus-Lindström et al., 2017) (see figure 18). The ability to control the state (fluid like or solid) of the granular materials by inducing a vacuum upon them when contained within an elastic membrane has enabled a universal robotic gripping device (Brown et al., 2010, Amend et al., 2012) (see figure 18). This is because when the granules are not subject to a vacuum the membrane's surface enables iterative plastic / adaptive surface deformations. In order to unpack how this is achieved a brief non-technical description of the universal robotic gripper head is provided based on how the granules and stimulus occur:

- Granules are encased within an elastic membrane, which are fluid like and can flow over one another easily (they are un-jammed).
- The granules free movement within the membrane can create a negative mould when pressed over any complex shape (see figure 18).
- When the air is removed from the elastic membrane (a vacuum induced) the granules are jammed together and become extremely hard.
- If the vacuum is induced upon the granules as they are moulded over any complex objects surface it is possible to pick it up, even delicate object, such as, eggs and glasses.
- The significant benefit of this state changing ability is that very irregular shaped objects can be picked up with the same, essentially simple tool head.

The properties and mechanisms of jamming raise several interesting factors in regards to materiality as well as highlighting how they can or have developed into novel architectural design and fabrication processes. The two interesting aspects that arise from a materiality perspective are;

- 1) As the jamming effect is dictated by neighbouring materials physically touching one another, which is inherently disordered (they do not have to be in an ordered state / position for the granules to achieve jamming) it opens up material abilities, such as, self-assembly, self-healing, dissipate energy and adaptive shape change of the membranes surface when the granules are in a fluid state (Jaeger, 2015). The jamming effect also opens ups a wide range of material shapes that can perform granular jamming, i.e. they do not have to be spheres but can be irregular shapes, which opens up the space for designing the components shape (Dierichs and Menges, 2016) as well as even mixing materials (fibres and rocks) to help promote jamming and maintain global shapes (Aejmelaeus-Lindström et al., 2017).

- 2) The ability to induce and change the state of the vacuum over time and to varying degrees informs the amount the granules can locally flow over one another until a threshold is reached, which causes the granules within the elastic membrane to temporarily jam together around hold onto the object they are shaped around. The stimulus of the vacuum enables membranes' adaptive surface abilities.
- 3) Interestingly, in regard to the stimulus of a vacuum in this system it behaves globally and creates a somewhat homogenous material response i.e. there is no local variation within the jammed matter, typically it is uniformly hard. Comparatively, when the material is in a fluid state there is the ability to manipulate the local material units in relation to one another. Essentially, in the vacuum and membrane system, it is difficult to achieve localised material properties when subjecting them to the stimulus of a vacuum. However, digital analysis of the forces transmitted between the granules during the jamming phase reveals a rich and diverse vein-like network with significant variation in the forces magnitude, which have been digitally visualised in 2D (Radjai et al., 1996) and 3D (Sanfratello et al., 2009, Murphy et al., 2017a) (see figure 18). These network of forces are termed 'force chain networks' (hereafter FCN) (Radjai et al., 1996).
- 4) The FCN can also reconfigure to form new networks patterns when the stimulus is removed and re-introduced or fluctuates in terms of where it is induced, which enables the self-healing abilities (Keller and Jaeger, 2016).
- 5) The variable magnitudes present within the force chain networks again highlight material computational abilities for generating localised variation.
- 6) The FCN reveal a means for developing a novel fabrication strategy in which the FCN are physically and continuously laid (in the form of a continuous fibre / thick sting) as the granules are deposited (Aejmelaeus-Lindström et al., 2018). Significantly, this removes the confines of typical membranes as well as enabling greater variation in 3D forms, ones not resulting in slopes or mound formations. However, the phase transition is removed in these strategies and the structures cannot be reconfigured based on stimulus as the force chain network has become materialised.

In regards to reconfiguring formations of granular matter based on stimulus and are not confined by a membrane can be witnessed in an example of Jenny's Cymatic (discussed in section 3.1.3) experiments who alludes to the sound stimulus offsetting gravity's effect on the granular materials (Jenny, 2001). The effect of sound frequencies being able to guide granular patterns is particularly evident in the fine lycopodium powder experiments (see figure 16) as a multitude of mound formations and structures can be reconfigured by changing the sound frequencies induced upon the powder. The energy created by the frequencies distributes them and causes them to restack and form new patterns. The materials *'angle of response'* (Jaeger et al., 1998) may also be affected by the sound frequencies. The angle of response dictates the limit at which the granules start to flow across the top the collected slope (Jaeger et al., 1998). Excitingly, this again highlights the role in which stimulus can be tuned and induced upon materials to guide self-assembling patterns (Jaeger et al., 1998) with variable properties potentially leveraged if stimulus could be used to manipulate force chain patterns in which the variable magnitude impacted upon the localised and collective properties of the granular material properties. Imagine larger forces being transmitted upon granules makes them more rigid or made them heat up or causes them to produce energy, like a piezo crystal vibrating when a force is applied to it. Now imagine if a building's structure was created from these types of materials they could potentially generate their own heat for energy as wind loads were induced upon them as the live loadings would impact on the FCN. Dade-Robertson explores how bacteria sensitive to pressure and incorporated into soil can be used to cement neighbouring soil particles together (when subject to sufficient loading forces) and increase mechanical properties, leading to self-constructing foundations (Dade-Robertson et al., 2016a, Dade-Robertson et al., 2017d). Due to the emergent 3D patterns of FCN produced naturally within the soil, only areas beyond a threshold pressure will be bound together. Meaning material efficient foundation networks could be created that can adapt as the loading changes and the FCN update simultaneously because of material computational processes. The use of biological agents (bacteria) that can be programmed to perform computational processes, synthesise materials and adapt to varying conditions will be reviewed in chapter six along with many other material platforms to understand the abilities and strengths for generating an adaptive design and fabrication systems.

As previously mentioned though, the issues of granular matter typically producing mound formations can be addressed by containing them within a membrane. However, other recent strategies have moved beyond the confines of a predetermined membrane. The first strategy to address the issue of mounds basically materialises the FCN by depositing a continuous fibre via a robot. This strategy and its trade-offs will be reviewed next. The final strategy reviewed will be one which designs the shape of the material units and what material properties they achieve when deposited via robotic units.

3.4.1 Between the Granules

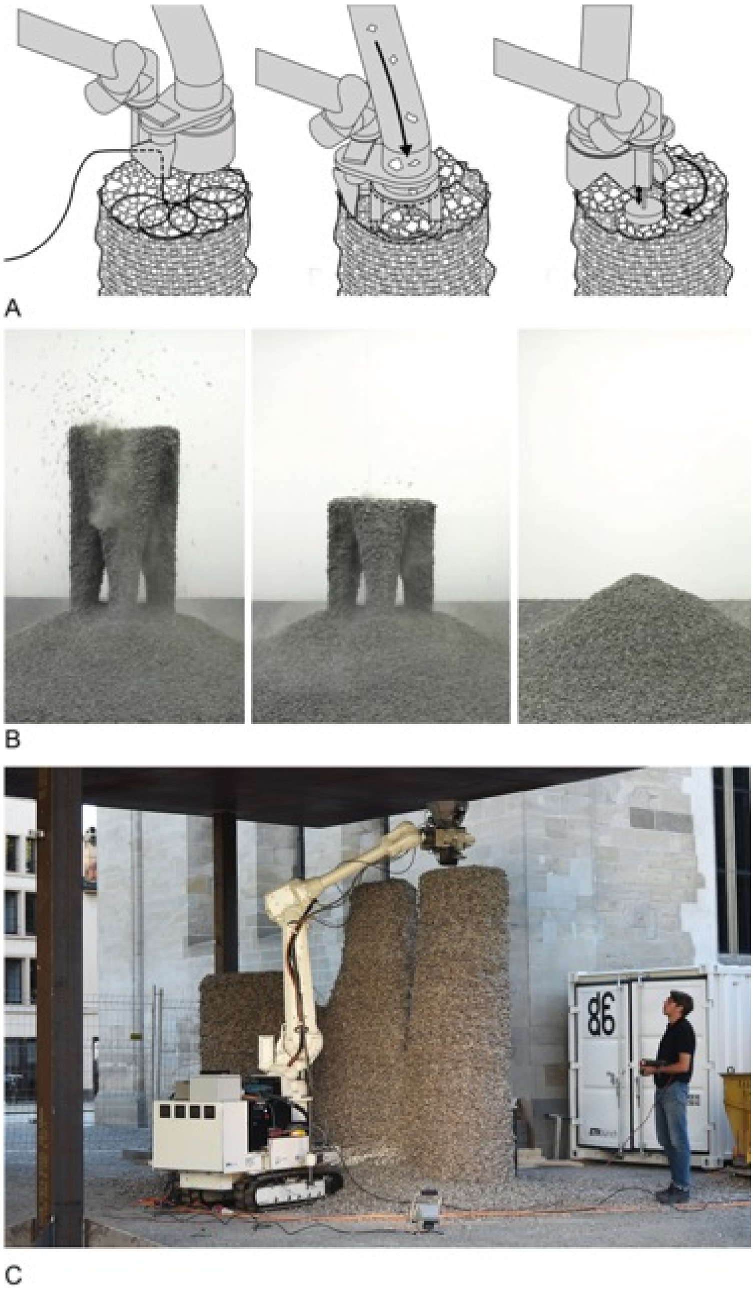


Figure 19: Loading bearing granular jamming processes and prototypes. A) Illustration of granular jamming constructing process, where the robotic arm simultaneously depositing string and aggregates in incremental layers. The string enables structures to be created that are not limited to sloped forms. Source: Rusenova, G Year: 2018. B) 'Rock Print', fully reversible and recyclable structures. Removing the string from the top of the structure dismantles it into its constituent parts, highlighted by the series of images. Source: Gramazio Kohler Research (ETH Zurich) and the Self-Assembly Lab (Massachusetts Institute of Technology – MIT). Year: 2015. C) Jammed architectural scale structures fabricated on site without the need for additional formwork. Source: Gramazio and Kohler research / ETH Zurich. Year: 2018.

Fabricating structures out of these aggregate materials marks a shift away from the typical approach of precisely designing and imposing forms on materials, which results in components with specific functions and connection details (Aejmelaeus-Lindström et al., 2016). The main strategy described here focuses on creating viable architectural scale structures that are vertical (walls and columns) as the materials work in compression. The proposed structures are fully reversible by combining abundant aggregate materials (rocks), which have structural capacity with a network string held in tension, which holds the aggregates in position (Aejmelaeus-Lindström et al., 2016) (see figure 19). Various aggregate types and binding materials were investigated to reveal the most suitable combination and strategy for addressing a criteria of: *"buckling length of jammed material column, the load capacity, stiffness, congruent behaviour, and suitability for upscaling to an architectural scale"* (Aejmelaeus-Lindström et al., 2016), which investigate the primary question of stability in order to create viable architectural scale structures termed; *'Jammed Architectural Structures'* (JAS) (Aejmelaeus-Lindström et al., 2016).

An approach of particular interest in this strategy are the role and abilities of the aggregate materials in combination with networks of string and how they are deposited simultaneously via *'direct deposition'* (Aejmelaeus-Lindström et al., 2018, Rusenova et al., 2018) (see figure 19). Here the string temporarily binds the aggregates together. The string is continuously deposited in circular patterns via a robotic arm and custom end-effectors as the aggregate and string are deposited simultaneously in layers (Aejmelaeus-Lindström et al., 2016, Rusenova et al., 2018, Aejmelaeus-Lindström et al., 2018).

Direct deposition; as previously stated granular material transmit forces upon neighbouring units and create FCN throughout the total material when subject to stress, in this case, loading. The strategy for depositing the string was refined to circular patterns of a maximum radius by contouring a digital 3D computational model of the structure and using the contours as a guide for generating a digital blueprint and tool path for the string dispenser and carrying out iterative experiments (Aejmelaeus-Lindström et al., 2016). The string holds the position of the aggregates and enables forms to be created that are not restricted so slopes. Furthermore, the direct deposition process enabled by a custom robotic arm negates the need for cumbersome formwork (Aejmelaeus-Lindström et al., 2018, Rusenova et al., 2018). Significantly, this highlights the role CAM process / robotic units can play in being able to guide material interactions instead of typically imposing form upon materials and carrying out highly deterministic fabrication processes. That said, the string almost acts as a materialisation of FCN that occur throughout the material of the JAS as it acts as a temporary binding material (Aejmelaeus-Lindström et al., 2016, Aejmelaeus-Lindström et al., 2017, Aejmelaeus-Lindström et al., 2018, Rusenova et al., 2018). As a result, the string material limits the collective granular matters ability to globally reconfigure as imposed forces fluctuate by either changing position or amount, which makes them suitable for architectural applications but could limit their self-healing and adaptive abilities (Jaeger, 2015) as the structures have become more ordered, i.e. the strings restrict the movement of the particles, which are what generate and update the FCN. However, the strings which act as a framework for the granular materials can also play a crucial role in determining the internal conditions (pressure and material deformation amounts) by integrating them with sensors (Rusenova et al., 2018). Critically, the strategy of integrating a material framework with localised sensing abilities can be used to establish feedback between design, fabrication and material properties by determining if a desired material property (e.g. volume) has been fabricated from self-assembling materials. Furthermore, it leads to the possibility of using the framework as a means of inducing localised stimulus to guide self-assembling material interactions. In order to achieve this though for a fabrication system based on stimulus and self-assembling materials, material properties that generate resultant conditions that can be monitored in relation to induced stimulus must be determined and will be unpacked in chapter 6.

Another form of granular jamming that can fabricate structures that are not restricted to sloped formations by designing the material units form will now be discussed and the variable properties they achieve.

3.4.2 Designed Granules

"Designing the individual particles of granular materials defines novel material characteristics of the overall granular system. This opens up a range of possibilities for architectural applications that are fully reconfigurable as the particles are not bound to each other."
(Dierichs and Menges, 2017b)

There are two main aspects of interest in this section, with the first enabling the second. *Firstly,* the intentional micro design of the material components 'grain morphology' (various shapes and properties of material component) and their multiple variables (size, aspect ratio, concavity) turns them into programmable materials (Dierichs and Menges, 2015, Dierichs et al., 2015), resulting in various properties at the structures macro scale (global properties), such as variable and functional gradients dictated by the materials units packing density abilities. The process, typologies and benefits of designing material morphology will briefly be discussed to setup the second and main point of interest, which is how robotic units and environmental data can enable feedback between design conditions (solar gains) and variables of the fabrication process, which guide material properties. Significantly, these material properties perform material computational process to generate global properties (Dierichs and Menges, 2015). Briefly, the several benefits of designing the material unit's morphology, which achieve some of the same properties described in the previsions strategy as well as additional abilities, are:

- Designing the shape of the individual components also liberates them from sloped forms and the confines of frameworks, such as gabion walls, where rocks are contained within wire structures (Murphy et al., 2017b)
- Determining the shape of the materials units govern material computational processes of packing and jamming densities to create freestanding structures which have loading capacities (Murphy et al., 2016a)
- Gradient structures can be created by governing the micro properties of the material units in combination with variables within the fabrication process
- Actuated granules can further enhance packing densities and local material transformation by fabricating the units from composite materials.
- Scalability, as the overall structure, does not have to be defined and the process involves self-assembly. Meaning granules can be added or removed to change the size and or shape of the structure (Dierichs and Menges, 2017b).

How these abilities are achieved will be discussed next by first examining the various properties and variables of the granules morphology and finally how robotic fabrication units can guide material computational processes over time to achieve variable properties.

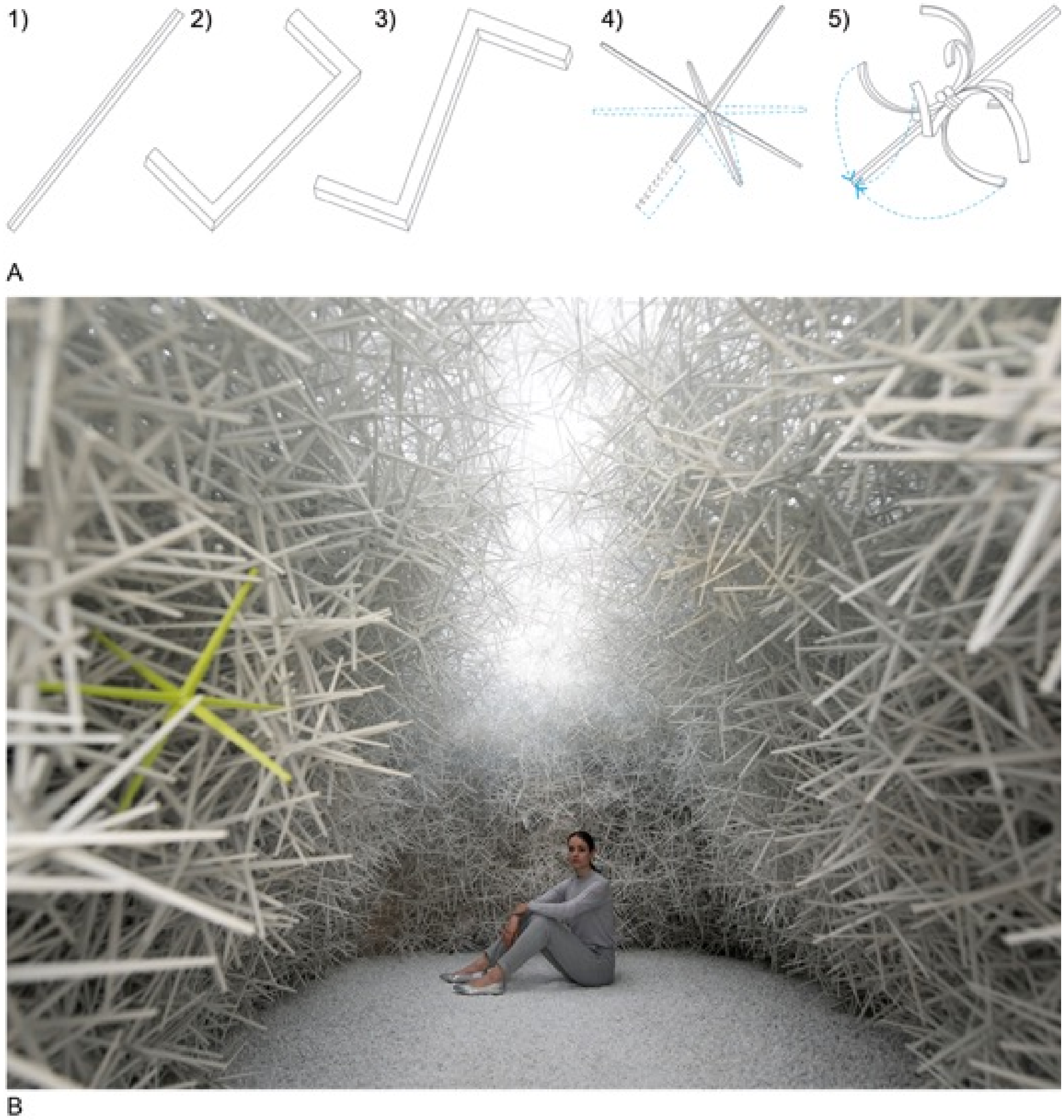


Figure 20: Design granule typologies. A) A selection of some of the shapes explored to achieve jammed architectural structures. A1) Convex shape - stick (Dierichs and Menges, 2017b), A2) non-convex shapes, U shapes (Gravish et al., 2012), A3) Z shaped (Murphy et al., 2016b), A4) X shaped. Some of the main variables of the X shape are highlighted with blue dashed line which are: number of arms, size of arms and length of arms. Altering these variable informs their packing densities (Dierichs and Menges, 2015). A5) Convex state and double non convex state. State of the shape can transform as its material properties are programmed by creating composite wood layers, which respond to humidity levels (Dierichs et al., 2017b). B) Aggregate structures with variable light properties achieved by material computational processes informing packing densities. Source: ICD University Stuttgart anad

Halbe, R. Year: 2018.

As mentioned previously the advantages of designing the individual material units of the aggregate system enables them to become a programmable material (Dierichs and Menges, 2015, Dierichs et al., 2015), where variable properties can be achieved by variations in the fabrication process (Dierichs and Menges, 2012). These aggregate materials in combination with the fabrication processes create an aggregate system, which can create architectural scale structures (Keller and Jaeger, 2016, Dierichs and Menges, 2016, Aejmelaeus-Lindström et al., 2016) where the materials are held in position by friction and a benefit of designing them requires not additional binding material or formwork (Dierichs et al., 2015), which enable vertical structure types to be created (walls, columns) (Dierichs and Menges, 2012, Angelova et al., 2015) and can have structural capacities (Murphy et al., 2016b)

The morphology of the material units (variable of the materials' shape) has an impact on the global properties of the structure along with fabrication processes that guide the material units' collective computational processes. The various shapes of the material units are highlighted in figure 20, which are typically categorised as: 1) *convex*, basically a simple stick shape (Dierichs and Menges, 2017b), 2) *non-convex*; an array of shapes ranging from U shaped (Gravish et al., 2012), Z shapes (Murphy et al., 2016b) and X shaped (Dierichs and Menges, 2015), 3) *double non convex ($ shaped)*; where the granule can form curved hooks from an initial convex state (stick shaped) as a composite material (wood laminates) transforms and curl as relative humidity increases i.e. that granule transforms from a convex state to a double non-convex state (Dierichs et al., 2017b). The interesting aspect of the Z shaped particles is that they enable high flow-ability whilst also maintaining structural capacities (Murphy et al., 2016b). The high flow-ability is something achieved by the $ shaped granules in their convex state, which also enable greater numbers of the materials to be transported if they were to be used as building materials and as they transform (to a double non-convex state) they take up a create volume (Dierichs et al., 2017b). The ability to change state addresses the problem inherent within double non-convex state, which entangles the granules so much that they can no longer flow, meaning, they cannot be poured for the fabrication process (Dierichs and Menges, 2015). However, the ability for the material granule to transform based on relative humidity levels endows the individual material units with the ability to perform localised material computational process (Dierichs and Menges, 2012, Dierichs and Menges, 2015, Dierichs and Menges, 2016, Dierichs et al., 2017b, Dierichs and Menges, 2017b), such as, the material units collectively creating multiple localised openings in the structure to passively increase airflow through it and cool the building (Dierichs et al., 2017b).

The X shaped particle will be discussed in more detail as research involving them discusses its' local variables and how of variables within robotic fabrication processes (flow rate, pouring angle, amount picked up / deposited) generates global variable lighting properties (Dierichs and Menges, 2012, Dierichs and Menges, 2016), which additionally can be functional, providing feedback between data values, sensors, fabrication processes and the structures global variables (Angelova et al., 2015).

The X shape as several local variables, these are: arm length, arm diameter / taper, number of arms and overall granule size (Dierichs and Menges, 2012, Dierichs and Menges, 2015). Significantly, variations to these properties have major impacts on the structures global properties; *"A doubling of arm length, for example, leads to an average tenfold decrease in packing density"* (Dierichs and Menges, 2015). Essentially, these material variables affect neighbouring material interactions and global material computational processes. The primary material computational process in this system is packing density. Additionally, the means in which the particles are deposited via 6 axis robotic arms with custom end-effectors to handle the particles can also be tuned to inform the packing densities with high degrees of control (Dierichs and Menges, 2012, Dierichs et al., 2012). The variables of the fabrication process involving an armature that pours the granules the robotic arm control are: *"pouring speed, angle, the distribution of different particle grades as well as pouring paths"* (Dierichs and Menges, 2012). Variables for an armature that grab multiple granules and drop them into desired positions is predominantly the amount the gripper picks up in one go (Angelova et al., 2015, Dierichs and Menges, 2016). These variables in the robotic fabrication process are actively used to guide the granules position, which informs the overall spatial qualities throughout the structure's volume (Dierichs and Menges, 2012). The active and major role the robotic units play in the fabrication process is the reason for examining this material platform in the fabrication section; the aggregates are susceptible to the stimulus of gravity but it is induced using a robotic arm. Comparatively the other material platforms examined later can be deployed within a system where stimulus can actively guide them without the need of an external robotic unit.

Interestingly though, due to the CAM fabrication process and the variables involved within the pouring / grabbing processes and the materials themselves, it opens up the ability of feedback within the system by incorporating sensors to create an iterative and informed design and fabrication process.

3.4.3 Granules: Feedback and Simulations

Here main strategies of interest for monitoring physical material formations, deviations and variations to a corresponding digital simulation within granular jamming material systems that have been discussed are;

- In JAS (structures created from rocks) the conditions of the structure are monitored (material deviation) by embedding; *"silicone-coated glass fibre sensor—placed as the string pattern for measuring local deformations"* (Rusenova et al., 2018). The aspect of interest here is that the formwork (string) also has the ability to monitor conditions, which highlights potential avenues for using the formwork for both inducing and monitoring local conditions to guide and determine if desired material properties have been fabricated.
- The use of optical sensor (web camera) is used to monitor sunlight levels and resultant / desired sunlight levels transmitted from the fabricated aggregate structure, creating 'graded light' (Angelova et al., 2015). Here the robotic fabrication process is informed by the sensors readings and deposits granules in various amounts, locations and densities (determined by digital simulation models) to fabricate walls with functional gradients in relation to the amount of sunlight transmitted through them based on digital models (Angelova et al., 2015). Significantly, this demonstrates the abilities of material computational process to create emergent functional gradients (Angelova et al., 2015).
- Aggregate structures with voids created by an 'online controlled inflatable formwork'. The inflatable formworks are balloons with their inflation and deflation controlled via Arduino, which enables the formwork and materials to act as a system, where the formwork is adapted based on the *"actual stability state of the simulated formation"* (Rusenova et al., 2016).

The 'online controlled inflated formwork' (hereafter OCIF) is reviewed in more detail next as opposed 'graded light' the robotic strategy because The OCIF uses stimulus in the fabrication process. However, the OCIF does not use sensor values to determine material properties were as the graded light process does.

Previously, inflating balloons to various sizes within box-shaped formwork has been used to create void spaces within the aggregate materials (Hensel and Menges, 2008). The ability inflate the balloon to various sizes enables them to act as a flexible and temporary formwork. The OCIF strategy is of particular interest as a stimulus (air pressure) is used to transform the multiple balloon formwork's by inflating or deflating them, which is controlled via Arduino based on data acquired from multiple digital simulation i.e. a digital counterpart of the physical experiment is used to simulate the particles' behaviours, which is carried out simultaneously with physical experiments in order to govern feedback of the balloons inflation and deflation (Rusenova et al., 2016). For both digital and physical experiments of the OCIF, the inflatable formworks are placed within a box formwork, with 450 six-armed or ten-armed X shaped (non-convex) particles poured into the boxes. After the initial pour of the aggregates have settled the box formwork is removed (in both physical and digital experiments), which results in a 'second-settling' phase for the aggregates (Rusenova et al., 2016). During this phase, the digital model calculates areas that are unstable, which result in the physical inflation of the balloon to temporarily support these areas and create physical voids and volumes similar to the digital models (Rusenova et al., 2016). The digital model in this system employed algorithms developed in a previous simulation, which was able to model non-convex particle behaviour (Dierichs et al., 2015). Post analysis of initial physical experiments in these systems have been recorded via multiple visual methods, such as: photogrammetry (Rusenova et al., 2016) and laser scanning (Dierichs and Menges, 2015), which highlighted deviations between physical results and digital simulations to refine the digital simulations parameters and more accurately model / represent the physical aggregate behaviour (Dierichs et al., 2015, Rusenova et al., 2016).

Significantly, the feedback in the OCIF aggregate systems is informed by a corresponding digital simulation based on discrete element method (DEM) (Cundall and Strack, 1979). The DEM represents physical interactions that occur between particles (gravity, collisions, friction, acceleration). The OCIF employed a DEM that has been developed to account for interactions between non-convex particles (Dierichs et al., 2015), which is used to simulate the material units' behaviour, resulting in fabrication processes that are predictive in nature i.e. the fabrication process is not highly deterministic but accounts for material computation, enabling highly desirable benefits, such as, functional gradients. Critically, this changes the relationship with materiality in regards to a design approach. Instead, the designer interacts with materials and observers their behaviour (Dierichs et al., 2015). In these relationships of design, fabrication and materials the use of inducing and tuning stimulus to manipulate and guide material interactions again provides rich grounds for exploration, raising the question of; *what types of digital design strategies would be suitable for inducing and monitoring stimulus to guide processes of material scale self-assembly?*

For this reason, several digital design strategies are reviewed in the next chapter before going onto review multiple material platforms. Examining the various digital design strategies is intended to help understand what parameters and resolution they could possibly engage with to govern and monitor environmental stimulus of the proposed adaptive design and fabrication system. Examining these tools will also help to inform what material platforms are suitable for explorations and future possibilities.

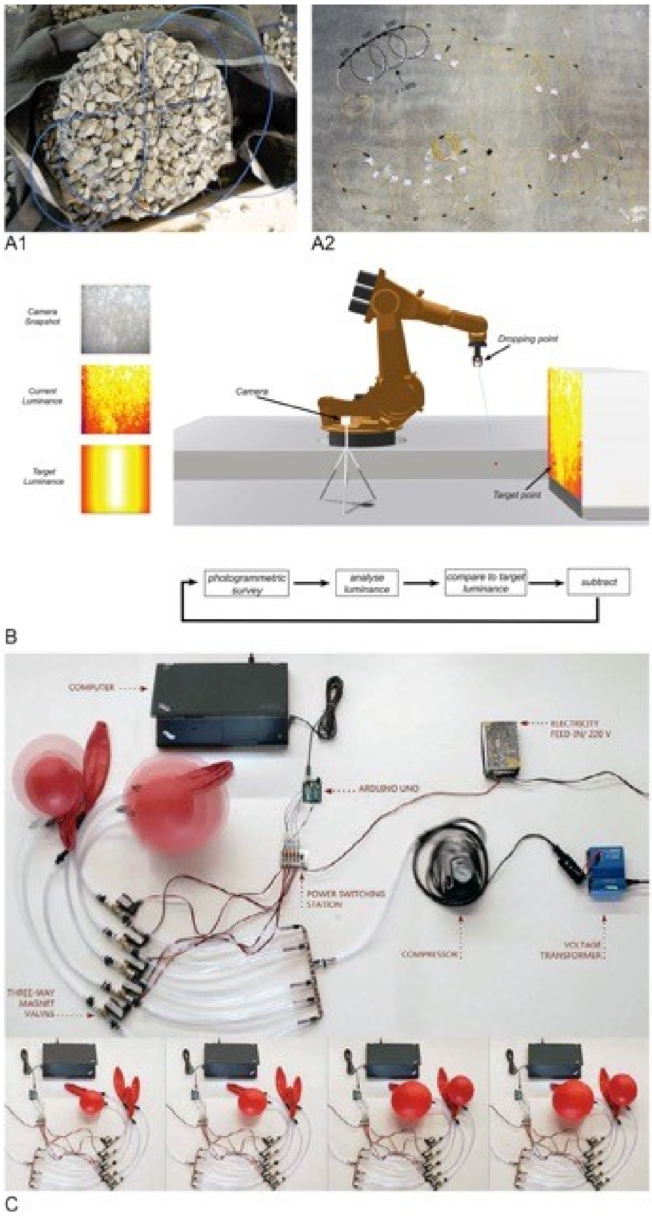


Figure 21: Sensors for 'Jammed Architectural Structures'. A1) Steel-coated glass fibre sensor incorporated into the structure as the string medium and used to determine the overall behaviour of the structure Source: Rusenova, et al. Year: 2018. A2) silicone-coated glass fibre sensor used for measure local deformations. Source: Rusenova, et al. Year: 2018. B) Optical sensor (web camera) integrated into the fabrication system so as to monitor real-time daylight transmittance values enabling feedback between design model and a predictive fabrication process. The real-time sensor values are used to update fabrication instructions (e.g. where and the amount of aggregates to deposit) based on desired values associated with the digital model. Source: Angelova, et al. Year: 2015. C) 'Online controlled inflatable formwork' is a series of balloons, which are automatically inflated or deflated based on digital simulations predication to support fragile areas of the aggregate structures as the settle (both digitally and physically). Source: Dierichs, et al. Year: 2016

3.5 Chapter Summaries

Key areas of interest from each section are briefly summarised but centre around material computational abilities and mechanisms present within each fabrication processes.

Additive manufacturing processes

- The incorporation of a contrasting support medium alleviates layer-by-layer constraints and provides a space to explore how to transmit stimulus upon materials being deposited into it so material scale self-assembly can be guided throughout the 3D volume.
- Cymatics reveals how a stimulus (high-frequency sounds) in combination with various material properties (granularities and viscosities) creates reproducible and reconfigurable 2D patterns.

Robotic fabrication processes

- Robotic fabrication processes enable the design amendments / augmentations to be carried out on the fly but typically treat materials as inert
- Robotic fabrication units with mobility enable structures to be fabricated at architectural scales. However, the property of the material and construction system dictates the resolution / sensitivity of possible adaptations. Typically, global adaptations can be easily achieved but incrementally.

Granular Jamming

- Designing variables on the micro scale (material units) enables global properties that have variability throughout the structure, such as functional gradients.
- Variable within the fabrication process (pouring angle, speed, location) are also used to guide material computational processes. Highlighting how changing relationships with design, fabrication and materials can further leverage material computational abilities to enable physical adaption.
- Cymatics in combination with mechanisms of granular jamming (angle of response) reveals how stimulus can be used to alter 3D formations (sloped mounds), which could be dictated by design tools to create an iterative design and fabrication process.
- Finally, feedback between design, fabrication and material properties (global and local) can be achieved by either real-time sensor data (graded light structures) and or corresponding design simulations.

Overall the main restriction that is apparent across all of the AM, robotic fabrication and granular jamming processes discussed is their inability to simultaneously change the local and global properties of a design when it is subject to a stimulus during the fabrication process, especially post-fabrication. Next, digital design platforms are reviewed to understand how they could be employed to guide self-assembling interactions and at what resolution.

4 Linking the Digital & Physical

The possibility of adapting a design / structures physical shape and space in anticipation of environmental / climate, programme, occupation demand (among others) changes and interactions by moving defined materials units was previously described in the SEEK research project (Negroponte, 1970, Negroponte, 1975). Where gerbils are placed within a container filled with towers made of small metal cubes. The gerbils activity is monitored by a camera and as they disrupt / move the towers a robotic arm / gantry activity would reposition the cubes if disrupted, resulting in a self-regulating architecture based on circular causality and feedback between gerbil activity, material components and global form (Negroponte, 1970, Negroponte, 1975). Additionally, the proposed projects of Cedric Price also describe architectural structures and urban systems that can self-adapt to these fluctuating design demands, such as, the adaptive self-reconfigurable structure of the 'Fun Palace' proposal (Price and Littlewood, 1968, Mathews, 2006, Mathews, 2005). An adaptive strategy was also scaled up to an urban system for reconfigurable student accommodation during term time in the 'Potteries Thinkbelt' proposal (Price, 1966).

All of the physical reconfigurations within these past proposals and research projects was governed by cybernetics (Wiener, 1948). Cybernetics reveals how existing systems (animal, social, mechanical) can communicate with one another (Wiener, 1948) and can also be used to regulate proposed systems, such as, the architectural proposals of Price. The principal of understanding and regulating these systems is based on 'circular causality' and feedback between components within the system. With this notion of feedback between relationships in mind the next section examines a digital design strategy, which establish an iterative relationship between digital design representation (parametric model) and fabrication achieved by inducing stimulus (Ayres, 2012b). Significantly, it is the ability and role of inducing stimulus can play in linking design, fabrication and material properties. With the notion of stimulus as the fabrication mechanism in mind digital strategies are reviewed again that can have a discourse with material computational processes and material behaviour at a granular material level. In doing so, the chapters aim is to highlight principles within these strategies to help understand how they could be employed within the proposed design and fabrication system to determine if desired material properties have been fabricated from SA material processes and potentially even used to reveal complex interrelationships that could guide more subtle material properties, such as, surface texture, which may not be directly effect by a single stimulus but a collection of them.

4.1 The 'Persistent Model'

"Persistent Modelling" (Ayres, 2012b) is a research agenda that challenges the physical fixation of material units post fabrication. In persistent modelling, the relationships between the representational mediums of the designs processes (sketches, models, digital models) and final physical objects are emphasised and 'persist' throughout the lifetime of the object. The relationships between the two allows for time to be accounted for so that change can occur via feedback between the digital design representation (e.g. the parametric model) and the situated physical structure. Ayres, demonstrates this concept by creating a real-time link between digital parametric model and material (metal sheets welded together) by inflating the metal sheets (Ayres, 2011) (see figure 22). The connection between design and fabrication enabled by inducing a stimulus (fluid pressure), which acts as a global stimulus and transforms the welded metal sheets by inflating them. This is the major aspect of. The stimulus induced and monitored via design tools enables, a continuous discourse between design, fabrication and to an extent material properties. The variation in fluid pressure and its ability to transform the predefined metal components (increasing its diameter when inflated) by expanding them allows for iterative transformations. The stimulus has discourse with the materials own computational abilities as it governs the transformation / adaptive properties. Additionally, informing these material transformations can be based on improving the structures environmental performance by increasing its solar shading ability i.e. inflating the material units creates a large surface area and improves solar shading abilities (Ayres et al., 2014). These materially adaptive abilities enables architectural structures to enhance their environmental performance making them more sustainable (Sterk, 2012). However, several aspects of interest arise from the material units being physically transformed, which could potentially be extended and addressed by incorporating self-assembling materials and examining alternative design representations.

- *Firstly,* a single material unit can only adapt its shape within a certain range if its global shape is predefined (Ayres, 2011, Ayres, 2012a). A collection of these individual units begins to address certain aspects of this issue, as witnessed in the varied global patterns achieved in 'persistent model #3' (Ayres et al., 2014)

- *Secondly,* the transformations are limited to the materials elastic limit, which once exceeded results in permanent deformation (Dunn, 2012). Again this is due to predefining the global shape of the material units as welding the sheets together results in variation in the metal sheets materiality (harder in some areas and softer in others) (Ayres, 2012a).
- *Finally,* the variation in the physical components materiality is further highlighted as non-uniform localised material surface textures / deformations occur during inflation, which are not accounted for in the digital parametric representation (Ayres, 2012a) (see figure 22). Meaning a restricted discourse between the resolution of the digital representation and the physical components materiality is created.

The final point is a consequence of the parametric design tools used to represent the physical model, which is based on b-reps and predefined associated relationships with a linear cause and effect outcome. The assumption being that increasing pressure in the digital model X amount results in X amount of uniform physical inflation. The consequence of representing digital geometries as b-reps in the software means material properties are treated as totally homogeneous (Michalatos and Payne, 2013, Richards and Amos, 2016) i.e. they are all uniform in the digital software, which would create linear results. As a result two issues arise:
1) A separation between the virtual and the physical as the virtual model is based on geometric representations and struggles to account for material properties and fabrication constrains (Oosterhuis et al., 2004, Oxman, 2010a, Oxman, 2010b). The separation is partly bridge inducing stimulus, which leads to the second point.
2) A restricted discourse occurs as the physical material is not uniform and is highlighted by Ayres material analysis, which examines a cross-section of the material component under a microscope, revealing varied granular microstructures, meaning localised material deformations (surface textures) are not accounted for (Ayres, 2012a) (see figure 22).

For these two reasons this chapter examines other possible digital models / strategies that can account for materiality and or behaviour as they have the capacity to represent material units and processes that occur within a self-assembling / self-organising fabrication system. Although just because these digital models can account for materiality it may still result in the same degree of control over the physical material properties, especially if a global stimulus is subjected to the material component, which are not locally monitored like that of pressure in the persistent model experiments. For this reason of sensitivity and global stimulus, design tools are examined that could also determine or reveal potential material properties that could be mapped to localised induced stimulus as well as a collection of them creating global environmental threshold conditions. Examining these digital platforms also extends work of the emerging design process of *'Fabrication Information Modelling'* (FIM) (Royo and Oxman, 2015). FIM acknowledges that current design workflows are separated into linear stages but achieves feedback between certain components in a series of case studies (Royo and Oxman, 2015). More importantly, FIM seeks to incorporate material computational processes, form generation and digital fabrication back into the virtual models to create designs that are increasingly functionally integrated (can account for multiple demands), multi-scale performance (material to global properties are performance orientated) and novel aesthetic qualities (Royo and Oxman, 2015). These aims of FIM are potentially more potent with the incorporation of self-assembling materials as the fabrication materials as: 1) they are inherently based on material computation processes (Menges, 2012a), 2) they provide a scalable process (Whitesides and Grzybowski, 2002), which could heighten a designs' performance and functionality. 3) Self-assembling materials / processes have the ability to reconfigure (Dierichs and Menges, 2012, Tibbits, 2014b, Jaeger, 2015, Papadopoulou et al., 2017, Tibbits, 2017b), enabling transformation and adaption across time domains, which again would enhance a designs' performance orientation as fluctuating demands (aesthetic, programme, occupation) can be accounted for.

Critically, the ability of design representations maintaining discourse with physical artefact enabled in persistent modelling is due primarily because of stimulus and this is the main aspect of interest. Persistent modelling and stimulus could potentially be further extended with the notion of FIM and use of a self-assembling material platform susceptible to local stimulus by creating a design and fabrication system based on interrelationships, which is not based on linear work flow but one where each component is inherently linked to one another (digital model, fabrication process and material) (see figure 23). The main intent from this point onwards is to explore how persistent modelling could be extended by incorporating self-assembling materials and understand other types of digital tools, platforms and strategies that could further guide self-assembling material processes by being able to account for or determine localised properties (surface texture, porosity) to create adaptive physical designs with greater sensitivities. The overarching factor that connects the following design strategies is the fact that they account for or a based on multiple stimuli, which is possible as they are agent based i.e. the local material units / agents that compose the global model behave in response to conditions and local interactions. The benefit would be their potential ability to determine relationships between digital and physical properties (material properties in relation to stimulus and design instructions) especially if the proposed system becomes increasingly complex because of multiple conditions (gravity, pH, temperature, voltage, agitation) being able to affect and produce emergent physical material results like that of localised surface texture in persistent modelling.

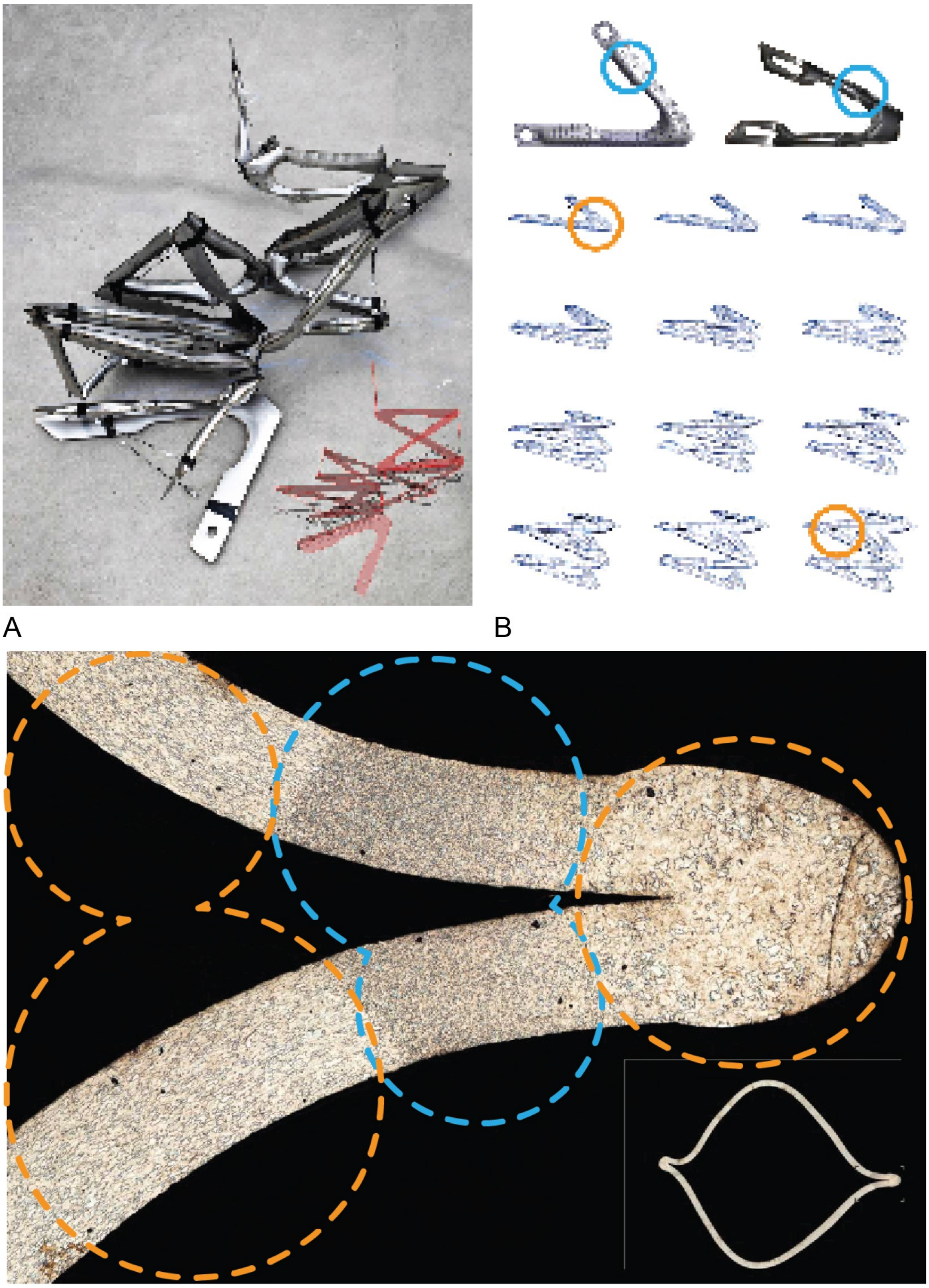


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Figure 22: Persistent Model deformation and materiality. A) Transformation of digital representation linked to physical artefact by inducing stimulus. Source: Ayres, P. Year: 2012. B) Deviations in uniform transformation of digital model based on b-reps and non-uniform transformation of physical model. Source: Ayres, P. Year: 2012. Annotations: Author. C) Microscopy image reveals variation in materials granular organisation as a result of welding, creating harder and softer areas. Source: Ayres, P. Year: 2012. Annotations: Author.

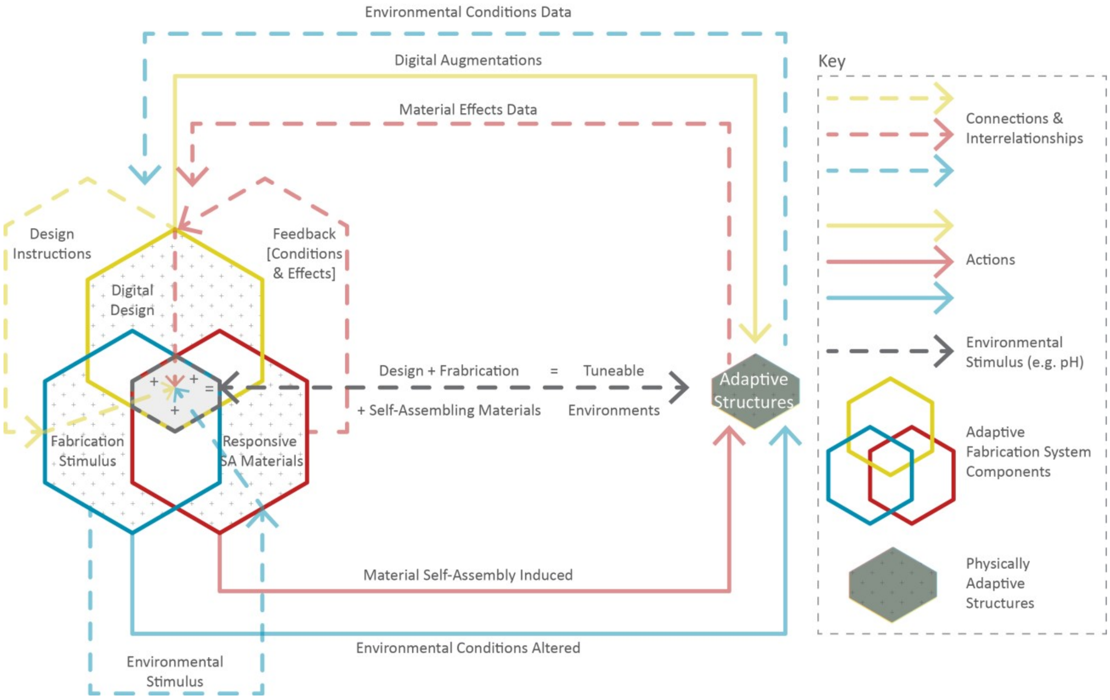


Figure 23: Aim of interrelationships within the proposed design and fabrication system enabled by utilising stimulus as the fabrication mechanism.

4.2 Material Agents and Processes

From here on this chapter focuses on strategies that can generate digital models composed of multiple-material agents (bacteria, cells, material units) and not geometry (b-reps) like those of persistent modelling. It extends and reiterates the strategies (MBDC and CPPN-NEAT) examined in chapter 2 for several reasons by relating it to how stimulus can enable feedback between design representation, physical artefact and material properties:

- Feedback can be achieved between physical and digital global (shape transformation) and local (compositions, surface texture) properties as the digital model is composed at a granular resolution.
- The granular nature of the following digital models also resonates with fabrication processes that utilise SA materials as they both generate designs based on interactions between agents / material units.
- Interactions between digital agents / materials units can also simulate the physical processes and behaviour occurring in physical SA materials guided by varying conditions / parameters that inform processes and behaviours.
- Time plays a crucial role in maintaining a coherent discourse between digital and physical processes of SA and digital strategies that can simulate a vast number of material interactions.

As highlighted in granular jamming it is possible to simulate a collection of material unit's and the interactions that occur between them based on the conditions that are acting upon them (gravity, friction, collisions) resulting in the digital simulation resembling the physical fabrication process / final physical structure (Dierichs et al., 2015, Dierichs and Menges, 2015). The ability to *'programme'* these aggregate material units (shape, radius, arm length, arm number) can be taken beyond inert materials and be used to create 'living materials', which can be described as materials that display either: motility, sensitivity and complex behaviour (Spiller and Armstrong, 2011b). For example, bacteria can be programmed to perform computational processes, such as OR, AND, NAND, NOT logics and can be used to solve *Hamiltonian path problems* (Amos, 2014). In essence, bacteria can be programmed to respond to various environmental conditions (e.g. pH levels / Urease) to perform desired actions (secrete bioluminescent proteins) once a threshold level is reached (Dade-Robertson et al., 2013, Dade-Robertson et al., 2015). Essentially, the bacteria are carrying out a process they have been programmed to do. More will be discussed about bacteria and its potentials as a material platform that can enable adaptation will be discussed in the following chapter.

It has been demonstrated that digital design tools can begin to have a discourse with these 'living materials' (bacteria used as a means of fabricating materials) by creating customised design tools based on the behaviour of bacterial agents, as shown by SynthMorph (Ramirez-Figueroa et al., 2013). The digital agents / bacteria's behaviour in the SynthMorph design tool is based on the 'ten cellular mechanisms of morphogenesis', originally defined by Davis

(Davis, 2005) as well as simulating processes of mammalian morphogenesis (Davis, 2008) and biomineralization (Dade-Robertson et al., 2013). The SynthMorph example is able to create 3D digital models which, *"approximates form through the behaviours of biological agents rather than through geometric rules"* (Ramirez-Figueroa et al., 2013), meaning the stages of morphogenesis in the digital model can be linked to the physical processes that will occur in physical materials that incorporate bacteria. The design exploration develops the possibility of opening up architectural structures that become "ever-changing organism" (Ramirez-Figueroa et al., 2013) enabled by the potentials of 'bio-bricks' (Knight, 2003, Ferber, 2004, Check, 2005). The potential role of incorporating bacteria into materials to create a self-sensing, self-computing material, which can respond and adapt to varying stimulus / conditions will be discussed further in the following chapter, for now, the focus throughout this section discusses how digital tools can have a discourse with these novel material systems. The methodology of developing SynthMorph is also iterative by employing the dual evolutionary strategy (Hallinan et al., 2012). Meaning, the physical and digital experiments inform one another to understand bacteria's behaviour as a design agent, revealing potentials and restrictions.

Extending the role of these digital tools has also been established by incorporating engineered bacteria within a soil matrix that respond to pressure changes within the soil when loaded, where the bacteria carry out a process of synthetic biocementing to increase the soils mechanical loading capacities (Dade-Robertson et al., 2016a). Resulting in an improved foundation footing / bedding for architectural structures. The role of the customised designed digital tools in this strategy is to *"map values of gene expression"* of the bacteria when a threshold value of pressure is induced upon them and in doing so help with the discovery of useful genes and creation of gene circuits (Dade-Robertson et al., 2016a). The digital tools again have discourse with the physical materials as they are based on processes that occur within the bacteria. The design tool can help to visualise gradient based patterns created from induced pressures of a raft foundation, revealing volumes where gene expression occurs (Dade-Robertson et al., 2016a, Dade-Robertson et al., 2017d, Dade-Robertson et al., 2018b) i.e. voxels are highlighted in areas subjected to a threshold pressure value that would initiate the biocementing process being carried out by the bacteria. The model also accounts for the varying state of the soil (saturated by water), which varies over time and impacts of pressure transmittance. Significantly, this highlights fluctuating states that inform the living materials behaviour.

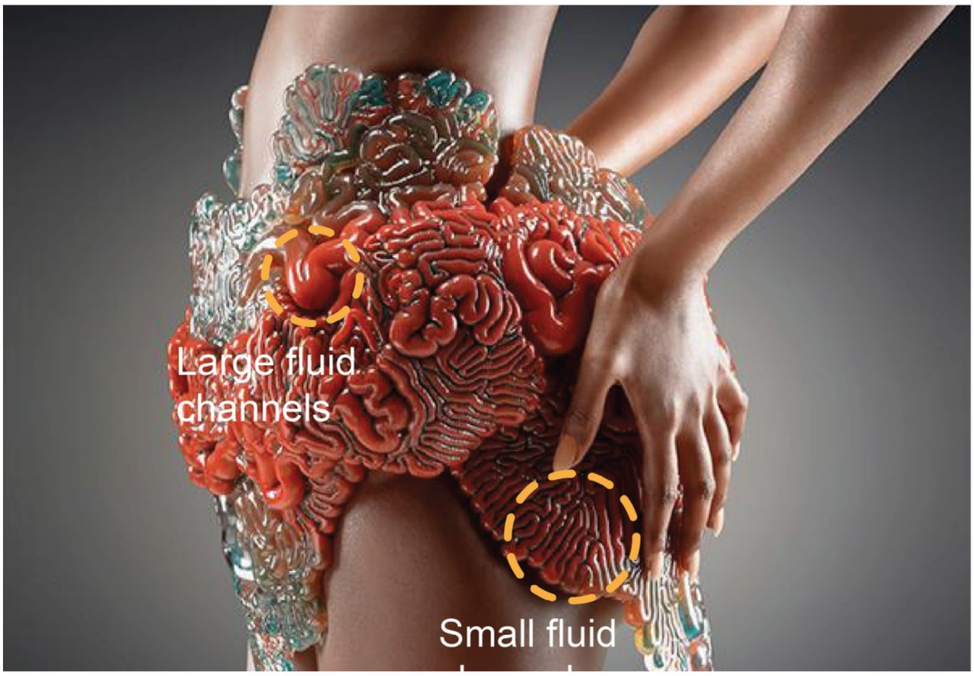
Conversely, at the product scale (speculative wearable's) it has been demonstrated that digital design processes can also be informed by bacteria's activity to create geometrically complex and multi-material (variable colours and transparencies) designs' (Bader et al., 2016b) that are 3D printed (see figure 24). *'Mushtari'* is part of a series of these product scale wearable's that form a speculative research project called *'Wanderers'* (MIT, 2015). Within the Mushtari wearable, there is a single continuous fluidic channel that houses the bacteria. Along the channels' length, it varies in diameter and in material transparency, which physically governs the bacteria's / microorganisms activity (Bader et al., 2016b). Furthermore, it has been demonstrated that microcolony growth / behaviour, composed of thousands of cells, which are affected by environmental conditions, cell-to-cell interactions (among other factors) can also be robustly simulated (Bader et al., 2018b). The digital model Bader discusses is agent-based (each digital material unit can respond to conditions) using position-based dynamics (Müller et al., 2007) (hereafter PBD). The model enables global pattern formations to be generated based on local agent interactions with the model being informed by principles of synthetic biology (Bader et al., 2018b). Critically, because the physical material is intended to be bacteria, the pattern formations can be tuned and adapted to an environmental stimulus (as bacteria can be programmed via DNA). Bader's digital model enables parameters to be highlighted that can tune pattern formations, which begins to bridge the gap again between digital and physical materials (Bader et al., 2018b). A benefit of being able to engineer living materials (programme a response to a certain stimulus) enables materials or structures composed of these materials to self-heal (Wiktor and Jonkers, 2011). The *'Wanderers'* research project goes a step beyond and speculates at creating a symbiotic relationship between novel types of wearable technologies and user for interplanetary space exploration enabled by the microcolonies activity to produce habitable conditions for the user. More will discussed on the potentials and demonstrated abilities of various material platforms in the following chapter and how they can be leveraged or extended via stimulus and digital design tools.

Significantly, the digital models provide a testbed for determining parameters and creating conditions for leveraging desirable behaviour from the bacterial / microcolonies i.e. they are used to simulate behaviour digitally. A potentially powerful space again to explore with these bacteria based materials in mind would be to utilise the digital design model to be able to tune physical environmental parameters as the digital models' account for environmental conditions (such as fluid velocities) as they impact on the properties of the design (e.g. local and global colour patterns) (Bader et al., 2018b), and as highlighted by Persistent Modelling (Ayres, 2012b) would facilitate discourse between digital and now physical 'living' materials to be maintained. Additionally, employing these multi-agent based models could extend persistent modelling as local and global properties could be tuned and accounted for both physically and digitally.

However, a challenge arises from digitally representing a large number of material units or agents if the uses large numbers of parameters to describe complex structures (such as ones composed of multiple materials / voxels), which do not scale well and take large amounts of time to process modifications to the design due to the larger design search space created from the multiple parameters (Richards and Amos, 2015). Meaning if complex digital models composed of multiple parameters are used a possible time lag between digital simulations and potentially rapid physical material computational processes could occur, which could reduce the sensitivity of dialogue between one another when design tools are used to manipulate stimulus. Possible courses of interest in addressing this issue are:

- Utilise digital methods based on their speed of processing abilities like that of PBD which are robust enough to simulate millions of cells and their interactions (Bader et al., 2018b). Or the CPPN-NEAT strategy (Richards and Amos, 2015), which can generate complex designs based on compressed encodings (few parameters required) using CPPNs (Stanley, 2007) and utilising NEAT to determine if higher-level relationships between initially emergent / less defined material properties (surface texture, density, composition) and induced stimulus / environmental conditions can be revealed and tuned in real-time.
- Employ, a physical material platform as the fabrication / material source that takes longer durations of time to significantly respond or adapt to the stimulus. However, this could ultimately limit the possible material type's available and potential applications. Imagine a really slow 3D holographic television, where the frame rate could only be updated every hour or so because of the slow responding material processes. Meaning a movies' run time could take years.

A benefit of generating design tools with the intention of incorporating living organisms within the physical artefact forces a rethink of designs' relationships with fabrication and materials. Instead, design becomes embedded between the two, removing the separation that can occur between them when geometry is the focus of design processes (Ramirez-Figuera et al., 2013). Additionally, the incorporation of living materials opens up the opportunity for the physical structure to adapt based on engagement with environmental conditions (Hensel, 2006, Spiller and Armstrong, 2011b). More critically, a convergence is attained between digital models and physical processes here, as physical conditions and material properties inform the parameters of the digital model. For example, the stimulus of loading pressures, which dissipate and creates gradient patterns as well as soil mechanics are incorporated into the digital models along with the bacteria's behaviour / processes when subject to threshold pressure values. These explorations are informed by carrying out both *in vivo* (in the living) and *in silico* (silicon-based computing) experiments, which enable mapping of properties between the two without restricting emergent behaviour as the variables are not predefined like those in associative modelling. This raises the questions; *what properties of a SA material platform can be mapped to stimulus governed by digital design tools? And, how can sensor values from resultant conditions be mapped to SA material properties that don't restrict desirable emergent properties?* Next design simulations based on biological processes of self-organisation establish how threshold values can be employed to inform neighbouring and global material properties, states and activities.



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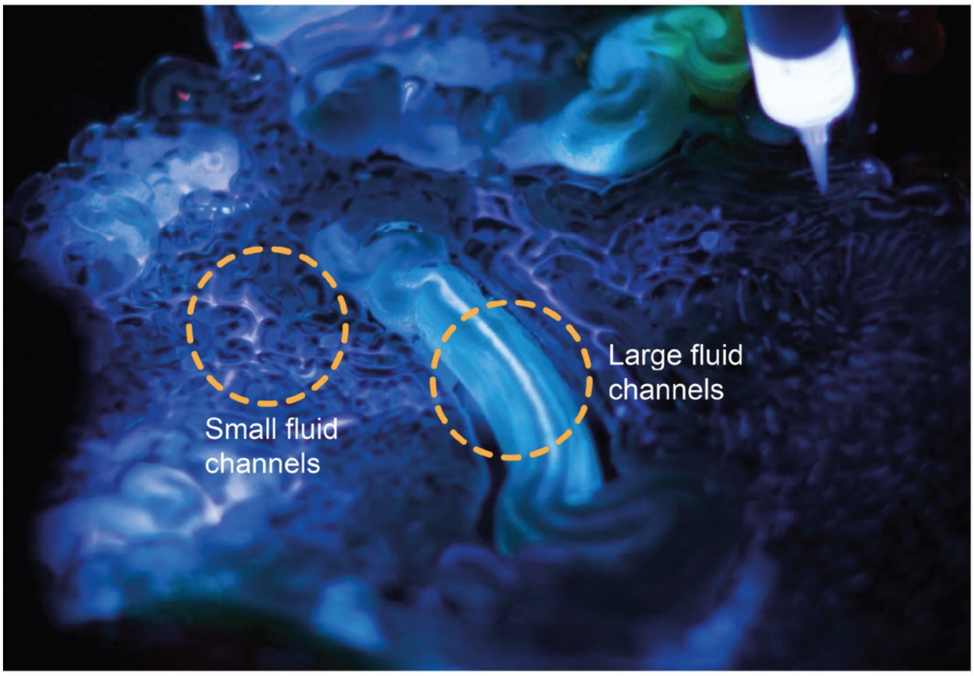

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Figure 24: Mushtari. A) Mushtari, a speculative, symbiotic wearable technology housing bacteria / microorganism within a continuous fluidic channel. Its complex geometric form is based on biological processes and impacts the microorganisms' activity by creating channels of variable dimensions. Source: Bader. C, et al & MIT Mediated Matter. Photograph: Reshef, Y. Year: 2015. Annotations: Author. B) An Internal fluid channel filled with a chemiluminescent liquid to clearly highlight the variable dimensions and lengths, which impacts the microorganisms' activity. Source: Bader. C, et al & MIT Mediated Matter. Year: 2015. Annotations: Author.

4.3 Morphogenetic Engineering

Morphogenetic Engineering (hereafter ME) is a recently defined field of research that aims to understand and integrate the precise self-formation abilities of complex biological systems and collective insect constructions into technological planning (Doursat et al., 2013), with a range of applications, from: self-assembling mechanical robots, to, self-coding software, to potentially self-constructing buildings (Doursat et al., 2013). The basic rules present in complex systems of biological systems and insect construction have been utilised in ME as the approach for generating complex, functional digital designs, such as 'growing robots' (Doursat et al., 2012, Doursat and Sánchez, 2014). In this example, globular type digital robots are generated and composed of multiple cells (the cells are the agents in this system), which develop into various sub-structures via cell division (main body, short limb, long limb) (Doursat et al., 2012). The global forms and substructures (mapped by assigning colours of cells) are all generated based on simple rules and mechanisms, such as, threshold values and diffusion gradients, which inform if a cell divides (or not) to grow the body or an appendage and the cells properties (body or limb), which informs neighbouring cells / collective cell behaviour (Doursat et al., 2012, Doursat and Sánchez, 2014). Significantly, the properties of the self-organised structures and conditions can be analysed to understand how they have emerged to generate certain traits or properties.

Briefly examining ME and potentially utilising principles of ME for governing the stimulus and material properties of the proposed adaptive design and fabrication system has revealed three main aspects that resonate with properties of a SA material fabrication process based on stimulus:

- The ability to utilise simple rules and mechanisms, such as, threshold conditions and concentration gradients to govern material properties (e.g. a cells' state) could be used to 'fine tune' SA material processes and properties using stimulus that behaves as a gradient and dissipates over distance or time. For example, concentration gradients used to guide protocells through mazes (Cejkova et al., 2014) or evaporation rates governing their shape (Cejkova et al., 2016).
- ME can reveal and determine how emergent properties arise from the system's interactions, which could be used to guide the fabrication process of new designs to further enhance desirable traits (Doursat, 2009, Varenne et al., 2015), such as fast growth rate and a smooth surface texture governed by heat and light stimulus.
- A fabrication process based constituent parts such as SA materials bears a strong resemblance to principles of morphogenetic engineering (Doursat et al., 2013) due to the decentralised properties / agency of the materials in both. Meaning growing materials by enabling a discourse between the processes of SA and ME would be more intuitive then pre-imposing form on material units and manipulating them as the materials granular nature is engaged with from the beginning.

In terms of what this would mean for fabrication processes that could grow various designs (patterns, shapes, object scale, architectural structures) from SA material that are guided by ME tools; imagine a couch that could increase in size to accommodate more people if pressure induced upon it could be sensed by the sofas' material makeup resulted in material division / increased size of the sofa and the magnitude of pressure, which dissipates (forming a gradient pressure map) informed the materials rigidity throughout the sofas' volume. As these mechanisms and rules are scalable based on the mechanisms and simple rules witnessed in biological processes / systems imagine new kinds of architectural structures and cities, which could vary in size, shape and material properties to accommodate a fluctuating population size based on the scale of granular materials, their states and processes.

The final digital platform to be reviewed that could extend the digital parametric representation of persistent modelling is the CPPN-NEAT strategy developed by Richards and Amos (Richards and Amos, 2015), which was discussed in depth in section 2.5. The following section reiterates these points briefly and extends the past section in relation to resolution, time and varied voxel shapes (not restricted to cubes) afforded by the CPPN-NEAT strategy.

4.4 Resolution Infinite

As mentioned previously in section 2.5 it is possible to generate functional patterns and complex structures using CPPNs (Stanley, 2007). The CPPN enables efficient / compact encodings as they are mathematical functions enabling non-associative parameters to be created. Meaning a reduced number of parameters can be used to govern multiple properties of a complex 3D design (gradient patterns, local and global shapes) (Richards and Amos, 2015). Significantly, the control afforded by a reduced number of parameters enables rapid manipulation of highly granular (high resolution) 3D digital designs, enabling their local material composition to programmed in relation to and have a discourse with global properties (shape) and demands (loading, aesthetics), creating designs that can adapt across their length scales. This is because simple information about the designs' individual and or neighbourhood of voxels (x and y coordinates), which are the material units in this strategy, can be feed into a mathematical function (sin, cos) of the CPPN and using NEAT (Stanley and Miikkulainen, 2003) reveal the mathematical functions that create higher level features and relationships, such as, location of materials (voxels) with increased rigidity in relation to a structures internal architecture and global shape.

Now in the context of utilising the CPPN-NEAT strategy for guiding interactions of SA based on inducing stimulus there are three aspects of interest that could prove to be extremely beneficial: 1) resolution, 2) time and 3) voxel shape.

- **Resolution**; As previously mentioned in section 2.5 the CPPN-NEAT strategy can potentially generate patterns of infinite resolution possible (Richards and Amos, 2017) (highly granular designs), which begins to more closely resemble a physical materials makeup; addressing the restricted discourse create from b-rep digital models as highlighted by Ayres (Ayres, 2012a). Meaning more nuanced relationships and finer material properties could be guided because of the high level of resolution attained via CPPNs.

- **Time**; The compact encodings (reduced parameters) afforded by CPPN, which can still generate complex structures enables multiple design solutions to be generated (that can be performance orientated) and their properties manipulated extremely fast (Richards and Amos, 2015). The time taken to design, manipulate and evaluate relationships of the complex designs is extremely fast, which could prove vital for guiding and determining effects of stimuli on extremely fast material computational processes (e.g. ink diffusion patterns in water). Meaning time may not be a limiting factor for selecting a material platform and a coherent or real-time discourse could be achieved between complex digital models and complex physical processes.
- **Shape**; the voxel units are not restricted to their typical cube volumes / forms ((Richards and Amos, 2017, Richards, 2017), which means a more diverse range of physical materials can be accounted for that are not square in shape, such as, sand or soil, which is more spherical. The ability to more accurately represent the shape of the material increases the reliability of the digital simulations interactions (Dierichs et al., 2015) and could help to determine why certain behaviours or properties are being created in the physical materials.

These three factors in combination with the idea of stimulus based fabrication mechanisms point towards a convergence between the materiality of digital design tools and physical material computational processes that can occur at a high resolution and potentially rapid physical and digital adaptability; depending on the rate of physical material computation processes that are significantly observable / visible. Based on the 3D structures, multi-material properties and rapid generative properties made possible by the CPPN-NEAT strategy and coupling it with stimulus based SA process, such as ink diffusion clouds within a 3D volume it is easy to imagine a new kind of TV, much like a 3D holograph. Imagine 3D dynamic images composed of multi-material patterns, which can rapidly, physically adapt material properties, such as, a single colour, multiple colours, opacity, shape and texture by utilising the CPPN-NEAT strategy to tune and monitor, to determine the required environmental conditions / stimulus needed to update material properties and images. Now because SA material processes are scalable (Whitesides and Grzybowski, 2002, Tibbits, 2012a, Tibbits and Flavello, 2013, Tibbits, 2014b, Tibbits, 2016, Tibbits, 2017a, Papadopoulou et al., 2017) as well as the CPPN-NEAT strategy being scalable (due to the compact encodings / mathematical functions) (Richards and Amos, 2015, Richards and Amos, 2016, Richards and Amos, 2017) it could be easy to imagine the proposed new kinds of TV not being restricted to the 2D dimensions or more interestingly the 3D volumes of typical TVs. Imagine, sitting in your living room or a cinema and instead of watching on a screen you can sit within the movie by seeing the material interactions and occur around you in 3D (see figure 25).

Beginning to attain the physical material potentials (healing, adaption, 3D physical holograms) requires suitable material platforms to be explored and understanding of how to engage with them, so materials properties at various scales can be tuned and adapted. For this reason the following chapter examines strategies of guiding SA material processes along with multiple material platforms to determine suitable platforms for experiments that can develop and prototype the idea of an adaptive design and fabrication system, creating interrelationships between design, fabrication and material.

Figure 25: Future cinemas. Speculative image imagining people sitting within a cinema and watching a movie of 3D physical holograms.

4.5 Chapter Summaries

This chapter extend the abilities of digital design tool discussed in chapter 2 by utilising stimulus to link design representation with physical artefacts as highlighted in 'persistent modelling'.

Persistent modelling

- Critically, manipulating stimulus (in this case fluid pressure) via digital design tools can link design and fabrication processes by transforming predefined metal units.
- Parametric design tools provide a sound starting point for guiding SA material interactions as initially, stimulus that has a significant impact / direct relationship with a material property (e.g. magnetism and material aggregation) can be mapped to parameters and controlled digitally.
- Persistent modelling could be extended by incorporating SA materials as local and global properties could be tuned as comparatively the predefined metal components restrict the possible amount.
- Significantly, the fluid pressure induced acts as a global stimulus in as far as the transformation occurs globally there is no deliberate local transformation.

The following sections have been reviewed as they are all capable of representing materials on a granular level by composing them on either: material units (voxels), agents or cells.

Material Processes and Agents

- Dade-Roberston reveals how employing the dual evolutionary strategy enables digital models to simulate physical material processes, which could potentially enable a discourse between the two.
- Bader demonstrates that the *position-based dynamics* (agent-based) models can be used to robustly simulate the behaviour of thousands of cells based on multiple real-world factors (e.g. environmental conditions, cell-to-cell interactions).
- The time taken to simulate and evaluate complex digital models in relation to material computational processes could limit a coherent discourse between them.

Morphogenetic Engineering

- Employing biological / physical mechanisms, such as, diffusion gradients and threshold values to inform the digital models material behaviour (e.g. cells state, division) and interactions have strong correlation and resemblance to physical processes and conditions that can be used to guide SA material interactions.
- The digital simulations behave as a system of distributed parts, which again bears a strong resemblance to a fabrication process based on SA materials.
- ME highlights how complex systems can be generated from simple rules but critically the system can be evaluated to understand how emergent properties arise from conditions and interactions.

CPPN-NEAT

- The CPPN-NEAT strategy can generate complex 3D structures at a high material (voxel) resolution begins to resemble the granular nature of physical materials.
- The shape of the material units (voxels) within the CPPN-NEAT strategy is not restricted to the typical shape of a cube, catering for a wider range of material platforms and processes.
- The use of CPPNs can generate multiple designs and manipulate them rapidly due to the compact encodings. Meaning potential material platforms that perform material computational processes rapidly could also be catered for as a coherent discourse between stimulus guiding material properties and simulation evaluation are maintained and not inhibited by time.
- The use of NEAT can be then potentially be used to evaluate higher-level relationships created between more subtle material properties and processes and less defined stimulus and or global conditions so they can be used to adapt and tune these properties based on real-time environmental sensor data.

The next chapter examines existing and current approaches for guiding SA along with other material platforms that perform SA at the material scale, so as to select a material platform for developing experiments.

5 Searching for Material Platforms

The primary aim of this chapter is to highlight material scale SA platforms for developing experiments. Significantly, the platforms must be able to establish feedback between digital design, fabrication mechanisms and material properties, based on stimuli. The two main benefits that then arise are;

- 1) Mechanisms are part of the SA processes, which could be exploited to create a material system (Tibbits, 2017a). Meaning, adaptive potentials latent within the SA material platform could be drawn out or further enhanced if they could be guided by tuning stimulus.
- 2) As established by Ayres (Ayres, 2012b) stimulus provides a means of connecting design representation and physical artefact but it also provides a means of engaging with mechanisms of SA to tune and adapt material interactions and properties that occur within the process.

Significantly, stimulus acts as the energy component of the three ingredients required for SA (in a design context) defined by Tibbits, which are: "I - Materials and Geometry; II - Mechanics and Interactions; III - Energy and Entropy" (Tibbits, 2016). Being able to tune and adapt the magnitude of the stimulus supplied to the SA materials could enable the interactions between the components to be guided. However, mechanisms must be discovered to determine if desired material properties have been fabricated if the materials themselves are incapable of self-sensing or generating their own feedback. Enabling feedback can be used to develop adaptive design and fabrication system by determining associations between desired material properties based on resultant conditions, all generated from inducing stimulus means a *Closed-Loop Control System* (hereafter CLCS) could be developed.

A CLCS means the control action, in this case, a physical stimulus (e.g. electrical current, pH, temperature) have feedback with process variables of the SA material, such as volume, density, composition, surface texture. Here, feedback can be achieved between design tools, fabrication processes and material properties by monitoring resultant environmental effects that correspond to certain material properties. Conversely, the control actions in Open Loop Control Systems (hereafter OLCS) do not have feedback between process variables. In order to develop an adaptive design and fabrication system based on material scale SA and resembles a CLCS material processes and interrelationships must be highlighted from the following strategies and developed within the design experiments of this research.

The structure of this chapter is;

- *Firstly*, this chapter examines biological processes of fabrication to understand what mechanisms dictate material adaptation and if aspects of them could be applied to guiding and determining material properties of SA materials.
- *Secondly*, various strategies and material platforms are examined to understand how they achieve SA using artificial units.
- *Thirdly*, material platforms that can achieve SA on a material scale are highlighted for developing experiments, which are initiated by inducing stimulus.
- *Finally*, other viable material platforms (synthetic biology and protocells) and strategies are briefly discussed, which are also sensitive to being guided by environmental stimuli / conditions.

The strategies examined are organised into three main sections of SA materials, which are then further broken down. Significantly, within these sections mechanisms and possible resultant material effects that could be produced from stimuli are determined, which can then be;

- Mapped to relevant design parameters or ultimately discovered by the design tool based on data.
- Used to determine if a desired material property has been fabricated (e.g. material volume and location).
- Developed to create an adaptive design and fabrication system based on stimulus and feedback. For example, an increase in temperature increases material aggregation rate, which results in an increase in pH.

The resultant effect could be monitored to relate it to material properties. Understanding and engaging with mechanisms present in material systems has begun to enable dialogue between diverse research areas, such as art, design, engineering, chemistry, biology and has led to new creative potentials (Tibbits, 2017a).

5.1 Biological inspiration: bone remodelling process

Biological fabrication processes provide the main inspiration for rethinking design and fabrication processes and how to interact with materials. Primarily because biological structures can continually adapt their shape (across length scales) and material compositions to suit environmental demands as external forces (e.g. mechanical loading) inform material deposition (Vogel, 2003), producing extremely multifunctional, materially economic and gradient-based structures. Additionally, some of the desirable properties of biological fabrication processes instilled in its structures are scalability, robustness, emergence, complexity and physical adaptation (Speck et al., 2015).

An example of a biological structure that demonstrates adaptive abilities is evidenced in the bone remodelling process (Frost, 1990). Bone remodelling is a process in which mineralised bone (old bone) is removed by osteoclasts and continuously replaced by new bone via osteoblasts to heel micro-damages (Frost, 1990, Hadjidakis and Androulakis, 2006, AMGEN, 2012). Remodelling occurs in three consecutive phases: *"resorption, during which osteoclasts digest old bone; reversal, when mononuclear cells appear on the bone surface; and formation, when osteoblasts lay down new bone until the resorbed bone is completely replaced"* (Hadjidakis and Androulakis, 2006). The process occurs locally and globally (throughout the skeletal system) and it is governed by various biochemical and mechanical factors (Hadjidakis and Androulakis, 2006). The global process is dictated by numerous hormone levels (e.g growth hormone) whereas the local process is typically governed by various cytokines, which are small proteins. Ultimately the osteoclasts and osteoblasts activity is in balance and prevents a certain cell activity from predominating. Significantly, the mechanism that governs the process is that of threshold conditions. Being able to measure variations in environmental conditions, for example, a rise in pH or temperature could potentially be used as a means to determine roughly what material process is being carried out or if a corresponding material property has been fabricated using a SA material platform. This raises the question; *what material platforms create fluctuating conditions when subject to stimuli to determine material properties?*

5.2 Self-Assembly: Predefined Components and Properties

The strategy of SA examined in this section typically predefines the artificial material unit's geometries or the location and arrangement of the designs' material properties. Essentially programming the designs material make-up and instilling information within the material (Tibbits, 2016, Tibbits, 2017a). There are three sub-sections:

- *Firstly,* predesigned cubes, which are embedded with hardware and able to perform computational processes, such as self-sensing (Frazer, 1995, White, 2005, Zykov et al., 2007, Gilpin et al., 2010, Gilpin and Rus, 2010, Levi et al., 2014).

- *Secondly*, predesigned geometries, which are able to perform computational processes, such as error correction but without the need for hardware by designing connection / material interfaces (Papadopoulou et al., 2017). It then discusses the impact and role external energy can have on guiding SA material interactions.
- *Finally*, 4D printing is examined, where a design's material properties are 'programmed', enabling it to respond to conditions, such as humidity (Correa et al., 2015).

5.2.1 Self-inspecting units

This section examines research projects which embed hardware (e.g. sensors, power supplies) into individual material units with predefined geometries. The embedded hardware enables: 1) self-inspection between neighbouring units, 2) information between physical configuration and digital representation to be relayed back and forth and 3) self-assembly in 2D and 3D. However, embedding hardware into material units is not the only way of achieving self-assembly and error correction as highlighted by Tibbits et al (Tibbits, 2011, Tibbits, 2012a, Tibbits, 2012b, Tibbits and Cheung, 2012, Tibbits, 2014b, Tibbits, 2016, Papadopoulou et al., 2017), which will be discussed in the following section

Frazer et al explored the idea of integrating hardware into material units as a more intuitive means of exploring architectural design ideas compared to current software in interfacing technologies of the time (Frazer et al., 1980, Frazer, 1995) (see figure 26). The material units (cubes) embedded with hardware and electronics made up the *'three-dimensional intelligent modelling system'* (Frazer et al., 1980, Frazer, 1995). The cubes could be connected together manually both physically and electronically using a plug type interface to create 3D forms. The embedded hardware in each cube enabled 'self-inspecting' for neighbouring connections between other cubes on each of its 6 sides. The information was then relayed to a computer graphics interface, which reproduced the initial physical forms created. Frazer et al extended the system's sensing abilities and material beyond cubes to include oblique angles in the *'flexible intelligent modelling system'* project (Frazer, 1995), which provided a greater number of possible formal arrangements and typologies. The self-inspecting abilities enable discourse between: a) neighbouring material units and b) design software / representations. These systems did not self-assemble because:

- The interface connections are not induced by the hardware
- The interface connections are not sensitive or robust enough to connect to one another when supplied with energy.

The first point has been addressed, to a degree by two other projects research projects where the material units are also embedded with hardware and sensors and can also self-inspect neighbouring connection. The second point will be examined further in the next section, where material components that do not contain hardware can SA when supplied with energy as their geometries and connection interfaces are predesigned (Tibbits, 2014b, Tibbits and Flavello, 2013).

Regarding the first point, Gilpin et al partly address the issue of self-assembly, on more of a 2D level. The system is again composed of custom cubes but on a smaller scale at 1cm (Gilpin and Rus, 2010, Gilpin et al., 2010) (see figure 26). Again the material units have a pre-designed geometry and are embedded with hardware, which enables self-inspection / communication but additionally relay this physical information back to a digital interface, which records and displays the inspection and connection process of the cubes as well as the final shape of the assembled shape. In Gilpin et al system, the material units can induce neighbouring material connections / bonding as they can induce electro-permanent magnetic bonds (Gilpin and Rus, 2010, Gilpin et al., 2010). The self-induced bonding, which can be turned on and off between units makes it possible to;

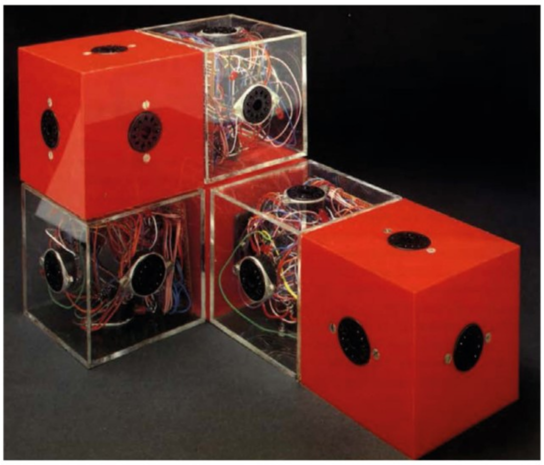
- Reproduce rectilinear / pixelated shapes that are incorporated into / arranged between the material units, due of the self-inspecting abilities (Gilpin and Rus, 2010, Gilpin et al., 2010).
- Reproduce digital shapes created using custom visualisation software or transmit the physically generated shapes back to custom software (Gilpin and Rus, 2012). Meaning, feedback is maintained between design representation and physical materials.

However, the material system itself is not overly robust and only partly achieves self-assembly as the units themselves have to be pre-arranged into grids so the units' faces are aligned and within a certain proximity to one another.

A strategy for addressing this partial self-assembly using hardware is to provide the material units with mechanical movement (Romanishin et al., 2013, Levi et al., 2014) (see figure 26). Individual material units endowed with their own mechanical movement means they can deterministically move to a desired location and connect with one another. A problem with this though is scalability becomes limited. This is because of the increased challenges of power and mechanical actuation (White, 2005). That said, the self-moving, self-assembling collection of units points towards robotic units that behave like swarms, where the collective structures can adapt via reconfiguration (Romanishin et al., 2013, Levi et al., 2014) to suit various tasks at hand (White, 2005) and even self-repair (White, 2005, Levi et al., 2014). The units are able to act as a set of distributed, modular parts and as a result, damaged components can be easily switched out for new ones, making the fabrication process and structure itself more robust as it is easier to fix when damaged.

The limitations of predefining the components' geometries and embedding them with electronics results in a limited material resolution and limited sensitivity of adaption, which are typically constrained to global shape changes. This is because these aspects are dictated by the size of the individual units and difficulties of reducing electronic components to enable movement (White, 2005). As a result of these predefined units, SA multi-material structures and SA gradients which could potentially be reconfigured cannot be achieved with predefined components geometries that require mechanical connections. The various benefits of multi-materiality and functional gradients were discussed in chapters 2, 3 and 4 but mainly they are, reduced material waste due to varied internal architectures, mitigated mechanical damage as a result of abrupt material interfaces, multi-functional and integrated designs.

Examined next is an alternative approach to SA. These strategies can still perform computational processes (e.g. error correction) but without the need for embedding electronics into the materials units. Again the units' geometries are pre-designed, but additionally the interfacing connections between the units are also considered (White, 2005, Zykov and Lipson, 2007, Tolley and Lipson, 2010, Tibbits, 2011, Tibbits, 2012a, Tibbits and Flavello, 2013, Tibbits, 2014b, Tibbits, 2016, Papadopoulou et al., 2017). As a result, the material units themselves are embedded with information (Papadopoulou et al., 2017). These strategies are able to fabricate smaller-scale material units and create a material system with larger numbers as challenges of electronic challenges and self-movement are not present (Tolley and Lipson, 2010). Instead, the units are supplied with external forms of energy (e.g. agitation both fluid and air), which is one of the required 'ingredients' needed to perform material SA described in the context of design (Tibbits, 2016). Additionally, these strategies also further reveal the key role inducing energy / stimuli can play in guiding material interactions in these material systems (White, 2005, Zykov and Lipson, 2007, Tolley and Lipson, 2010).



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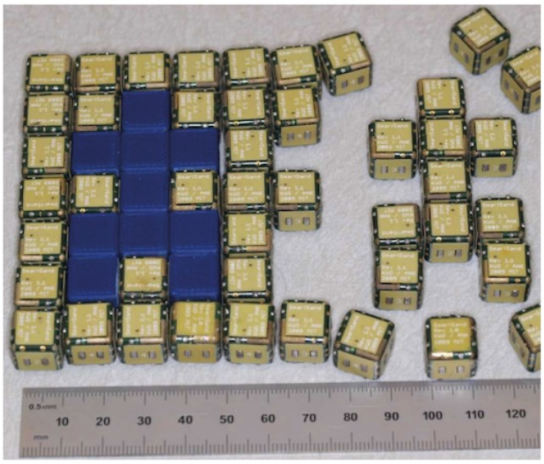

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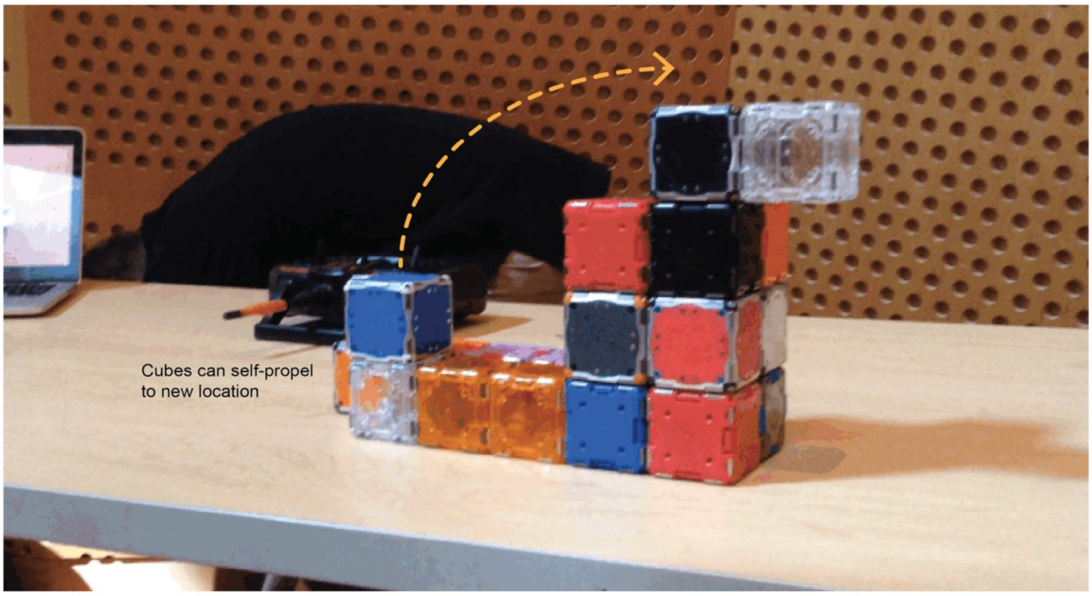

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Figure 26: Robotic self-assembling and self-sensing units. A) Cube material units that make up the three dimensional 'Intelligent Modelling System'. The units are embedded with hardware, which enables self-inspection and can then relay connection information back to computers as a means of generating architectural forms more intuitively. Source: Frazer, J. Year: 1995. B) 'Robotic Pebbles' is a material system that is able to reproduce 2D pixelated physical shapes embedded into the material units as the presence of neighbouring material units can be detected within the distributed system. Source: Gilpin, K. and Daniela, R. Year: 2010. C) Material units that are capable of self-movement via mechanical energy are capable of deterministically self-assembling and self-reconfiguring. Source: Romanishin, J. et al. Year: 2013. Annotations: Author.

5.2.2 Pre-designed components and connections

This section examines strategies of SA which do not incorporate electronics into the material units but are still capable of generating global designs and performing computational tasks, such as binary (Tibbits, 2011, Tibbits, 2012a, Tibbits and Cheung, 2012) and error correction (Tibbits, 2012a, Tibbits, 2012b, Tibbits and Flavello, 2013, Papadopoulou et al., 2017). The two factors that enable SA here are;

- The pre-designed geometries and interface connections of the material units, which will be examined first.
- The supply of energy (e.g. agitation) from external sources, such as pumps, which initiate interactions between units and produce a SA fabrication process. Designing the geometries and interfaces of the individual distributed material units that make up the global design is one strategy for creating 'programmable matter' (Tibbits, 2017a).

The computation abilities of these strategies are embedded directly into the materials themselves as the component geometries and connecting interfaces are designed (Tibbits, 2011) i.e. the mater is programmed. Meaning the SA fabrication process itself can represent a series of logics. For example, the logics are represented by how neighbouring materials are orientated and positioned in regards to one another (Tibbits, 2011, Tibbits, 2012a, Tibbits and Cheung, 2012) (see figure 27). The interface connection details ultimately inform if the units can a) even connect and b) form robust enough connections that can be maintained throughout the SA as material units continually impact with one another or into the boundaries of their container. These less than robust material connections, which are ultimately weeded out during the fabrication process, are made possible by incorporating materials into the interface that can cater for less than ideal connections, such as, two Velcro pads that do not fully align and adhere (Papadopoulou et al., 2017) or arrangements of magnets that repel a connection in one location (Tibbits, 2012b, Tibbits and Flavello, 2013). For example, interface connection details created using magnets with north and south polarities can be organised in different patterns on the edges of various components (Tibbits, 2012b, Tibbits and Flavello, 2013, Tibbits, 2014b). The magnetic properties ensure corresponding connections with other units must all align with other magnetic arrangements to produce a robust connection (Tibbits, 2012b, Tibbits and Flavello, 2013) (see figure 27). Significantly, these component interface designs instil error correction abilities within material units but without the need for self-sensing electronic components. The interface details and self-error correction abilities enable the SA process to be, *"self-adaptive, responsive to the environment, and a reversible process" (Papadopoulou et al., 2017)*. Additionally, because the fabrication process is based on SA it is also scalable but only up to the resolution of the designed material unit and degree of flexibility allowed by the interfaces, which also impacts on the degree of adaptability. The problem with pre-designing the geometry and interfaces of the components mean recursive patterns are inherent within the material system (Tibbits, 2014b), limiting the degree of adaptability (see figure 27). However, throughout the fabrication process, desirable traits of a structure may arise, which may not have been conceived during initial design processes (Tibbits and Flavello, 2013). This is due to two reasons;

- *Firstly,* the objects and structures being fabricated are composed of a series of distributed parts and
- *Secondly,* the fabrication process is not deterministic. Meaning there is not set order to construction sequence, which enables novel typologies to emerge throughout the fabrication process (Tibbits and Flavello, 2013).

However, in order to initiate material interactions between these material types they must be supplied with energy from external sources, such as liquid agitation. Meaning, supplying external energy to the components creates a non-deterministic fabrication process.

Energy is one of the three ingredients defined by Tibbits (in a design context) required to achieve self-assembly. Tibbits primarily focuses on guiding SA processes using the first and second ingredients by designing the components and interactions via geometries and connection types. Typically energy supplied is not monitored or tuned to guide interactions in these systems, which means it is random. Resulting in random interactions, which are not tuned (Tibbits and Flavello, 2013, Tibbits, 2014b, Papadopoulou et al., 2017) (see figure 27). Critically, the energies role in these systems initiates interactions and dictates if the fabrication process can take place as a threshold amount must be supplied to the components to initiate movement. The notion of threshold energies highlights it is a factor that can be tuned to guide SA interactions as parameters of the force can be varied (i.e. force and direction) over time.

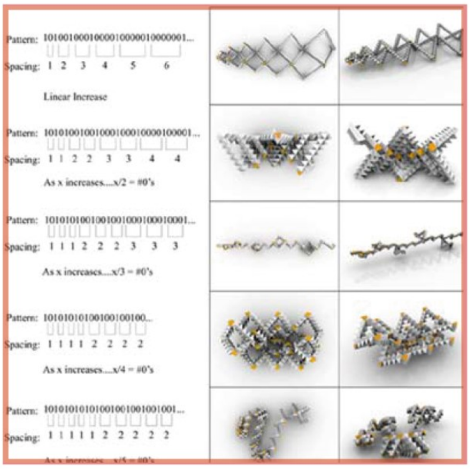
In the research of '*modular robotic assembly*' it has been demonstrated that desired 3D designs can SA at an increased rate if the energy supplied to the geometrically and interface designed material components are tuned so the material interactions are guided (White, 2005, Zykov and Lipson, 2007, Tolley and Lipson, 2010) (see figure 27). The material units must be placed in a volume that enables Brownian motion (random trajectory and speed of materials, where speed increases relative to the energy supplied) such as, a vacuum or volume of fluid (White, 2005). Essentially the environment is used to transmit and tune the magnitude of forces supplied to the material units (White, 2005, Zykov and Lipson, 2007, Tolley and Lipson, 2010). In these research examples, fluidic agitation is used to guide SA material processes and several factors have been highlighted to increase fabrication time of a desired 3D shape, these are; A) increasing the density of material units. B) Increasing magnitude of agitation within the fluid. C) Attraction strength of the binding sites. D) Retention strength of the bonding mechanism (White, 2005). Significantly, the ability to tune the external energy supplied to material units means:

- A stochastic fabrication process is created, one based on predicting interactions and manipulating environmental conditions which enables reconfiguration (White, 2005).

- Reconfigurable designs can be created as bonds are temporary, both electromechanical (White, 2005, Zykov and Lipson, 2007) or friction-based (Tolley and Lipson, 2010).
- Fluid environments and components with neutral buoyancy enable 3D designs to SA and reconfigure (Zykov and Lipson, 2007).
- Smaller-scale material units (micro) and a larger number can be guided by stimulus (White, 2005). Removing hardware enables miniaturisation of geometrically designed components and reduced production costs and times (Tolley and Lipson, 2010).

The ability to guide material interactions via tuning the energy supplied to them opens up the notion of *'tuneable environments',* which could act as an additional strategy for programming materials and material computation. This raises several questions; *do material components need to be pre-designed? What scale of material SA and what properties can be guided via tuneable environments? What mechanisms could be monitored to determine if a desirable design or material property has been fabricated when using materials that cannot self-inspect?*

The strategies examined above explore a SA fabrication process, where the material units of a design are programmed by pre-designing the components' geometries and interfaces. Another method of programming matter is to programme the material make-up of a design. Here, material properties with variable sensitivities to conditions (e.g. plastics that expand different amounts when submerged in water) can be spatially organised in relation to one another throughout the design to create composites. When the composite materials are subjected to a stimulus, for example, changes in humidity, the composite materials respond differently at the local scale, resulting in global deformations (Correa et al., 2015, Menges and Reichert, 2015, Reichert et al., 2015). In regards to SA, programming material properties means an initially flat design can SA by folding up (Raviv et al., 2014, Tibbits, 2014a, Tibbits et al., 2014). This strategy of self-assembly will be discussed in the next section to understand what role stimulus play in the SA process and restrictions that occur from programming material properties.



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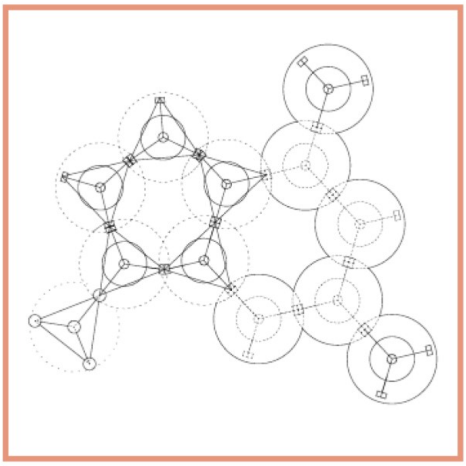

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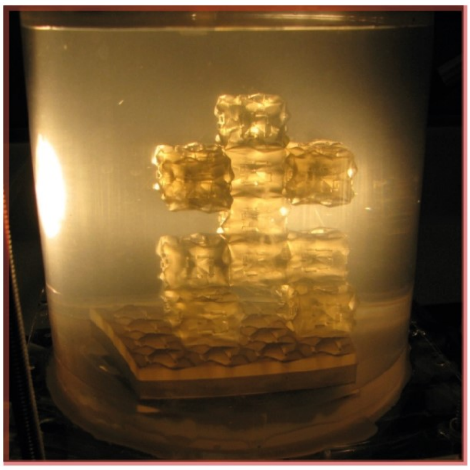

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Figure 27: Geometrically pre-designed self-assembling units performing computation. A) 'Logic Matter' represents a construction material that informs neighbouring material connection locations and orientations based on binary input and logic gates. The various orientations are dictated by physical logic gates (AND, NAND, OR), resulting in construction information and sequences being embedded into the materials themselves. The process enables a scalable robust fabrication process. Source: Tibbits, S. Year: 2011. B) The material units from the research project 'The Self-Assembly Line' have their interface details programmed based on various magnet location and polarities (north or south). These interface details dictate if a robust connection is created and enables self-error correction. Source: Tibbits, S. Year: 2012. C) Recursive patterns are created as a result from pre-designing the material units' geometries and interface details. This limits the scalability, reconfiguration and adaptive sensitivities of the material system. Source: Tibbits, S. Year: 2014. D) Supplying geometrically designed material units with external energy (fluid agitation in this case), which is tuneable (magnitude, location and duration varied) has been demonstrated as a means of guiding SA interactions and speeding up the fabrication process. Source: Tolley, M. and Lipson, H. Year: 2010

5.2.3 Programmable matter and 4D printing

It is also possible to create '*programmable matter*' to perform SA processes or responses by governing the material composition and organisation of a design's material properties (composition) (Tibbits, 2016, Tibbits, 2017a). The two strategies of programming the material properties of a design discussed here will be:

- Components and scale structures that are created from laminated layers of wood to create planar composites.
- The use of 3D printing technologies to spatially control the organisation (orientation and location) of multiple materials with various properties.

These forms of SA differ from the geometric units as it occurs at the material property scale and within or at set locations of the design itself, not from a series of distributed parts. Significantly, these composite materials SA by responding (folding, deforming) when subjected to changes in environmental conditions. For example, plastics that can expand when submerging in water (hydrophilic polymers) causes them to bend and deform, resulting in initially 2D shapes self-assembling to form scale 3D objects and structures (Raviv et al., 2014, Tibbits, 2014a, Tibbits et al., 2014) (see figure 28).

It has been demonstrated that changes in environmental humidity can result in architectural components (Menges and Reichert, 2015, Reichert et al., 2015) and scale architectural structures (Wood et al., 2016, Wood et al., 2018) responding, by deforming and changing their shape to a certain degree (Menges and Reichert, 2015, Reichert et al., 2015). More complex or multiple shape deformations can be achieved by creating a structure from multiple laminate components, where 2D scale architectural structures can SA into 3D forms (Wood et al., 2016, Wood et al., 2018). In these examples, the responses are achieved by fabricating the designs from multiple thin layers of wood (lamination of veneers) to create composite materials (Reichert et al., 2015, Wood et al., 2018). Varying the orientations of the wood laminate fibres and global shape of the design results in multiple bending types / shapes being achieved (Reichert et al., 2015, Wood et al., 2018) (see figure 28). Essentially, the material properties themselves are programmed and become actuators i.e. the materials become actuators as they can bend. The benefit of these material based actuators negates the need for: 1) complex mechanical and heavy parts, 2) complex connection details, 3) power supplies to the materials as they achieve movement passively (Menges and Reichert, 2015). Furthermore, the ability to programme material properties at this scale to achieve SA has been extended by 3D printing technologies because greater control and material variation is achieved. Programming material properties to create more varied deformations by incorporating 3D printing technologies has given rise to the term 4D printing (Tibbits, 2014a). Various benefits of utilising 3D printing technologies to programme material properties are:

- **Increased 3D geometric complexity**; designs can SA into more complex 3D shapes, such as long chains representing protein folding (Tibbits, 2014a, Tibbits et al., 2014) (see figure 28) to 2D nets (Tibbits et al., 2014) and double-curved surfaces (Raviv et al., 2014).
- **Multiple actuated / bending locations**; various locations throughout the design can be programmed with various material compositions or orientations to achieve multiple bending angles and shapes (Correa et al., 2015, Raviv et al., 2014, Tibbits et al., 2014) (see figure 28).
- **Exotic materiality**; It is possible to incorporate bacteria (Bacillus Subtilis), within various materials. The bacteria are sensitive to humidity and act as a nano-actuator (Yao et al., 2015a, Yao et al., 2015b), which could be further extended via the bio-brick principle (Knight, 2003, Ferber, 2004, Check, 2005) to enable increase computational abilities, bioluminescence and shape-changing in response to heat.
- **Variable surface textures**; can be created when a component is compressed as a softer material can have multiple rigid shapes located within it (Guttag and Boyce, 2015).
- **Multiple sensitivities and shape changes**; by varying the material compositions throughout the designs enables its make-up or different locations to respond at varying times or by various threshold conditions (Hu et al., 2016).

These forms of SA created from embedded material based actuators that can respond to varying conditions have been shown to have a wide of applications, from responsive scale architecture structures (pavilions) (Wood et al., 2016, Wood et al., 2018) and architectural components (Correa et al., 2015, Menges and Reichert, 2015, Reichert et al., 2015) to SA assembling products and large scale, simplified protein chain models (Tibbits, 2014a, Tibbits et al., 2014) and even the food industry (Wang et al., 2017). They demonstrate a shift towards no longer treating materials as inert, as seen in typical CAM processes, and engaging with / leveraging material computational processes, which are governed by CAM technologies that are able to precisely organise a design's material properties, in particular, orientation and location, enabling them to respond to environmental stimulus. However, a significant restriction that occurs from the incorporation of CAM is that the SA processes and responses are limited to set ranges i.e. the design can only bend or change surface texture through certain ranges dictated by their predefined and fixed material properties (orientation, composition, location) and shape (see figure 28). The designs and materials can SA but the process is deterministic as the shape has been set. As a result, stimuli would not be able to force a material adaption using these forms of SA. For this reason, several material platforms are examined that SA on the material scale (molecular or nanoscale) when subject to stimuli and do not have designed material geometries or interfaces. Finally, protocells and synthetic biology are examined as they are agent-based (can be programmed and have motility), meaning they can respond and physically move to varying conditions, highlighting other material platforms that could create physically adaptable designs / structures.

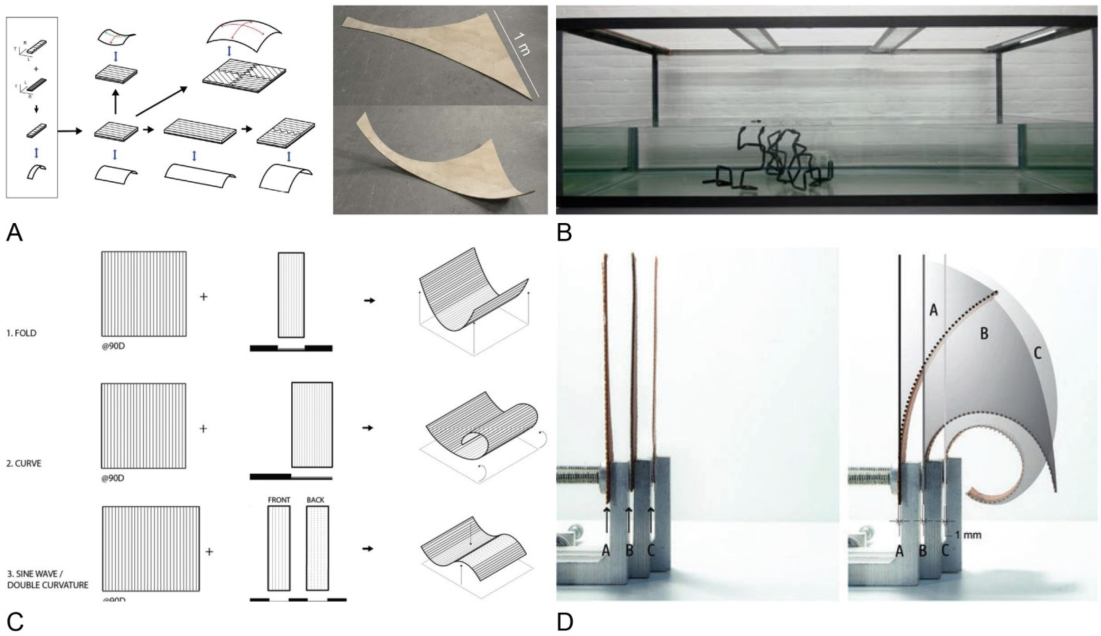


Figure 28: Programmable matter strategies and responses. A) Various wood laminate orientations producing different shape responses as humidity changes. Source: Wood, C. Year: 2018. B) A simplified large-scale protein chain created using 4D printing processes. The chain self-folds / self-assembles when submerged in water as hydrophilic plastic located at the joints of the chain expands when submerged in the water. Meaning the materials act as a passive actuator. Source: Tibbits, S. Year: 2014. C) 3D printing technologies enhance the sensitivities of programming matter as material properties can be varied and organised in relation to location, orientation and shape, which enables increased variation in self-assembling formation typologies. Source: Correa, D. et al. Year: 2014. D) A limitation of the 4D printing strategy is that finalised shapes / objects have a fixed range of response i.e. they can only bend from X-Y amount. The fixed range of response is dictated by pre-defining material properties (composition, location, orientation) and the global shape. Source: Reichert, S. et al. Year: 2015

5.3 Self-Assembly Guided by Stimulus

This section focuses on identifying suitable materials platforms for carrying out design experiments and generating both an adaptive design and fabrication system and methodology. The main criteria for selecting a material platform are:

- The material units do not need to have pre-designed geometries, interfaces, properties (defined compositions and orientations) or embedded electronics to SA.
- SA occurs on the material scale when subject to stimulus.
- The material properties (location, volume, composition, surface texture, colour) must be sensitive to being guided by varying parameters of stimuli (e.g. magnitude, location, duration).
- Adapting and tuning parameters of stimuli / environmental conditions results in the tuning and adapting of relevant material properties, for example, surface texture adapting from smooth to rough.
- The stimuli induced and resultant material effects and properties can be monitored to establish feedback between stimuli and material properties so as to create a C*losed Loop Control System.*

The two material platforms examined for developing experiments are: 1) ink, paint and other liquid mediums that mix, creating diffusion patterns in 2D and 3D, partially mix or do not mix creating 2D globular patterns. 2) The *mineral accretion process* (Hilbertz, 1978), which is the electrolysis of seawater. Additional material platforms (chemical systems, protocells, synthetic biology) are also briefly discussed to understand their strategies and how they could also be implements to create an adaptive design and fabrication system.

5.3.1 Turbulence

"...turbulence is also a mode of communication, how different species and niches inform each other."

(Kelly, 1994)

Artist Perry Hall asks the question; *how can a painting be grown (Hall, 2015)?* Exploring this question Hall initially using and experimenting with decalcomania methods to create paintings having taken inspiration from the earlier work of artist Max Ernst (Hall, 2015). Decalcomania is a material process that creates a series of bifurcating / branching patterns that subdivide down to a micro-scale, meaning they behave like fractals, where the subdivision process is limited when the substrate surface breaks up (Hall, 2015)(see figure 29). The branching patterns occur when pressure is applied from one surface (e.g. a palette knife) and the paint's own surface. Significantly, the patterns are generated and affected by a combination of the paint's viscosities, the substrate surface texture and applying pressure from a smooth surface on top of the paint. Hall interacted with these generative material processes by creating large palette knives and using various substrates, from rough canvases to smooth surfaces like x-ray films, to generate varied 2D surface texture patterns (Hall, 2015). However, time becomes a critical part of being able to explore the notion of growing a painting, which is limited in this process and through these materials as once the paint dries it can no longer be interacted with.

Again the process engage with material computational abilities but highlights the issue of materials changing state over time, which limit if they can be interacted via the same initial processes to change the patterns. Addressing this issue of time Hall has created a *'live painting'* series (Hall, 2011), which is described as a generative painting system (Hall, 2015). These 2D paintings are able to generate patterns as various paint materials (oil, acrylic) and other mediums are used (ferrofluid, water), which either: mix, partially mix or do not mix with one another. The materials and interactions occur under a layer of water, which prevents them from drying and changing state, from liquid to solid, which means the materials (oil and acrylic paints) can be continually manipulated (see figure 29). Critically, the various viscosities and mixing abilities of the materials makes them susceptible to introducing turbulence into the system (Hall, 2015). Where turbulence is the act of introducing energy into the paint mixtures, for example, in the system titled *'Turbulence Drawing System'* (see figure 29) the ferrofluid (magnetic fluid) is agitated and moved amongst the other paint material from underneath via a magnet. As a result, the various surface tensions and mixtures of the paint keep generating new globular forms and fine branching trails of paint, which can be altered based on the manual energy and movement supplied to the ferrofluid.

The material systems Hall creates highlight how introducing turbulence (energy / stimuli) into the system can be used to create interactions and some consistent globular and trail like patterns between materials that do not have geometrically pre-designed components. The use of turbulence also enables relationships to be created between materials. The impacts and relationships created from turbulence can also be witnessed in biological systems, which ensures robust, co-evolving relationships develop between organisms (Kelly, 1994). Significantly, these material platforms highlight that a combination of various materials that contrast in terms of mixing can be used to generate patterns, which additionally, can be reconfigured and manipulated when turbulence is introduced turbulence (energy). For this reason, paints and other mediums will be used as one material platform in the design experiments. They provide a means to explore and understand mechanisms of material interactions based on the impact of energy / stimuli and how stimuli can be used to guide the patterns to create adaptive designs based on digital design instructions. However, several challenges arise as a result of examining Hall's generative paint systems, in combination with previous related work, in order make the patterns materially adaptive and tuneable based on relationships being defined between digital design tools and material properties, these are:

- The patterns are currently 2D.

- They are manually generated. Meaning stimuli or energy introduced would have to be governed by a digital design tool to enable materially tuneable or adaptable patterns based on design representations.
- Feedback and relationships need to be established and discovered between the generated material patterns, stimuli parameters (magnitude, location, duration) and digital design representations.

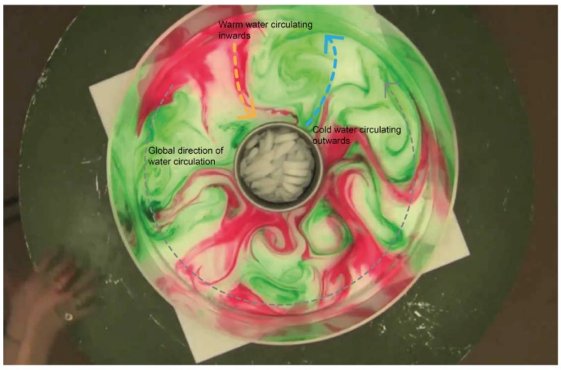
The issue of 2D patterns can be addressed by the mechanism of diffusion as it can occur in 3D. Illari et al exploit the mechanism of diffusion to physically create and demonstrate scale weather pattern simulations / formations (Illari et al., 2009). The materials used are dyed coloured salty water (denser water), which diffuses and sinks throughout a doughnut-shaped volume of freshwater (see figure 29) (Illari et al., 2009). The doughnut-shaped volume of water is rotated (supplied with energy) and at the centre of the doughnut shape is a container of ice that cools the water. The cold water in combinations with the fluid dynamics induced from the rotation creates 2D convection current patterns when viewed above as visualised by the dyed saltwater (Illari et al., 2009). Significantly, the rotational energy induced creates more stable 3D 'curtains' of colour as the dye sinks, in comparison to random dye patterns diffusing within a tank of water that is not rotated (Illari et al., 2009). Additionally, these analogue models have been used to inform digital models to help further understand conditions that inform the patterns generated (Illari et al., 2017).

Being able to tune and manipulate diffusion patterns by tuning energy supplied to them also provide another material platform for developing experiments. It serves as a sound material platform as Illari et al demonstrate the mechanisms and patterns are sensitive to altering conditions (temperature), induced random turbulence / energy (via fluid rotation) and altering material properties (densities). However, in order to develop the diffusion interactions into an adaptive design and fabrication system the issue of feedback highlighted from examining Halls' painting systems in combination with controlling diffusion rates. This is because the rate (time taken) for the dye to diffuse throughout the whole support mediums volume could have a significant impact on the degree or amount the patterns could be manipulated and reshaped iteratively over longer periods of time. Alternatively, contrasting materials that do not mix could be used but they would need to be neutrally buoyant. This raises the question; *how can diffusion rates manipulated so diffusion patterns can be tuned via turbulence over longer periods of time?*

The main challenge of determining feedback between induced stimuli and corresponding material properties needs to be addressed in order to develop a CLCS. For this reason, a second material platform is examined next, which is the mineral accretion process to understand how resultant material effects can be used to establish feedback and maintain conditions for sustained material growth.

A

B



C

Figure 29: Self-assembling paint and ink patterns. A) 'Decalcomania 2017-4 Oil on aluminium'. The subdividing branching and bifurcating patterns created using the decalcomania method are a result of smooth surfaces contacting one another and the surface tension of the paints. The patterns are informed by paint viscosities, substrate texture and applied pressure. Painting Size: 12.7 x 17.8 cm. Source: Hall, P. Year: 2017. Annotations: Author. B) 'Turbulence Drawing System' is a generative painting system where the 2D patterns can be constantly manipulated by introducing turbulence into the system. The patterns are created from a mixture of oil paints, acrylic paints, ferrofluid and water that remain in a fluid state. Source: Hall, P. Year: 2011. C) Scale weather patterns physically simulated by introducing dyed salt water into fresh water, which is cooled at the centre via a container of ice. The doughnut shaped volume of fresh water is also rotated to introduce turbulence (energy) and in combination with the temperature difference creates complex 3D convection current patterns, representative of weather patterns. Source: Illari, L. et al. Year: 2011. Annotations: Author

5.3.2 Mineral Accretion and Resultant Conditions

This section examines the *mineral accretion process* (Hilbertz, 1978) as a material platform that will be explored via design experiments to enable feedback between material properties and the stimuli induced / required to initiate the material scale SA process.

The *'mineral accretion process'* (Hilbertz, 1978) (hereafter MAP) is the electrolysis of seawater, which is a superabundant material (Hilbertz, 1991). In order to carry out the mineral accretion process, a cathode scaffold (negatively charged) and anode element (positively charged) must be submerged within a volume of seawater and supplied with a potential difference (voltage). As long as there is a voltage supplied between the cathode(s) and anode(s) elements the ions (Ca^{2+} and Mg^{2+}) within the seawater solution will precipitate upon the cathode and form volumes of crystal growth (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981). Hilbertz initially proposed the MAP to be employed as a building construction process, which could form a type of carbon sink and ecosystem and (Hilbertz, 1970, Hilbertz, 1991, Hilbertz, 1992, Cureton, 2013). In this construction process buildings could be repaired or adapted by placing them back into the ocean to (re)grow material on damage or new areas as the fabrication process is based on a stimulus that governs material scale SA (Hilbertz, 1970, Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Cureton, 2013). Additionally, the MAP also produces additional resources, such as hydrogen, which as a by-product of construction material growth could be used to stimulate or add towards a hydrogen-based economy (Hilbertz, 1991). Chlorine gas is also created, which could be a potentially undesirable by-product (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Goreau, 2012). However, inhibiting the production of chlorine gas can be achieved by supplying a voltage between 1.23V and 1.36V, but practically doing this is challenging (Goreau, 2012). Instead of employing the MAP as a building manufacturing process it became used as a method for restoring coral reefs as it was deemed too slow for a viable building construction process (Hilbertz, 1979, Hilbertz and Goreau, 1996, Sabater and Yap, 2004, Goreau, 2012).

Significantly, voltage is the major stimulus that governs material SA in the mineral accretion process and more importantly, has parameters that can be tuned (magnitude, duration and location). The challenge is; to determine and map the parameters of voltage to various material properties it can effect, such as: volume, material type / strength, composition and rate. The initial parameters of voltage and how they inform and create relationships with material properties are highlighted in figure 30. Additionally, figure 30 highlights several other factors: 1) how relationships can be created between the components of the adaptive design and fabrication system, which are; digital design tools, fabrication stimuli and material properties. 2) where feedback is lacking in order to determine if a desired material property has been fabricated. 3) how and what hardware can be used to monitor resultant conditions.

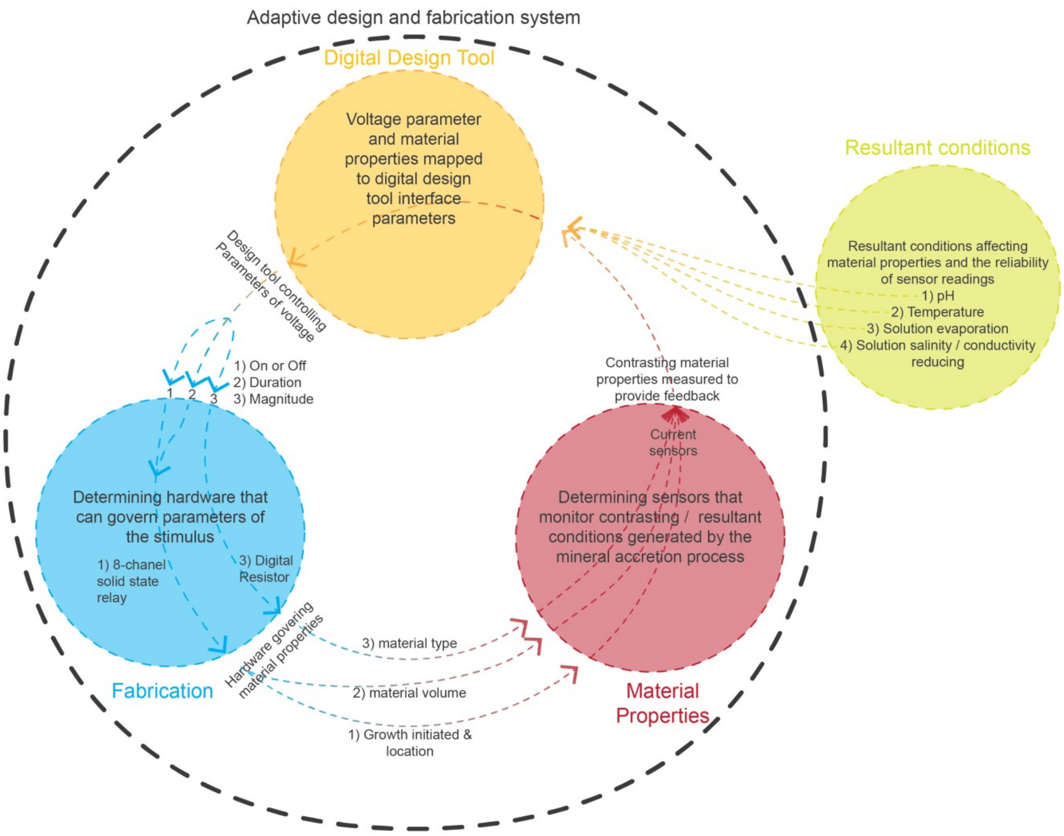


Figure 30: Initial interrelationships mapped for the miner accretion process. The relationships between the parameters of voltage (stimulus) and the resultant material properties of the mineral accretion process, which are mapped to design variables and hardware. The relationships are defined by examining past research on the mineral accretion process. Additionally, resultant material / conditions are mapped and how they can impact material properties and reliable feedback of the system.

Figure 30 serves as a basis for further discussing existing research of the MAP and developing new design experiments, which document and establish how additional material properties can be guided, such as: location, porosity, texture.

The experiments of Hilbertz et al were generally carried out within the ocean (of varying depths) (Hilbertz, 1979) and tropical reef areas (Hilbertz, 1979, Hilbertz, 1992, Goreau, 2012). Meaning, these experiments generally represent an open system as external fluctuating conditions, such as temperature, are not deliberately controlled. Nor do resultant conditions, such as changes to the solution's pH during the MAP predominate as the solution mixture is constantly changed due to constant solution flow and exchanges as a result of ocean tidal patterns (Hilbertz et al., 1977). Furthermore, the experiments were typically an OLCS as there was no feedback between material properties (process variables), such as material volume, and the induced stimuli of voltage that govern them (control action). Meaning it is not determined if desired properties (e.g. volume) had been manufactured from the process in these systems based on a design tool or design representation like that of persistent modelling (Ayres, 2011, Ayres, 2012a). By examining these experiments, there are several other factors and conditions that impact material properties, and more importantly arise during the MAP, which could be used to established feedback and create a CLCS.

These stimuli and environmental conditions are categorised as: A) an induced stimulus (**IS**), B) a resultant environmental condition (**REC**). C) A resultant environmental condition that arises from the induced stimuli, which affects material properties (**IS-REC**). D) An environmental condition that effects material growth but is predominantly due to the nature of the experiments open system (e.g. temperature) (**ENV**). They are then further discussed how they: 1) impacted (if at all) the set-up of past experiments, 2) if they could be governed or induced via hardware and 3) if the conditions or resultant conditions can be monitored via sensors to establish feedback. The several stimuli, conditions, resultant conditions and their parameters are:

Voltage (IS); voltage is the primary stimulus that governs if the MAP occurs and the material properties that grow upon the cathode scaffolds, these properties are: 1) the type of material grown is predominantly dictated by voltage (Hilbertz, 1979). Voltages approximately between 1.23~2 volts supplied between the anode and cathode results in calcium carbonate growth predominating (Hilbertz, 1979, Goreau, 2012). Higher voltages result in magnesium hydroxide growth predominating (Goreau, 2012). 2) Voltage dictates the rate of growth as calcium carbonate growth is slower and also denser than that of magnesium hydroxide (Goreau, 2012). Goreau highlights that growth rates around 1-2cm per year yields predominantly calcium carbonate and above these volumes magnesium hydroxide predominated due to the faster rate achieved from higher voltages (Goreau, 2012). 3) Voltage dictates the volume of material grown; as long as a voltage is supplied and the solution contains the required ions within it growth will occur. Significantly, as the material grows it insulates the cathode structure

(Hilbertz et al., 1977, Goreau, 2012). The material growth has been highlighted as insulating in two instances of past experiments.
Firstly, Goreau highlights that if a portion of material decays away or is broken off of the scaffolds this area's growth rate will be faster than the surrounding material growth until the initially broken area's growth is the same volume as the surrounding material (Goreau, 2012). Interestingly, this highlights the material systems ability to self-heal also.
Secondly, Hilbertz et al demonstrated that material growth rate and volume can be monitored because of the insulating properties (Hilbertz et al., 1977). In this experiment, a custom cathode element was fitted with a sensor comprised of evenly spaced needles (Hilbertz et al., 1977). As the accretion growth thickened voltages reduced, which was detected by the needles as the measured the differences between the voltage supplied to the cathode and the actual voltages recorded at the various needles locations (Hilbertz et al., 1977). Significantly, this highlights a mechanism present within the material system to establish feedback between material properties (type and volume) and stimuli supplied, which is resistance increases relative to an increase in material volume. As a result, digital current sensors could be used to monitor differences in voltages and inform if the stimulus of voltage still needs to be supplied to maintain growth to achieve a desired volume or not, which would create a CLCS.

The main properties of material type and material volume highlighted above reveal that the stimuli of voltage can have its parameters tuned and adapted so as to guide these material properties. These parameters are: 1) Voltage amount, which effects type and rate and could be altered on the fly using an analogue potentiometer or digital potentiometer, which is a variable resistor that can control voltages and current amount. 2) Duration of voltage supplied. Being able to disconnect or *'switch off'* the cathode from power supplied after an amount of time or when a voltage relative to material volume grown is detected can be used to dictate volumes grown. However, within these past experiments there is no control over the location of material volume grown or localised control over composition, which raises the question; *how can material growth location be controlled using the mineral accretion process?*

Additionally, it is documented in these past experiments that environmental conditions can arise as a result of the MAP, which affect material properties (e.g. pH) as well as the impact of external environmental conditions as the experiments are generally open systems.

pH (IS-REC); during the MAP the pH of the seawater solution becomes alkaline (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996). The alkalinity of the solution can continually increase if the volume of solution is stagnant / a closed system (Hilbertz et al., 1977) or if no contrasting solution or material is not added or present to off-set effects of the MAP in a closed system (Goreau, 2012). At a pH of 9 (alkaline) in the MAP process magnesium hydroxide and calcium carbonate materials are grown, whereas pH levels less than 9 results in calcium carbonate predominantly growth (Hilbertz et al., 1977, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996). Meaning, by tuning the solution's pH it would be possible to grow two materials at a time or enable calcium carbonate growth to predominate if the pH was maintained below a threshold level. This raises the question; *how can pH levels be monitored and tuned over time to affect material type grown.*

Solution conductivity (IS-REC); during the MAP the magnesium and calcium ions are removed from the seawater solution, which causes the solutions' conductivity to reduce (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996, Goreau, 2012) especially in a closed system if the solution is not changed (Hilbertz et al., 1977). The problem of solution conductivity being reduced in a closed system would mean unreliable readings for voltage differences would be created, which would be used to determine material growth volumes. The challenge then is; *how can solution conductivity be monitored and maintained to enable reliable voltage difference readings?*

Cathode design and anode properties (IS-REC); There are 3 main properties of the anode and cathode that effects material properties of the MAP. *Firstly,* the shape of the cathode structure and it's local properties, such as sharp bends, effect material properties as the sharp bends result in concentrated electrical fields, which results in initial growth predominating at these locations (Goreau, 2012). *Secondly,* the proximity between the anode and cathode impacts on the type of material grown, as magnesium hydroxide growth predominates on the cathode that is closer to the anode (Hilbertz, 1979). *Finally,* as the anode is perishable (it dissolves) if the material used can be corroded by hydrochloric acid, the anode will need to be replaced or the process cesses (Goreau, 2012). This raises the question; *how can cathodes be designed to govern material growth location?*

Evaporation (ENV); evaporation can occur due to ambient heat in a closed system (Hilbertz, 1979). A problem of water evaporation will result in solution conductivity levels increasing as the solution becomes more concentrated if the evaporated volume is not replaced (Hilbertz, 1979). Again this factor would produce unreliable results for determining desired volume growth based on voltage differences. *How can the volume of water be kept constant to maintain solution conductivity levels?*

Temperature (ENV); the temperature of the seawater can also impact on pH, conductivity and the type of material grown (Hilbertz et al., 1977). Material growth is harder and occurs faster in warmer tropical water temperatures (Goreau, 2012), which typically ranges between 20 - 28 degrees Celsius (Hilbertz and Goreau, 1996). However, as temperature has an effect on conductivity it will have to be maintained at a reasonable constant within 20 - 28 degrees Celsius to ensure reliable voltage difference readings. *How can temperature be maintained within a closed-loop system to ensure consistent pH and conductivity readings?*

Agitation (ENV); Agitation and flow of solution can also be directed / concentrated over areas to accelerate growth rates as the flow of ions is increased to a particular location (Goreau, 2012). *How can solution agitation be used to effect material growth?*

The variable mentioned above provides a solid basis for being able to tune and adapt them in order to guide and established feedback with material properties of the MAP. The MAP was chosen for several reasons:

- It is robust, low cost to set up in the laboratory, initially easy to set up and uses a super-abundant base material that is seawater.
- It SA on the material scale (Hilbertz, 1979, Goreau, 2012) and without the need for pre-designing the geometry, interfaces or connection mechanisms of the material units.
- It is a multi-material system where calcium carbonate (limestone / $CaCO_3$), which is hard, or magnesium hydroxide (brucite / $Mg(OH)_2$), which is brittle (Hilbertz, 1979), can be grown depending on the voltage.
- Determining data, resultant conditions and growth rate of the mineral accretion process in an OLCS has been established (Hilbertz et al., 1977), which significantly, highlights feedback between the material properties of growth rate and volume with stimuli (voltage) is possible and can be developed into a CLCS, where design tools govern the parameters of stimuli.
- A limitation worth mentioning is that it is a slow process and can take days to grow large amounts of material (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979). Meaning adaption rate of the material is ultimately slow.

An issue that arises from the MAP is that the material growth is constrained to the global shape of the scaffold. However, this does not have to be the case for crystal growth as it has been demonstrated that complex, 3D nano-crystal formations can be grown without the need of scaffolds (Grinthal et al., 2016, Kaplan et al., 2017). Interestingly, the various shapes (flower, coral, helical) are created by tuning and altering stimulus (temperature and pH) and their parameters (amount, duration) imposed upon the solutions in which the SA crystal formations grow (Grinthal et al., 2016, Kaplan et al., 2017). Significantly, this demonstrates the resolution and accuracy stimulus can have and could be potentially game changing.

The next section briefly examines other possible material platforms that could be used to develop an adaptive design and fabrication system.

5.3.3 Alternative material platforms

It is worth very briefly mentioning several other material platforms potentially capable of creating an adaptive design and fabrication system. The reason for this is that the two material types examined (protocells and bacteria) can be programmed, not geometrically but via chemistry or DNA, so they can perform actions when a threshold condition is reached.

Firstly, it has been proposed that protocells can be used as fabrication agent's architectural context (Hanczyc and Ikegami, 2009, Armstrong and Spiller, 2010, Spiller and Armstrong, 2011b, Armstrong, 2014). Protocells are artificial chemical systems comprised of oil in water or water in oil droplets, which can be programmed chemically to respond to threshold conditions (Hanczyc, 2014). Their application as agents for fabricating architectural structures are based on the ability to programme them, enabling them to: change shape, move on top of a liquids surface, self-divide and amalgamate (Hanczyc, 2014) and deposit different material types (Armstrong, 2011, Beesley and Armstrong, 2011, Cronin, 2011a). Utilising protocells as fabrication agents could enable structures to adapt and self-heal (Armstrong and Spiller, 2010, Spiller and Armstrong, 2011b, Armstrong, 2014). This is because protocells can deposit materials, both colourful carbonate materials (Armstrong, 2011, Beesley and Armstrong, 2011) as well as carbon non-tubes (Cronin, 2011a). The materials can then be deposited at desired locations as protocell movements can be governed by confrontation gradients (Cejkova et al., 2014). Several interesting and useful abilities have been demonstrated with this material platform that could enhance an adaptive design and fabrication system, these are:

- **Movement**; protocells can be programmed to move to locations of high concentration gradients (Hanczyc et al., 2007, Hanczyc and Ikegami, 2009, Hanczyc, 2011, Cejkova et al., 2014, Hanczyc, 2014), which allows them to move through 2D mazes (Cejkova et al., 2014) and could be used as a means of directing multiple protocell activity to deposit material where it is needed (Hanczyc and Ikegami, 2009, Armstrong and Spiller, 2010, Armstrong, 2014, Cronin, 2011a). Additionally, it has been demonstrated that various protocells can be added or removed overtime via the use of an automated syringe system (Gutierrez et al., 2014).
- **Self-sorting and self-amalgamation**; it is possible to create various typologies of protocells that can amalgamate (join and mix) with ones of the same type or repel ones that differ (Armstrong, 2014, Gutierrez et al., 2014, Hanczyc, 2014). Meaning numerous protocell types could be used as a semi-permanent movable framework to guide those that deposit material.
- **Shape changing**; protocells can also be programmed to change shape after certain durations when exposed to certain threshold conditions (Cejkova et al., 2016, Čejková et al., 2018), which highlights an alternative application for them as possible 3D physically adaptive displays.
- **Metabolism**; the protocells abilities mentioned above are enabled because they have a form of metabolism (Armstrong, 2014), which results in their activity having a restricted duration (minutes - hours) if the chemical system reaches equilibrium (Hanczyc et al., 2007, Armstrong, 2014, Hanczyc, 2014, Cejkova et al., 2016). The ability to introduce turbulence and controlled stimulus into these systems could prevent the activity from ceasing.

Secondly, synthetic biology is also capable of programming bacteria units, which are capable of responding and carrying out a desired activity when threshold conditions are imposed upon them (Dade-Robertson et al., 2013). For example, it has been demonstrated that bacteria (Bacillus pasteurii and Bacillus megaterium) can be used to induce crystallisation of calcium carbonate in a calcium rich environment when subjected to a threshold concentration of

Urease (Dade-Robertson et al., 2015), where the carbonate crystal shapes can be dictated by the bacteria type used. Additionally, it is possible to govern the sensitivity and activity of the bacteria based on varying conditions using the bio-brick principle (Knight, 2003, Ferber, 2004, Check, 2005). An example of the bio-brick principle is the E.chromi project (Davies et al., 2009, Ginsberg et al., 2014), where bacteria double up as biosensors that can also secrete a colour (visible to the naked eye) if a threshold amount of contaminants are detected in a water sample (Davies et al., 2009). The ability to programme these material units activity (protocells and bacteria) enables them to process information as a distributed system based on conditions imposed upon them and with greater sensitivity, which gives rise to emergent, increasingly complex and potentially desirable properties. More recently, bacteria have been incorporated with bio-active frameworks, which are materials that are 3D printed into desired shapes that can sustain bacterial life (Bader et al., 2018c). The benefit of this is that the bacteria can alter the properties of the support material to change its: colour, surface texture, shape, elasticity, among others, as environmental conditions change (Bader et al., 2018c).

These alternative platforms were not chosen as they are complicated to reproduce, can require expensive equipment and can be highly sensitive.

5.4 Chapter summaries

This chapter examined various SA strategies, material platforms and mechanisms which could be employed to guide and monitor SA process via stimulus. The key aspects from each section are:

Predefined components and material properties

This strategy predominantly guides SA by 'programming' material units and the material properties of a design. Some of the restrictions as a result of this are;

- **Self-sensing units;** embedded electronics restrict the size and number of material units due to cost and production time but enable a discourse between materials, design and fabrication.
- **Predesigned components;** restrict the resolution of the system and generate recursive patterns.
- **Tuneable energy;** governing the energy supplied to the material units establishes stimulus can be used to programme or guide interactions / processes of SA.
- **4D printing;** restricts the global properties of a design to responses, which occur across a defined state i.e. they can bend or compress between or to a certain degree

Self-assembly guided by stimulus

SA processes guided by stimulus opens up to possibility of guiding smaller scale materials that have not be pre-designed. However this raises challenges of feedback and robustness.

- **Paints and mediums;** combining various paint types (acrylic, oil) and mediums (water, ferrofluid) it is possible to create various patterns that can be altered by inducing turbulence. However, they do not provide feedback based on material computational processes or resultant effects.
- **Mineral accretion process;** the mineral accretion process is primarily explored as it has been demonstrated to generate a contrasting effect of insulation as material grows, which can be monitored to determine feedback between voltage differences (stimuli) and material volumes grown. Resulting in an adaptive fabrication system based on stimuli.

Alternative platforms

Alternative material platforms could also be used to create an adaptive design and fabrication system as these materials can have their activity programmed, which is then guided by induced conditions.

- **Protocells;** It is possible to programme these material units to inform their activity, which enables them to act as fabrication agents as they can: sense, move, self-dived, amalgamate and deposit various materials at locations dictated by stimuli they are programmed to.
- **Bacteria;** again, the material units can be programmed but because of the bio-brick principle they can respond to multiple environmental conditions and other bacteria activity more sensitively.

6 Methodologies

This chapter discusses how and why a *research through design* (hereafter RtD) methodology has helped to develop and explore how an adaptive design and fabrication system can be created. Essentially, a RtD methodology is employed through iterative physical prototyping, which explores new possible strategies for design and fabrication processes. Critically, all of the experiments carried out within the research are developmental prototypes, where the process of designing and fabricating each series of prototypes / experiments was iterative and reflective. Meaning it is a practice based processes. In order to understand the possibilities and address the limitations of each prototype, additional methods of actuation and sensing are implemented along with various material analysis strategies for each experiment, which generated material property results (during and post fabrication) that enable comparative evaluations.

The chapter is structured as follows; *firstly*, why and how a RtD methodology has been used to help carry out and create multiple prototypes for developing an adaptive design and fabrication system using various SA material platforms. Additionally, the limitations of employing a RtD methodology are discussed. *Secondly*, an overview of the experiments properties for each of the material platforms used (mineral accretion, paints and inks) is given and how the engaging with their properties help to explore the development of adaptive design and fabrication system based. *Thirdly,* the material analysis employed to compare and determine material properties generated during and post-fabrication. *Finally,* a chapter summary is provided, which tables each experiment, its properties (analogue, digital, closed-loop control system or open-loop control system) and the methods of analysis.

The experiment's set-up details / components of each experiment along with how each experiment is prototyped, fabricated and developed are discussed and highlighted in more detail in the relevant sections of chapters 7 and 8. Essentially these chapters highlight the methodology and processes of iterative prototyping as well as the results and key findings generated from each experiment.

6.1 Possible research methods

The This research aims to re-imagine design and fabrication processes but the intention and primary means of investigating this aim is to physically design and fabricate prototype systems to do so. As a result of this means of investigation, it scopes and highlights several suitable research methodologies, which additionally, do not limit the possibilities of re-imagining what future design and fabrication processes could be based on material computational processes. The significance of not constraining the design concepts to current incremental developments enabled novels applications areas and properties to be understood based on the properties and the material properties generated from the prototype systems. Primarily the research is intended to be rooted in the act of making and exploring conceptual design ideas. In order to understand and select a suitable methodology that facilitates the exploration of this research, a summary table is used (see table 1). The table provides a brief overview of the methodology, its potential strengths and also limitations.

Table 1: Possible research methodologies overview, strengths, limitations and comparisons

Research Method	Overview	Benefits	Limitations
Design Research (including: *Research Through Design, Research About / On Design and Research for Design*)	Design research methodologies can be seen to be comprised of multiple methodologies, mainly, research through, into and for design (Frayling, 1993). However, Cross also discusses design being linked with the sciences to varying degrees also (Cross, 2001). Essentially, design is at the heart of the methodology, where: I) *research through design* typically employs the design process as a means of enquiry (Forlizzi et al., 2009b), which typically acts in generating and creating artefacts (Frayling, 1993, Gaver, 2012). II) *Research about design* typically is centred around the human activity of a design process (Zimmerman et al., 2010). III) *Research for design,* where a variety of activities generate theories designers can use to improve design practice (Forlizzi et al., 2009b).	Significantly, all of the various forms of design research do not specifically set out to define a set answer to a particular problem and as a result, they are highly flexible (Zimmerman et al., 2010, Gaver, 2012). In the context of this research, design research can be comprised of and carried out through a series of design experiments and play an active role in generating knowledge and theory construction (Forlizzi et al., 2009a, Bang and Eriksen, 2014) typically this forms a *research through design* methodology. Additionally, the intention is to iteratively prototype multiple systems, which would generate a series / collection of artefacts that acts as an embodiment of the research (Gaver, 2012). Due to the flexible nature of these methodologies they can be used to imagine preferable and potential futures (Frayling, 1993).	Based on the flexibility of the methodology and it not being centred around specific challenges this could raise problems in developing prototypes that can accurately guide material processes and have tangibility to them. Additionally, it could be seen that the system and prototypes development is based on personal reflections on the challenges that need to be addressed based on the practice centric nature of the process(Friberg, 2010). Meaning shared and multiple perspectives are not highlighted and limit the sensitivity and application *'technologies / practice / process'* developed. Finally, design research also has a weakness in generating theory (Zimmerman et al., 2010)
Critical Design	Critical design is multifaceted in terms of the questions, provocations and issues it can raise and address in regard to multiple complex design challenges, from social, technological	It can highlight future possibilities without being constrained to current market and industry trends. It is liberated from the constraints to creatively explore a variety of possibilities to highlight preferable futures (Dunne and	It can remain distant from the problems it highlights as it can become abstracted. As a result, challenges that arise from prototyping systems could remain abstracted as it can remain at a high level.

	and ethical problems, among many others.	Raby, 2013). Significantly, the issues explored are enhanced and contextualised by physically making artefacts (Dunne and Raby, 2013).	However, future work could employ critical design to what the implications of an adaptive design and fabrication could be.
Scientific / Engineering	Traditionally, scientific and engineering research methodologies typically seek to address a set challenge with strict parameters or incrementally improve upon defined processes through quantitative analysis (Tibbits, 2016).	In regard to guiding processes of material scale self-assembly, the strategy of incremental improvement could be advantageous. The development of design research looked to define various research methods that incorporated scientific methodologies to varying degrees and highlights design and scientific research methods can co-exist (Cross, 2001).	The idea of incremental improvements can be limiting when the intention is to explore and re-imagine novel fabrication processes that will not be based on typical approaches / processes (Tibbits, 2016). For example, the highly deterministic CAD/CAM processes typically employed within architectural research impose form upon material and do not typically leverage material computational processes.

Outlining these various research methods and what they mainly encompass has helped to inform what methodology is most appropriate at this stage to begin to explore and prototype an adaptive design and fabrication system. The most appropriate methodology to be employed at this stage is *design research* methods as the centre around design processes, conceptualisation and making. However, it is necessary to determine which of the design research methods will be used to carry out this research. Either, research through design, research for design or research about / on design. Additionally, future work could explore these other methods once an adaptive design and fabrication system has been prototyped based on design research methodologies.

6.2 Why Research Through Design?

There are various methods of *design research*, these are mainly *research through design* (hereafter RtD), *research for design* and *research about / on design* (Frayling, 1993). Significantly, these various methods all have different focuses on what forms and types of research they develop, which Forlizzi et al outline;

> *"The first is Research on (or about) Design: a research focus on the human activity of design, producing theory that describes the process of design. The second is Research for Design: a theoretical outcome of many different activities that provides designers with theories they can apply to improve their practice of design. The third is Research through Design: a research approach that employs the design process as a method of inquiry on the near future, and that can produces theories in the area of research for design"* (Forlizzi et al., 2009b).

As mentioned previously, the main intent of investigating and developing an adaptive design and fabrication system if to physically prototype multiple systems. Meaning the research method is rooted in employing design and fabrication processes to investigate and understand the challenges, properties and processes of guiding material scale self-assembly. As a result, RtD is employed to develop a series of design experiments / prototypes, which investigate new and future possibilities of design and fabricating structures using stimulus. The series of experiments and prototypes themselves are iterative but principally, all of the prototypes engage with and try to leverage material computation. For example, the ability of multiple material components to self-assemble into shapes or patterns when subjected to varying conditions or stimuli (e.g. temperature).

Engaging with the computational abilities of materials and employing them within a fabrication process means the fabrication process is non-deterministic. As such, a non-deterministic fabrication process resembles a form of '*wicked problem'* (Rittel and Webber, 1974). Meaning, the fabrication process of the developed design and fabrication system is more open-ended and chaotic in comparison to the highly deterministic and precise fabrication processes commonly developed and employed by CAD/CAM technologies. This is because comparatively, the materials themselves play an active role in generating the design's physical properties (e.g. form, patterns and aesthetics) and fabrication logics i.e. the structures or objects properties are not predefined or fixed like as they typically can be in traditional design and fabrication processes, which typically impose the design intent upon the materials during fabrication (Spiller and Armstrong, 2011a). Alternatively, the physical material properties and fabrication logics within these series of design and fabrication prototypes can be emergent, both during and throughout the design and fabrication process, leading to potentially highly desirable traits being generated (Tibbits and Flavello, 2013).

The design and fabrication process in this research is the iterative development of multiple prototypes, which collectively highlight how an adaptive design and fabrication system can be created when using materials that are inert (i.e. cannot self-sense or move) and self-assemble on the material scale without predefined properties e.g. geometries. The benefits of employing a RtD methodology is that it enables a design process and fabrication process that is explorative and flexible, especially as the process and or prototypes become increasingly complex (Gaver, 2012). RtD enables flexibility as it is not looking to prove a set way of engaging with or determining an exact answer or process to the problem (Frayling, 1993, Gaver, 2012), in this case, guiding material computational abilities and material properties via stimuli. Instead, RtD facilitates the 'hands-on' engagement of interacting with these materials abilities by producing prototypes or artefacts (Frayling, 1993, Koskinen et al., 2011, Gaver, 2012). As such, the multiple experiments and prototypes form the research method, which themselves form the basis, insights and perspectives of how to engage with materials using stimuli and what this could potentially lead to in the future for design and fabrication.

The series of prototypes / design experiments are a result of combining multiple, more common, design (e.g. digital design) and fabrication processes (e.g. 3D printing processes) to create a new process by incorporating various hardware (e.g. microcontrollers and sensors) with material platforms that can self-assemble, in this case, the mineral accretion process and generative paint recipes. A benefit of incorporating these tools and processes has enabled interdisciplinary research, which has been facilitated by an RtD method. This is because these tools and processes are commonly used and their properties / variables understood within various research areas, for example, 3D printing in engineering and electrolysis (mineral accretion) in chemistry. Additionally, the benefit of creating these multiple prototypes is that they act as *artefacts* and *boundary objects*, which pull together these diverse research areas and enable collaboration and *'knowledge transfer'* (Star and Griesemer, 1989). As a result, the prototypes / artefacts have provided a platform for creating a common language to enable interdisciplinary collaborations between chemistry, engineering, computer science and electrical engineering.

An additional reason for employing RtD for developing this research is that it could be said that RtD plays an active role within current and diverse areas of architectural research. Some of these areas also explore, develop and prototype novel digital design tools, digital design and fabrication processes, alternative materials and material systems. A wide range of these architectural research areas are discussed within chapters 2 - 5, where design exploration from a practice-based approach (prototyping) generated new possibilities for designing and fabricating architectural structures. From the analogue form find prototypes of Otto and Rasch (Otto and Rasch, 1995) to sophisticated CAD tools and processes that can programme the material make-up of a structure (Oxman, 2010b, Richards et al., 2017). The accuracy and complexity of these digital models can be physically fabricated as various CAM / robotic fabrication processes have been prototyped and developed (Dunn, 2012, Gramazio and Kohler, 2014, Gramazio et al., 2014b). Furthermore and more relevant to this research, it has also been demonstrated that structures can be fabricated / fabrication processes can be based on distributed material systems, which are capable of performing computation (Tibbits, 2012a) or multiple processes as environmental conditions are altered (Hanczyc and Ikegami, 2009, Cronin, 2011a, Armstrong, 2014, Dade-Robertson et al., 2017a). As previously mentioned, controlling these environmental conditions and imposing them upon materials to perform computational enables relationships between design representations and physical representations (Ayres, 2012b). Significantly, these diverse research topics within architectural research have been developed and explored through practice-based research based on multiple prototype iterations.

Additional to these architectural research areas there are three main areas of research, two of which are recently emerging. Collectively combined these three areas closely resemble the experiments and challenges within this research, which also could be seen as employing a RtD methodology. The first area is *'Persistent Modelling'* (Ayres, 2012b), which is able to maintain relationships between design models and physical models by inducing stimulus upon physical materials, which are controlled and monitored via design tools. Importantly, this research demonstrates the strength of iterative prototyping as several 'persistent models have been developed to date, which address challenges and issues raised in the previous prototypes as well as highlighting potential real-world applications (Ayres et al., 2014). The two emerging areas are *'active matter'* (Tibbits, 2017a) and synthetic biology in the context of architecture (Dade-Robertson et al., 2016a, Dade-Robertson et al., 2017a, Dade-Robertson et al., 2017c, Dade-Robertson et al., 2018a, Dade-Robertson et al., 2018b). Both of these areas are highly interdisciplinary and design prototypes systems (construction, robotic and or material) and explore possible fabrication processes based on self-assembly / self-organisation. A major benefit of these research areas is that they highlight new ways of fabricating structures and how they can leverage material abilities, such as self-assembly, self-organisation, self-healing, self-reconfiguration and self-sensing. Furthermore, within active matter, interdisciplinary collaborations are enabled by focusing on processes within the system and how material interactions can be guided across scales (Tibbits, 2017a). These collaborations have generated new application possibilities and developments, from novel developments, in micro-fluidics and micro-robotics to responsive textiles / fashion and self-reconfigurable, self-responsive and self-assembled architecture.

The rich vein of architectural research developed, which could be said to employ RtD methodologies has provided a context and areas for which this research can extend and contribute towards. Mainly, self-assembly (Tibbits, 2012a, Tibbits, 2016), active matter (Tibbits, 2017a) and persistent modelling (Ayres, 2012b). Typically, these areas of research are practice-based, where physical prototypes of novel design and fabrication systems or strategies are developed, which creatively explore and propose new practices, systems, relationships, and abilities for designing and manufacturing architecture. Significantly, the main benefit of employing a RtD methodology is that it allows for multiple strategies to be thought of and physically prototyped without initial technical constraints or specific performance demands. For example, a specific material platform, which requires a desired performance criterion (e.g. comparative loading abilities). These forms of performance demands could be seen as more of a focal point within forms of *'applied research'*, which typically can be restricted to the incremental development and improvement of a technology or process and as a result can stifle creative innovation and novel discovery (Tibbits, 2016). The ability to explore, investigate and re-imagine novel design and fabrication processes is enabled by RtD and is central to the aim and the experiments of this research.

This research employs the same methodologies of physically prototyping systems, which will be used to help facilitate an understanding and develop principles and parameters for how design tools can interact with and guide material scale computational processes, such as self-assembly. How RtD has been employed in regards to practice and iterative prototyping will be discussed in next but the process is also documented within chapters 7 and 8.

6.2.1 How RtD Has Been Employed & The Benefits

This section firstly discusses how a RtD methodology has been employed, mainly via iterative, physical prototyping and secondly, the benefits of using a RtD methodology compared to science and engineering methodologies, which could be seen as more appropriate due to the chemistry involved in the experiments.

Within this research, RtD is implemented via iterative prototyping. As a result, the process of designing and making the prototypes is practice-based and accumulative, with each prototype highlighting challenges and opportunities the following one addresses and extends. A total number of 13 different prototypes have been developed within this research across three different material platforms. 8 in the mineral accretion experiments, 4 in the 2D paint experiments and 1 for the 3D ink experiment. The iterations and developments become more apparent across the series of experiments / prototypes within chapters 7 and 8. Collectively the iterations of prototypes have helped to develop a design and fabrication strategy based on;

- 1) Overriding factors.
- 2) Localised material control based on inducing localised stimuli.
- 3) Resultant effects that can contrast the induced stimuli, resulting in feedback and interrelationships.
- 4) The impact of where the interactions are carried out in regard to generative pattern diversity vs. homogeneity.
- 5) How contrasting materials can be used as flexing frameworks for guiding and delaying material interactions.
- 6) Engaging with and altering material parameters on the fly, which can inform properties of material computational process, such as inhibiting or slowing diffusion rates.

Additionally, the major benefit of exploring different material platforms is that it has developed and builds a strategy of how to engage with and guides material scale computational abilities (e.g. self-assembly) throughout the fabrication processes regardless of the material platform used. Meaning it has a wider range of possible applications. For example, the mineral accretion process being used to grow structural components for architectural structures or infrastructure, which could then adapt and self-heal. Or developing new forms of physical holograms, which could be achieved by more accurately guiding the rapid and complex patterns generated within the ink experiments. *'Tuneable environments'* is the strategy that has arisen from exploring multiple material platforms and the process of practice-based iterative prototyping. How *tuneable environments* arise and how it is defined is unpacked within chapters 7 - 8.

Another result and advantage of iteratively prototyping is that they act as a collection of artefacts, which form a body of research that explores a potential future of *'living-architecture'* where architectural structures can be grown from materials. Collectively the prototypes combined with the tuneable environments strategy could be seen as a means for transforming the current state of architectural practice to a personal 'preferred' state (Frayling, 1993), where architectural structures are fabricated based on material computational processes, which could lead to structures that self-heal, self-reconfigure, share material resources and potentially de-carbonise cities and urban areas.

In order to understand and develop the parameters of *tuneable environments*, which guide material interactions within the different material platforms used but also generates interrelationships additional methodologies are used. These supplementary methodologies are discussed in next.

6.3 Employing Additional Methods

RtD is the main methodology employed for exploring and developing an adaptive design and fabrication system. However, an additional method is employed typically from the sciences and engineering, which help to inform the parameters and interrelationships of *tuneable environments.* The additional method is *actuation and sensing.* Essentially, within these experiments a stimulus (actuation) is induced upon the material platform (mineral accretion or inks) and the resultant conditions, effects and properties are monitored via sensors (sensing). These cause and effect relationships, which are non-linear due to the multiple material interactions and parameters, are most prominent within the series of mineral accretion experiments and are used to establish feedback within the final system. Additionally, the incorporation of hardware to induce stimulus and monitor its impacts enables an aspect of repeatability and accuracy within the experiments. For example, the consistent control over the magnitude, duration and time intervals of a stimulus induced. This repeatability enables comparative analysis between experiments using the same material platform and highlights: 1) the impacts on pattern / material property generation when a parameter is altered. For example, impacts of altering the support solution viscosities and densities in the ink experiments. 2) The role altering parameters can play in developing tuneable environments in regards to interrelationships.

Actuation and sensing can be seen as having more commonplace in science and engineering, which typically seek to explicitly determine a desired material property or process and could be seen as having a contradictory relationship with the main RtD methodology employed but instead, they can co-exist and support one another (Cross, 2001). Essentially actuation and sensing form the basis of tuneable environments, which grow, guide and monitor material properties. But critically, the method of actuating and sensing has helped to support the explorations and iterative developments of the prototypes as they provide tangible properties (analysis and data) and inform / define parameters of a framework for developing an adaptive design and fabrication system based on interrelationships. Meaning, the interrelationships and the impacts of altering associated parameters are highlighted within the system.

It is now worthwhile discussing the limitations of RtD in regards to the possible applications based on the current extent of this research.

6.3.1 Limitations of The Methodologies Employed

Primarily, employing RtD has enabled a discourse and feedback to be achieved between digital design tools and the material properties of material scale self-assembly throughout the fabrication process. To this extent, RtD has been extremely useful. However, RtD becomes limited in regards to how accurately less defined material properties can be guided / controlled within all of the prototypes. For example, the material porosity, surface texture and tubular forms generated within the mineral accretion experiments are not defined or under precise control across all of the experiments. As a result, the methodology becomes limited in regards to new possible design and fabrication processes as well as viable new materials for creating adaptive architectural structures as the precise control over desired material properties is currently limited. The lack of precise control over material properties (surface textures) is also apparent within *'persistent modelling'* if the material does not act uniformly / homogenously (Ayres, 2012a).

The limited control over material properties can be addressed by shifting to known scientific processes within chemistry that are capable of establishing high degrees of control, where materials with desired properties can be synthesised from the molecular scale to growing complex 2D patterns and 3D shapes from material scale self-assembly. Examples of these processes within chemistry, which are capable of reproducibly generating complex 2D patterns and 3D shapes from material scale self-assembly are; concentration gradients (Petrov et al., 1993), fluid advection (Barge et al., 2015), precipitation (Grinthal et al., 2016, Kaplan et al., 2017), evaporation (Cejkova et al., 2016), reaction-diffusion (Knoll et al., 2017) or diffusion (Libbrecht, 2017). Furthermore, these processes highlight that specific patterns can been grown through the manipulation and control over various conditions i.e. highly controlled *'tuneable environments'*, which reveals the possibilities of creating a more coherent discourse between complex material properties and forms with sophisticated digital design tools, which together could pave the way for new forms of design and fabrication processes which are adaptable, precise and viable in terms of industry application. However, this may require a shift towards more science and engineering-based methodologies / processes or perhaps more advantageous an increase in interdisciplinary collaboration, which can be facilitated by a common understanding of the systems / material processes (Tibbits, 2017a).

6.4 Overview of Experiments

As the experiments have not been presented yet in their entirety means they have no context. Because of this only the higher-level properties of the experiments are discussed in the flowing overviews along with how RtD helped explore each material platform. The higher-level properties of the experiments are: 1) the key principle(s) the series of experiments and prototypes explore. 2) How the prototypes are iteratively developed and how collectively the experiments inform one another. 3) How RtD has been used to facilitate the explorations, which is grounded in practice, physical prototyping as well as understanding material properties due to direct engagement / witnessing of them.

The details of the development are highlighted in the next two chapters as they both document the design process and challenges of creating an adaptive design and fabrication system.

6.4.1 Mineral Accretion Experiments

The key principle for the series of mineral accretion experiments is to establish feedback between digital design models, fabrication, stimulus and material properties, where patterns / material volumes are generated from material scale self-assembly.

Designing each prototype and carrying out the experiments revealed key parameters and principles that need to be addressed in order to achieve localised variable material properties. Additionally, the parameters of the stimuli (voltage) induced result in interrelationships being developed, which generate a non-deterministic and non-linear fabrication process. However, the interrelationships generate contrasting properties that can be monitored to generate feedback within the system and lead to a *closed-loop control system*. Critically, RtD helped to engage with the parameters of this material system through prototyping and reflecting on the limitations of each experiment.

6.4.2 2D Generative Paint Recipes Overview: Moving Away from Scaffolds

The key principle of both the 2D generative paint recipe and 3D ink diffusion experiments are to understand how to move away from the restrictions of the cathode scaffold structures, which are required within the mineral accretion experiments, whilst still examining the role stimulus can play within these material platforms. Both of these experiments are not intended to establish feedback between design, fabrication or material properties. However, specifically to the 2D paint experiments, no stimuli or resultant conditions are monitored via sensors.

The 2D generative paint experiments explore how multiple 2D patterns can be generated by changing the ingredients and ratios within the paint mixture recipe. Meaning the various patterns generated are based on the mechanisms created from the recipe itself. Essentially, various colours of high flow acrylic paint, which have various densities, are mixed with flow mediums and additives (silicone and or isopropyl alcohol), which make up the recipe's ingredients. The 2D patterns generated will highlight what the effects of the ingredient are as well as the impact of how the paint recipe is deposited on the canvases. The experiments attempt to emphasise the impacts of the ingredients by generally depositing the paints using a motor controlled syringe system to ensure a consistent flow / deposition rate across similar paintings.

Employing RtD helped to explore how the role of stimulus can be extended from the mineral accretion experiments into less defined material systems and interactions as it highlighted parameters and material properties that can guide 2D pattern generation.

6.4.3 3D Ink Diffusion Overview

The ink diffusion experiments are investigated as a means of extending the 2D paint experiments into 3D volumes. The experiment explores how volumetric ink diffusion properties can be manipulated by only varying the viscosity and density of the liquid they are deposited into. The parameters of depositing the 4 coloured inks (volume, time and intervals) into the volume of liquid as well as the parameters of agitating the liquid via two pumps (magnitude, duration and intervals) are kept constant. These parameters are set and kept consistent by creating a digital design tool and incorporating hardware. As a result, it is the properties to the liquids that are evaluated and how the impact on the inks volumetric properties, such as diffusion rate, dispersion rate and the forms generated. The inks will be deposited into 5 litres of various liquid mediums, these are; 1) water. 2) A sugar syrup at a ratio of 1 parts sugar to 2 parts of water and 3) vegetable glycerine. Where water is the least viscous and vegetable glycerine the most.

Again RtD facilitated the understanding of how a fabrication system could be developed based on stimulus and the material process of diffusion. Diffusion rates are engaged with and altering material properties of the support material. However, RtD within this experiment also facilitated the rethinking of 3D printing processes and applications, from a very slow, layer-by-layer, highly accurate and deterministic process where properties typically become fixed, to a rapid, volumetric, adaptable, non-deterministic process, which could lead to new forms of physical holographs or medical procedures where splints are rapidly grown around a patient's limb.

In order to understand some of the more general parameters and material properties that are generated within the material platforms various material analysis techniques are used. These are discussed next.

6.5 Material Analysis

Generating data from the results of each experiment will be done using various methods of material analysis, which will be used to determine and compare the material properties generated during and post-fabrication in both material platforms. The material properties analysed and methods of analysis to be used are described and separated into the relevant material platform.

6.5.1 Mineral Accretion Material Analysis

For the mineral accretion experiments, numerous forms of material analysis will be employed to determine the various material properties that are generated during and post-fabrication. The material properties and the relevant material analysis methods are;

- **Material type and composition:** During the initial experiments it is important to confirm if the set-up can grow either limestone, brucite or a combination / mixture of both and what conditions result in a certain material property of type to proliferate. In order to confirm the material type grown **X-Ray Diffraction** (hereafter XRD), **X-Ray Fluorescence** (hereafter XRF) and **Scanning Electron Microscopy** (SEM) will be used. Essentially, all of these methods are able to determine the composition or predominant type of material grown by comparing peak value wavelengths to know values of a 'pure' material sample. XRD and XRF both provide data values, which are obtained by grinding up a material sample of dry powder scrapped from the cathode and then placing it within the machine. This gives an overall evaluation of material composition. Alternatively, SEM analysis is able to analyse extremely specific areas of material growth. Instead of scraping material from the cathode, small lengths of the cathode wire are cut from the whole cathode that will have material growth upon them, which is then analysed by placing it within the machine. Again peak values of material composition are generated but from specific areas. Additionally, SEM analysis is also able to provide visual photographic evidence of the material growth at varying degrees of resolution / magnification down to a molecular / individual crystal scale.
- **Final growth volume:** For all of the experiments final growth volume will be determined by measuring numerous and set locations on each cathode using digital Vernier. The collective readings will then be used to provide an overall average value. The digital Vernier can record readings up to 100th of a millimetre.
- **Live growth volume and rate:** In order to determine growth rate over time as it is occurring, time-lapse photography will be used. Essentially, a series of photographs over time, at set intervals, will be taken to document material growth. The time intervals for the photographs will be noted in the relevant experiments that use this technique. Growth volume will be established by comparing it to a known distance, in this case, the cathodes' wire diameter.
- **Environmental conditions:** The conditions that vary during the mineral accretion process, which have an impact on the material growth properties will be recorded by sensors or maintained automatically are: electrical current (monitored and used to provide feedback), temperature, pH, solution salinity / conductivity (monitored and maintained or offset) and water level (automated). Additionally, the solutions are agitated but the fluid dynamics are not monitored. The significance and how these conditions are maintained will be discussed in more detail in the experiment's setup. The accuracy of the individual sensors will be noted in the annotations for each of the experiments set-up diagram.

- **Determining adaptive growth:** As material grows upon the cathode during the mineral accretion process it insulates the cathode (Hilbertz et al., 1977, Hilbertz, 1979, Goreau, 2012). As a result, the current values detected using the current sensor should decrease as growth volume of limestone or brucite increases. Meaning, a *conditional changes* or *contrasting effects* to the stimulus-induced is measured and used to determine growth volumes in real-time. For example, if electrical current decreases as material volumes increase these properties could be associated with one anoterh. Significantly, the electrical current values are recorded with timestamps, which corresponded to 'live' growth volume data determined via time-lapse photography. Various electrical current sensors are used within an experiment to determine which sensor gives the most reliable and accurate readings. The various electrical current sensors are noted within the relevant experiments.

The photography and video analysis for the mineral accretion experiment are the same used within the generative paint and ink diffusion experiments. The specifications and details of the cameras used are given in the next section as the paint and ink experiments predominantly use these forms of analysis.

6.5.2 Generative Paint & Ink Diffusions Material Analysis

For the 2D generative paint and 3D ink diffusion experiments the material analysis is: 1) still macro-photography, 2) time-lapse photography (with a macro or a zoom lens) and 3) videography (with a macro or a zoom lens). The reasons for each of the analytical methods are;

- **Still Macro-photography:** High-resolution and close up details of material formations can be captured, such as pigment particles and granulation.
- **Time-lapse photography (using a macro or a zoom lens):** Again, high-resolution images can be achieved and then composed into a video, which highlight material interactions occurring over longer periods of time. Time-lapse photography is used within the 2D generative paint experiments during the drying time of the paint as this takes a long period of time, which highlights slower material interactions and effects.
- **Videography (using a macro or a zoom lens):** Is used to capture real-time material interactions and pattern generation in both the paint and ink experiments as these interactions can occur rapidly. For this reason, higher frame rates are used so real-time interactions can be slowed to half speed within the video without compromising quality.
- **Agitation energy:** A flow meter is used in the ink diffusion experiments to highlight the effect increasing liquid viscosities have on the flow rate of the pumps. Specifications will be given in the diagramming highlighting this experiments set-up.

Table 2 documents the camera type and its specifications for all of the video and photographic data that will be produced from the experiments.

Table 2: Camera type and specifications

Camera	Pixels	Movie Size	Frames per Second	Lenses	Typical Use
Samsung A9 (Phone)	24 Meg Pix	UHD 4k 3840 x 2160	30	Main Camera EF-S 18-55mm	Videography Photography
Cannon EOS 600D (DSLR)	18 MEG Pix	1920 x 1080 1280 x 720	25 50	3.5-5.6 Zoom EF-S 60mm f/2.8 Macro USM	Photography & Videography

Table 3 compiles the experiments as well as the significant properties of each experiment. For example, if the experiment is analogue and what type of material analysis will be used to generate results.

Table 3: Table of experiments and their properties

Experiment Nº	Material Platform	Nature	Feedback	Material Analysis
Mineral accretion experiments				
1 (Cube)	Mineral Accretion	Analogue	No (OLCS)	X-ray Diffraction (XRD) & vernier
2 (Fence)	Mineral Accretion	Analogue	No (OLCS)	X-ray Diffraction (XRD) & vernier
3 (2 Wires)	Mineral Accretion	Analogue	No (OLCS)	Scanning Electron Microscopy (SEM)
4 (2D Grid)	Mineral Accretion	Analogue	No (OLCS)	X-Ray Fluorescence (XRF) & vernier
5 (Grown by Data)	Mineral Accretion	Digital	No (OLCS)	Vernier and Photographic
6 (Parametric Matter)	Mineral Accretion	Digital	No (OLCS)	Vernier and photographic
7 (Monitoring Growth)	Mineral Accretion	Digital	No (OLCS)	Sensors & videography
2DGenerative recipe experiments				
8a (Global Pattern)	Acrylic Paint	Digital	No (OLCS)	Videography & photographic
8b (Large Syringe)	Acrylic Paint	Digital	No (OLCS)	Videography & Photographic
8c (Flip Cup)	Acrylic Paint	Digital	No (OLCS)	Videography & photographic
8d (Surface Texture)	Acrylic Paint	Analogue	No (OLCS)	Videography & photographic
8e (Contrasting Bands)	Acrylic Paint	Analogue	No (OLCS)	Videography & photographic
3D Ink diffusion Experiments				
09 (Contrasting Interfaces)	Acrylic Ink with Water & oil	Analogue	No (OLCS)	Videography & Photographic
10 (3D Ink Diffusion)	Acrylic Ink with water / syrup	Digital	No (OLCS)	Sensors & Videography

6.6 Chapter summaries

This chapter discussed why and how a RtD methodology facilitated the exploration of an adaptive design and fabrication system based on stimulus and interrelationships, which was developed through iterative and practice based prototyping. The key aspects from each section are:

Research through Design

Employing an RtD methodology for developing and adaptive design and fabrication system is beneficial because;

- It enables explorative freedom within a process that develops based on previous design iterations.
- It is flexible enough to develop a fabrication system, which is non-deterministic and non-linear, which begins to resemble a form of wicked problem and becomes increasingly complex.
- Limitations of RtD arise in regards to material precision as it is not based on scientific processes of material synthesis.
- Material precision could be improved by further interdisciplinary collaboration, which can be enabled via RtD and the creation of artefacts that act as boundary objects.

Experiment Overview

An overview of the collective experiments / prototypes developed per material platform is given. These collective developments are;

- The key parameters of the experiments and how they engage with material computational processes by inducing and monitoring stimulus.
- How inducing stimulus and monitoring contrasting effects enables feedback within the mineral accretion experiments.
- How the 2D paint and 3D ink experiments extend the idea of tuneable environments into material systems that do not require constrained scaffold structures.

Material Analysis

Various material analyses that will be used to determine and compare material properties are discussed. These analysis methods are;

- **XRD, XRF and SEM**; determine the material type and composition of the materials grown from the mineral accretion experiments.
- **Sensors**; various sensors will be used to record real-time data of the resultant and contrasting conditions generated during the fabrication process based on stimulus
- **Macro photography and videography**; will be used to provide detailed, high resolution images and videos of the various material properties generated post and during fabrication.

The chapters 7 and 8 now present and discuss the details of prototypes set-up across various material platforms, the iterative development of the prototypes, results generated from each experiment along with the challenges and potentials that arise.

7 Design Experiments: Investigating Design and Fabrication Processes

This chapter now presents and discusses each of the experiments carried out within this research, which have facilitated in the understanding of how to develop an adaptive design and fabrication system based on interrelationships by employing *'tuneable environments'* to guide material scale self-assembly as well as generating feedback mechanisms to understand the systems variable interrelationships and how they affect material properties generated.

The chapter first presents the series of experiments that uses the self-assembling mineral accretion process. The development and challenges addressed throughout these experiments is presented in figure 31. These series of experiments are used to understand how an adaptive design and fabrication system can be created when using material self-assembly without predefined properties and altering parameters of stimuli to guide material interactions and properties generated. The system and its adaptive abilities are developed based on interrelationships. Following these experiments, the 2D generative paint experiments are then presented. Finally, the 3D ink diffusion experiment is presented. Both the 2D paint and 3D ink diffusion experiments explore how material self-assembly can be guided without the need for restricting scaffold structures. They do not attempt to establish feedback. For all of the experiments, they are either presented as a collection or individually based on their nature, for example, if the experiments are analogue. If the experiments can achieve localised variable material properties (volume, composition, type). If the experiments highlight parameters that be used to establish feedback between design tools, fabrication, material properties and stimulus i.e. can the experiment lead to *Closed-Loop Control System* based on how the sensors are incorporated into the system.

The series of mineral accretion experiments are presented as follows;
Firstly, experiments 01 - 03 are presented as a collection as they are all analogue in nature. Additionally, they fundamentally have the same cathode properties.

Secondly, experiment 04 is presented. Again the experiment is analogue but it is presented individually as its cathode properties differ from the first three experiments.
Thirdly, experiments 05 and 06 are presented together as they are the first two to automate the growth process by integrating hardware to control the variables of the induced stimulus. The stimulus is first based on data in experiment 05. The stimulus is then controlled using a parametric design tool in experiment 06.
Fourthly, experiments 07 and 08 are presented together as they inform one another. The set-up for the experiments is the same but the data experiment 07 is used to establish feedback between design, fabrication, material properties and stimulus in experiment 08.

The series of 2D paint and 3D ink diffusion experiments are then presented following the mineral accretion experiments in chapter 8. These series and the development the of experiments are mapped in figure 74, which are then discussed in chapter 8 as follows;
Firstly, experiment 09 which is composed of a series of generative paint experiments. The paintings are used to evaluate how generative patterns are formed based on ingredients, the impacts of how they are deposited and the impacts of where the paint interactions between the ingredients take place.
Secondly, experiment 10 is presented, which is a very small study to understand how the 2D properties of the paint experiments can be extended into 3D.
Finally, experiment 11 is presented, which explores and evaluates the impact on volumetric ink patters (3D), when depositing inks into varying support material viscosities and densities.

The chapter finishes by discussing the key findings across all of the experiments, which highlight future fabrication potentials based on material scale self-assembly, which can be guided by a stimuli or stimulus. At the end of each experiment section it will be noted if a corresponding paper(s) has been written / published.

7.1 Experiment and Prototype Overview

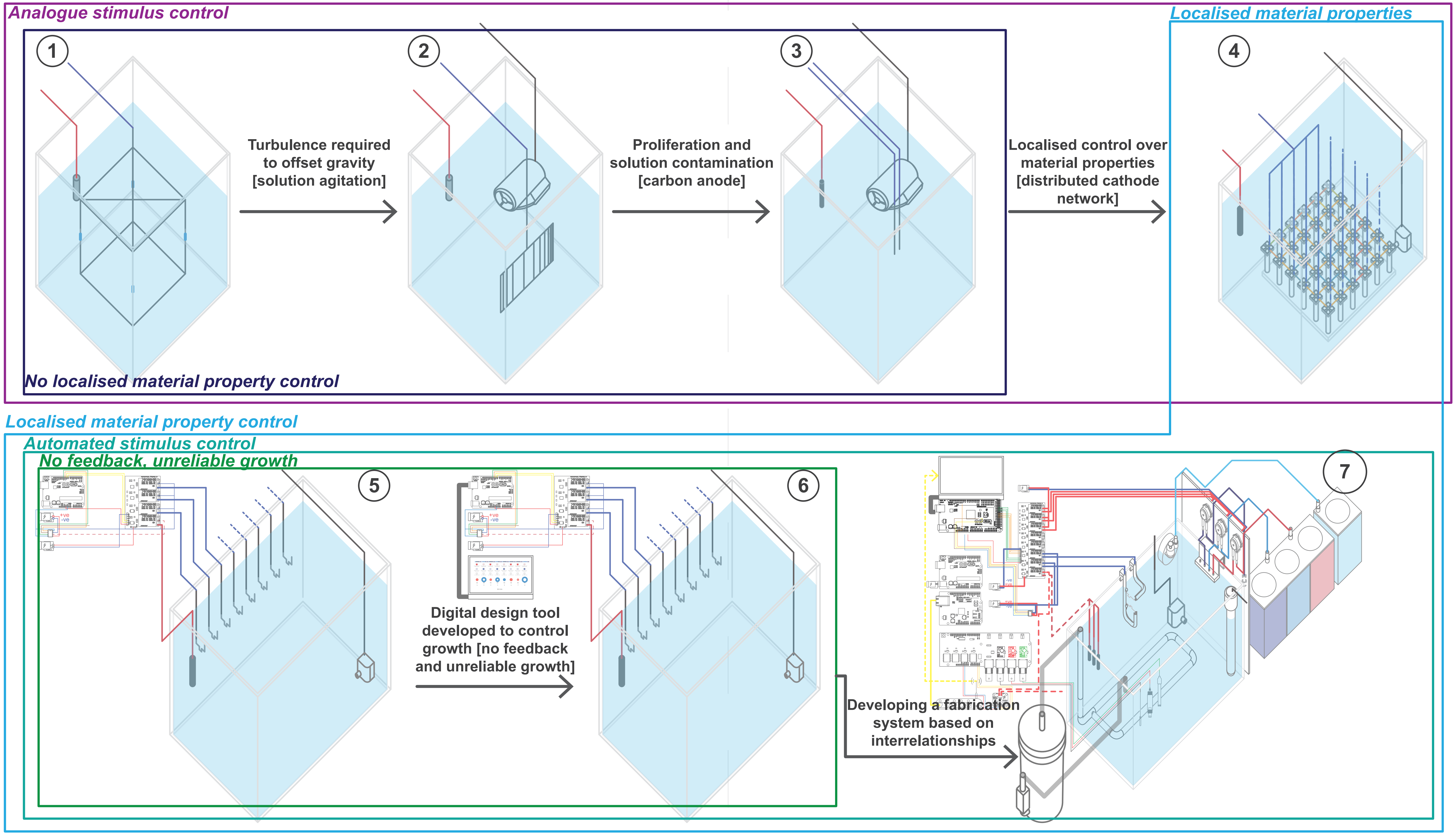


Figure 31: Overview and development of the multiple mineral accretion experiments. The experiments iteratively developed in four stages. Firstly, analogue experiments (1-3) with no localised control over material properties. Secondly, an analogue experiment (4) with localised control over material properties. Thirdly, automated experiments which incorporated hardware and predicted times required to grow desired material volumes. Finally, experiments that incorporated sensors to understand feedback mechanisms between stimulus and resultant conditions, which help develop an adaptive design and fabrication system based on interrelationships.

KEY

1) Experiment 01 [Cube Cathode]
2) Experiment 02 [Fence Cathode]
3) Experiment 03 [2 Wire Cathode]
4) Experiment 04 [2D grid Cathode]
5) Experiment 05 [Grown by Data]
6) Experiment 06 [Parametric Matter]
7) Experiment 07 [Monitoring Growth]

→ Key developments and challenges between experiment iterations

7.2 Mineral Accretion Overview

Prior to discussing the development and results of each experiment a brief summary of the mineral accretion process, its parameters and the variables engaged with are discussed. Further detail on the mineral accretion process has been discussed previously in section **5.3.2**.

Essentially, the mineral accretion process can grow limestone (calcium carbonate) or brucite (magnesium hydroxide) crystals upon cathode scaffolds volumetrically i.e. materials can aggregate upon 3D cathode scaffolds. Material is grown by submerging the cathode scaffolds (negative charge) and an anode (positive charge) within a volume of seawater or brine and then supplying a potential difference (i.e. voltage / direct electrical current) between them. The material will then aggregate upon the whole of the scaffold's volume as long as a potential difference (voltage and electrical current) is supplied. Material properties of the limestone or brucite that can be affected by conditions within this process are: volume, type, rate and composition. The main parameter dictating these material properties voltage, which can be varied in regards to time supplied and voltage amount. A break down is now given for how voltage variables inform these materials;

- **Volume** - the longer the cathode is supplied with voltage the greater the material volume grown as long as the solution is electrolytic or saline. However, the volume of material growth in previous experiments by Hilbertz et al and Goreau has resulted in somewhat uniform growth across the whole of the scaffold. Meaning localised control has not been established. This raises the question: *How can material growth of localised material properties be established?*
- **Type** - The voltage and amperage supplied dictates the material type grown, where calcium carbonate typically grows at lower voltages closer to values of 1.23 volts and brucite grows at higher voltages Hilbertz et al does not state a minimum or threshold condition to dictate the material type grown. However, a minimum of 1.23 volts is needed to initiate the mineral accretion process (Goreau, 2012). Additionally, temperature, pH, the cathodes distance from the anode and time also impact the material growth. Time affects material compositions as brucite transforms into limestone. However, this will not be monitored within the series of experiments carried out within this research. The favourable / threshold conditions for limestone and brucite production are tabulated in table 3 based on the findings of Hilbertz et al, Goreau and Streichenberger.
- **Rate** - limestone grows typically grows at a slower rate than brucite. Typically, the conditions for growing limestone are lower voltages / electrical currents and pH levels. Hilbertz et al provides some details on these material rates (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1991, Hilbertz, 1992). However, growth rates and volumes of both material types, occur first or can be concentrated at either; the cathode closest to the anode and or at the sharp extremities (bends or edges) of the cathode scaffolds due to concentrations of electrical field gradients (Goreau, 2012).

Additionally, solution flow over / at a specific location can increase the transportation of electrons (material ions), which also enhances growth rate and volumes (Goreau, 2012). Manipulating the properties of the cathode to create sharp extremities will be used to focus growth at a specific area. Concentrating solution flow will not be used.

- **Composition** - variable material compositions can be grown within the material volume if the voltage, pH or temperatures are altered over time to conditions that predominantly favour brucite or limestone growth.
- Additionally, temperature, pH, agitation, solution composition, distances from the anode as well as cathode shape can also have an effect upon material properties grown. These additional parameters could be used to fine-tune material properties that lay outside of the direct control of voltage, giving greater sensitivity to the material properties generated. Voltage parameters will be the only ones to be deliberately altered during material growth.

Further details that impact the mineral accretion process have been discussed earlier in section **5.3.2** and have been extensively explored in previous experiments (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Streichenberger, 1986, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996, Goreau, 2012). Surveying this literature has informed the threshold / favourable conditions that significantly inform the type of material deposited upon the cathodes, which are documented in table 4 below. The table is organised with the most significant factors that impact the material type on the left and have a diminishing impact towards the right. The literature / experiments surveyed were typically carried out within the open ocean or in open systems, which means conditions would fluctuate over the course of a day, such as salinity / solution conductivity and temperature (which effects solution conductivity) fluctuations. The experiments within this research will be a closed system and will therefore need to be able to account for these factors and other factors that may need to be offset or maintained during the mineral accretion process, such as increasing pH levels and decreasing solution salinity / conductions levels, which can affect the electrical current sensor readings. Maintaining and offsetting these resultant conditions are intended to achieve more reliable and accurate material adaptation based on electrical current sensor readings.

Table 4: Conditions for limestone or brucite production

Material	Variables controlled		Variables offset		Constants	
	Voltage	Amperage	pH	Temperature (°C)	Distance from Anode	Anode surface ratio to cathode
Limestone	1.23 - 1.5	Effected by the variables noted & number of cathodes	< 8-8.5	< 26	Further away	1:30
Brucite	> 3		> 9-9.5	>29	Closer as pH & voltage increase	1:2

7.3 Understanding the Mineral Accretion Process: Experiments 01, 02 & 03

The first three experiments presented are used as a basis to understand the main parameters of the mineral accretion process and what their impacts are in regards to developing a fabrication process based on inducing stimulus, which is results in a non-deterministic fabrication process as materials and material properties are not specifically defined. Each experiment, its results and the key findings are then discussed. The key findings highlight the challenges that need to be addressed in the following experiment but also build towards new future possibilities and potentials for fabricating structures that can be grown, can adapt and have feedback between design demands, stimulus-induced, resultant or contrasting environmental conditions monitored and material properties generated.

Each experiments overview, set-up / components, results, factors and key findings are discussed in individual sections. The development of the experiments is iterative and has helped to inform: 1) How they impact on design and fabrication processes. 2) What the key challenges are or the overriding factors that arise and need to be addressed in order to achieve localised material properties and build towards creating an adaptive design and fabrication system. 3) How the key findings point towards new forms of *'living architecture'*, which could behave like material eco-systems. These eco-systems can be made possible by engaging with and guiding the computational abilities of materials.

7.3.1 Experiment 01: Cube Cathode. Properties, Predictions and Analysis

The initial experiment sets out to provide a proof-of-concept that controlled crystal deposition could be achieved using electrolysis of seawater (mineral accretion) and or what are the requirements of a cathode typology are required to achieve localised material control. Figure 32 highlights the experiments set-up. Briefly, the cube cathode is placed within 4 litres of seawater, which was collected from Morecambe beach. The seawater solution was not replaced throughout the duration of the experiment. The cathode was then supplied with 1.6 volts at 0.14 amps for a total of 240 minutes. A steel anode is used and a consistent voltage is supplied using a bench power supply. The set-up resembles an *open loop control system*.

Properties

The main factor being explored in the experiment is how to control localised material properties of material type (brucite or limestone growth) and material volume. These properties are proposed to be achieved by separating the top half and bottom half of the cathode with four resistors. The intention of incorporating the resistors is to create two different electrical current / voltage values within the cube cathode. The experiment establishes if this cathode typology enables local control over the deposited material properties.

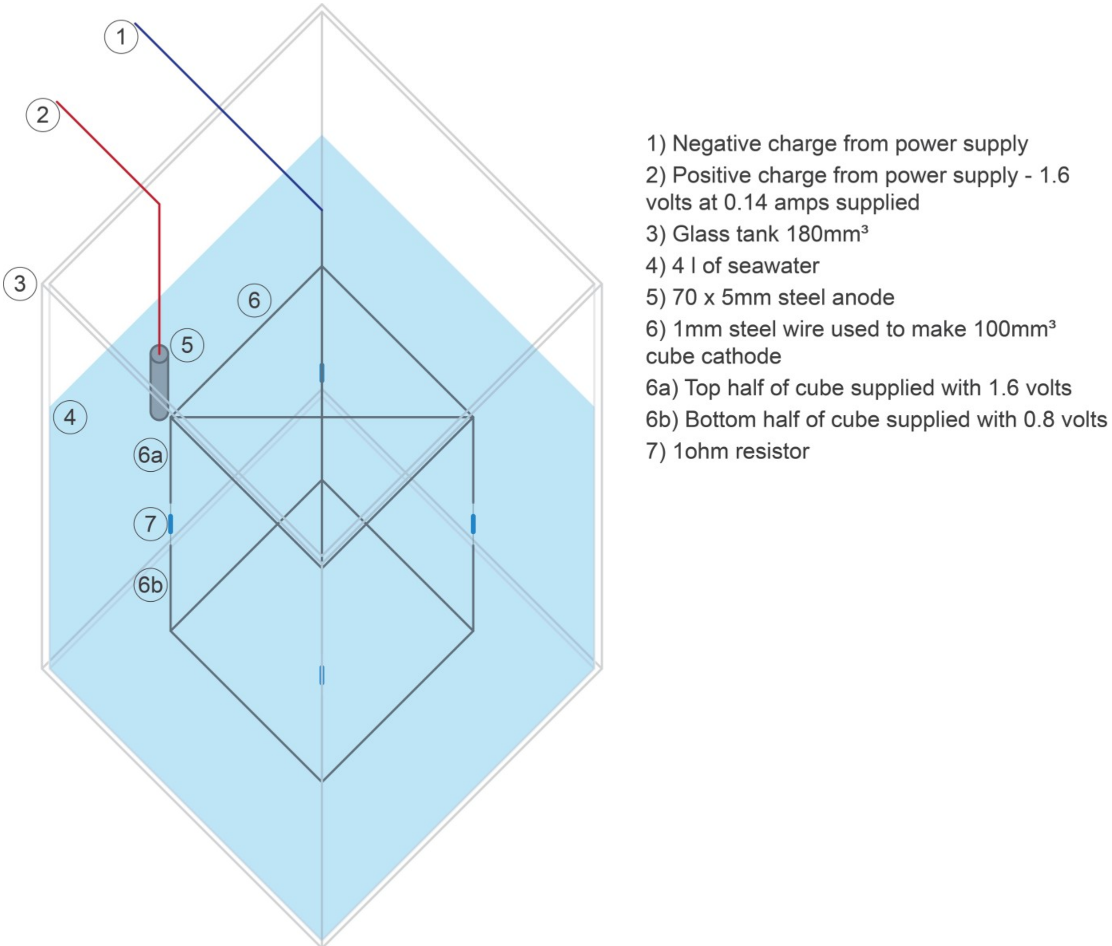


Figure 32: Experiment 01 set-up of the initial cube cathode experiment. The experiment is carried out to understand the initial properties of the mineral accretion process. The resistors that separate the cube cathode are intended to create a drop in voltage, so the top half grows brucite (higher voltage) while the bottom half grows limestone (lower voltage).

Predictions

The predicted material results for this cathode typology are; more material to accumulate on the top of the cube, which is predominantly composed of brucite compared to less material growth on the bottom, which is predominantly composed of limestone. These predictions are based on the research and result generated by Hilbertz et al (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996) as well as Goreau (Goreau, 2012).

Analysis

Material analysis is for the cube cathode experiment was carried out using X-ray Diffraction (hereafter XRD). XRD is able to determine the material composition of the materials grown in different locations, in this case, a sample will be taken from the top of the cube as well as the bottom. XRD confirms the material composition as it reveals different peak values for the material sample, which can be compared to or correspond to know values of the particular 'pure' material sample, such as calcium carbonate.

The results of this experiment will be discussed along with Experiment 02 and 03. Before discussing the results of experiment 01 the properties of experiment 02 and 03 and discussed.

7.3.2 Experiment 02 (Fence Cathode) & 03 Two Wire Cathode: Properties, Predictions and Analysis

Two further experiments that also explore the impacts of cathode typology have been carried out to further understand the properties of the mineral accretion process but additionally, also help to calibrate the system. The cathode typologies are a fence shaped cathode for experiment 02 and two individual wire cathodes for experiment 03.

Properties

Within these experiment set-ups, both of cathodes are suspended within 3 litres of a controlled consistent solution. The solution is created by dissolving 100g of marine salts in 3L of tap water at 25°C. Both experiments are supplied with 2.0V and 0.07Amps for 24 hours and again a steel anode is used. However, this time the solution is agitated by an aquarium wave-maker, which has a flow rate of 2000L/hour. Additionally, the salinity of the solution was monitored by analogue means using a Fluval salt sea hydrometer. Figures 33 and figures 34 highlight the set-up of the experiment.

Predictions

The fence cathode is composed of vertical members that are spaced irregularly; figure 33 highlights the spacing's between the members. The intention is to understand material growth between the vertical members. In particular, if the material can unite and grow as one to create a structure with varying densities of visibility i.e. do some portions of the fence cathode become solid as a result of material growth becoming united. The solid material growth / unification is predicted for the vertical members that are closer to one another.

The two-wire cathode is the most basic experiment as the cathode itself has not been designed to have any particular qualities. It provides a base-line. For this, it is just predicted that a composite material will be grown of limestone and brucite.

Analysis

XRD material analysis will be carried out on the fence cathode whereas material that is grown upon the two-wire cathode will be analysed by way of scanning electron microscopy (hereafter SEM). Again the material analysis will be able to determine the predominant material type grown within the material composition in both XRD and SEM. However, SEM analysis will also provide image data and extremely localised information as analysis can be taken from an area of the cathode by specifically 'magnifying' it.

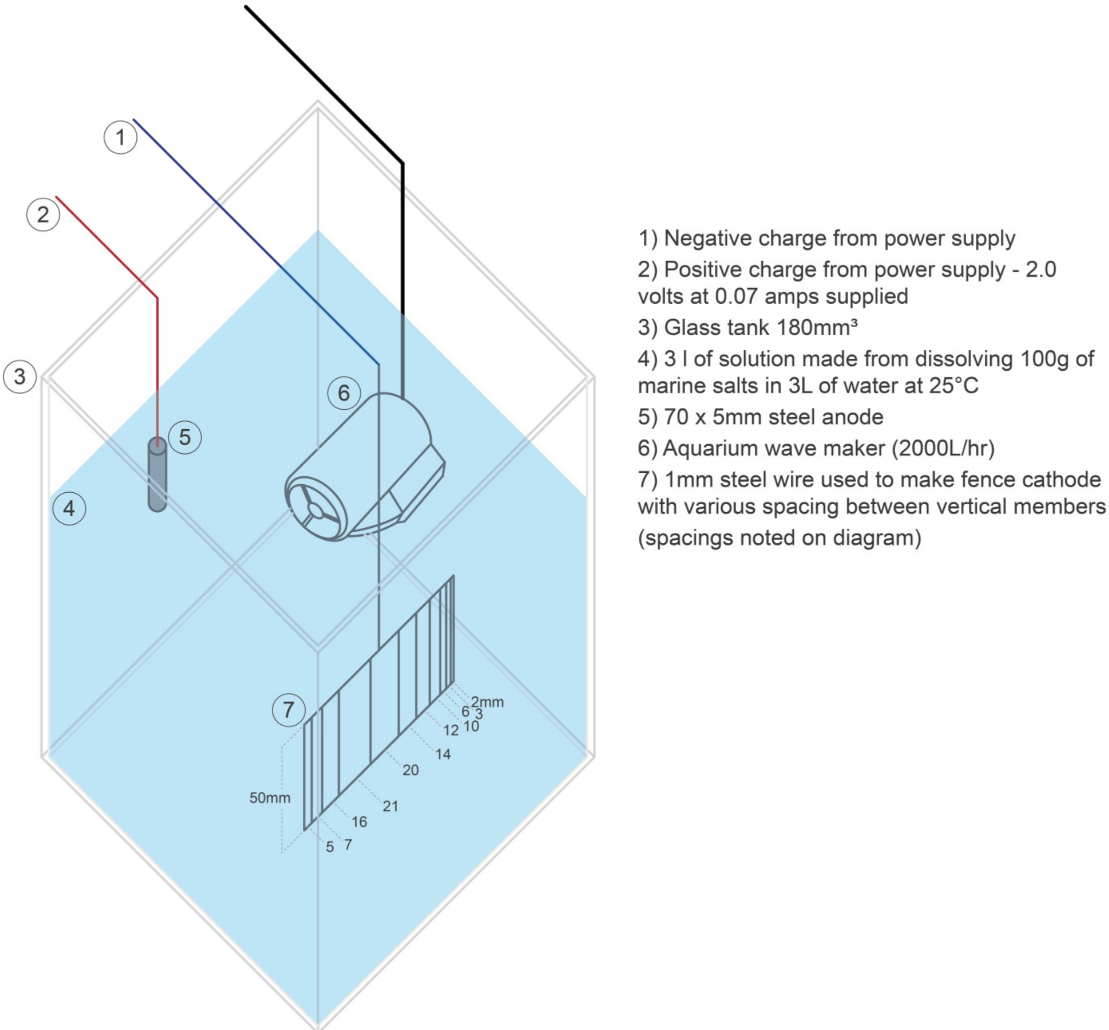


Figure 33: Experiment 02 set-up of the fence cathode. In this set-up agitation is introduced to understand its impacts. The various spacing between the fence wires is to understand if material growth can unify and how spacing impacts on growth uniformity.

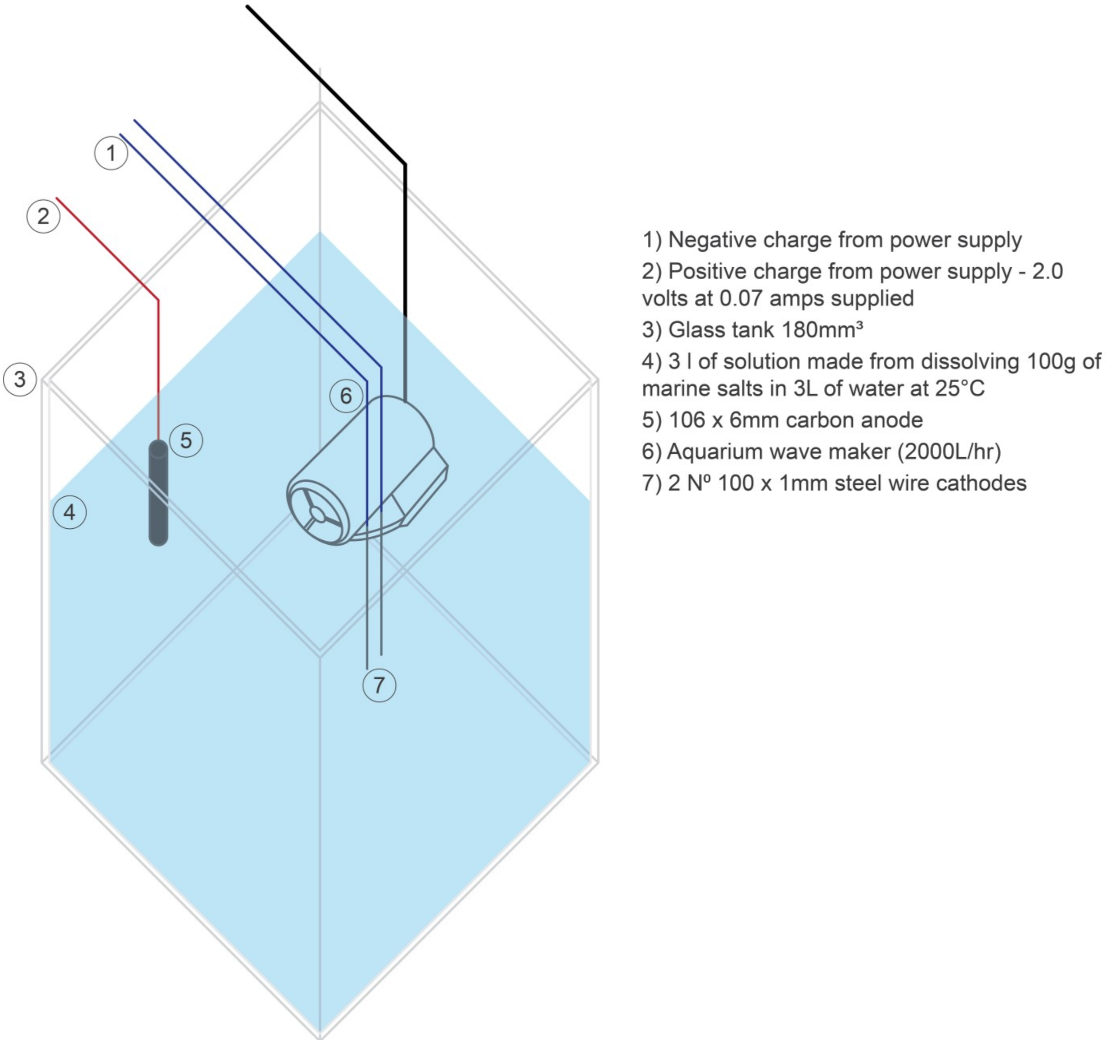


Figure 34: Experiment 03 set-up of two individual wire cathodes. The experiment is carried out to undertake SEM analysis and understand the impacts of the cathode material itself.

7.3.3 Experiments 01, 02 & 03: Results

The results from each experiment will now be discussed through increasing scales of resolution i.e. from macro to micro. *Firstly*, data will be discussed based on anything visible to the naked eye, which is captured via macro photography. *Secondly*, material composition analysis will be discussed based on the results from the XRD and SEM analysis. *Finally,* the images produced from the SEM analysis carried out for the two-wire cathode will be discussed.

The factors governing or generating these material results from each of the experiments are then discussed in the conclusion of this section. Additionally, the challenges that need to be addressed in the next experiment iteration will be highlighted.

7.3.4 Macro Results

Figure 35 is a series of photographs, which reveal two main factors in regards to cathodes typology: *firstly,* the impacts of cathode typology have on material properties grown. *Secondly,* the varying and emergent material properties generated from each of the experiments. The visual results of the cube cathode and the fence cathode are predominantly discussed as they have the most significance in this section. How these material properties arise within the system will be examined within the experiments discussion, which focuses on the necessity of *turbulence* within the system and the impacts of *proliferation*.

Cube cathode: examination of the material deposited on the cube cathode reveals that most material accumulated at the bottom of the cathode cube (figure 35), this was not the predicted result. The predominant growth occurring on the bottom of the cube highlights the overriding impact of gravity on the solutions materials / ions. Gravity causes the solutions ions to sink and concentrate at the bottom of the tank over time, resulting in an increase in material volume being grown. The environmental impact of gravity highlights how additional stimulus can be used to further guide material properties or override the stimulus of voltage within the system. These initial results establish the cathode cube typology does not enable control over localised material properties, in particular, volume. These results reveal the cube cathode typology does not allow for control over current value and location as the effect of the resistor on current is effectively by-passed by the surrounding seawater solution.

Fence cathode: the photographs reveal several interesting factors;

- The brown material grown was unexpected. This material growth is iron oxide and is a result of the steel anode dissolving, which contaminated the solution and resulted in proliferation. However, iron oxide growth only proliferated after the initial white material growth. These orders of growth highlight: A) threshold concentrations of the solutions material must be reached before proliferating and, B) the solutions dissolved materials / ions can be manipulated over-time to grow various composite materials.
- Material growth is uniform as a result of turbulence induced by the wave-maker.
- Material unification occurred between the closer vertical members, creating a variable visibility's.
- Emergent variations in surface textures are generated, from smooth to porous. Where the material porosity increases the closer the vertical member becomes.

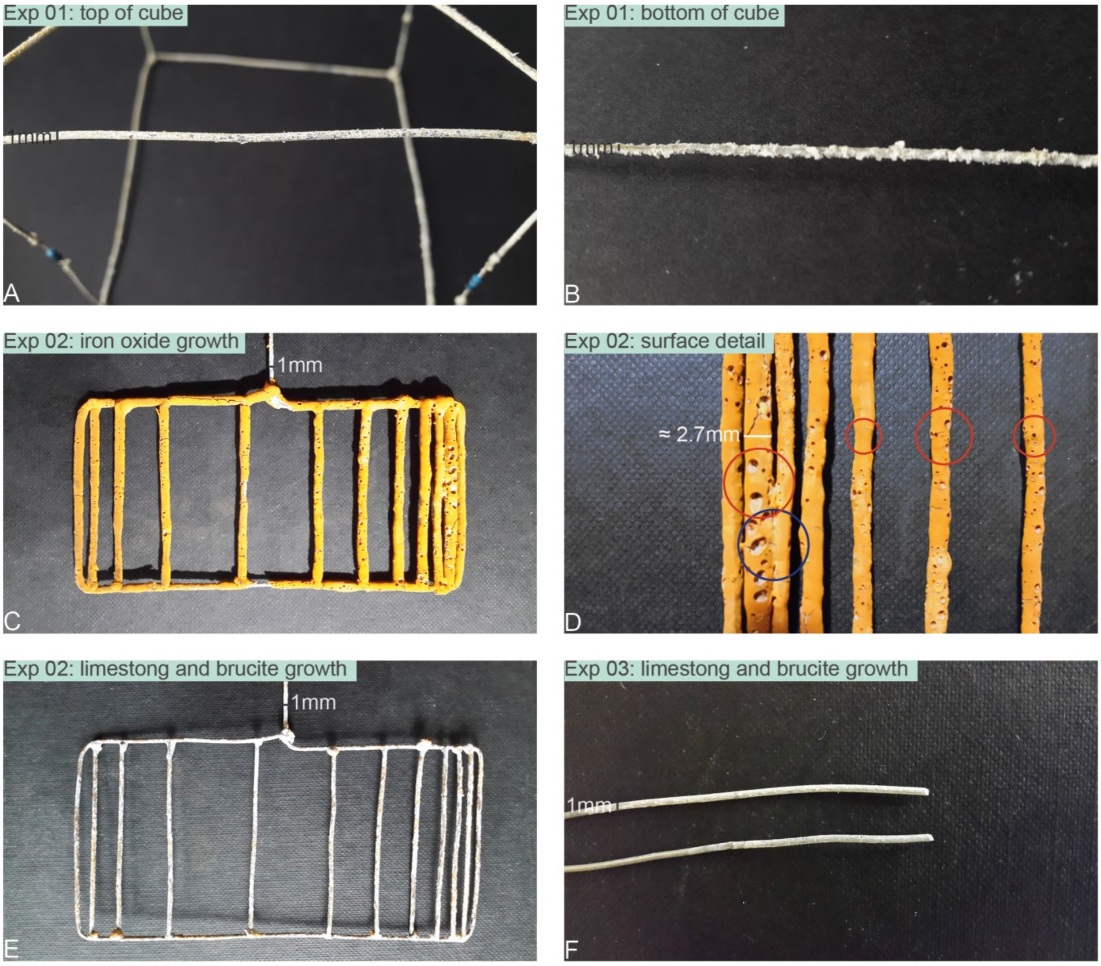


Figure 35: Material growth results from experiments 01 - 03 photographed. A) Highlights the minimal growth that occurred at the top of the cube cathode in comparison to B) the bottom of the cube cathode. This highlights the significant impact of gravity, which needs to be offset. C) highlights the effect of the solution being contaminated from the anode dissolving and the uniform growth achieved as a result of inducing turbulence. D) Highlights material unification and the emergent surface textures generated during growth. Surface texture porosity increases as the vertical members become closer. E) Highlights that the solution must have threshold amounts of materials / ions in order to proliferate as initial material growth is white. F) Uncontaminated uniform growth that occurred upon the two individual wire cathodes.

7.3.5 Material Composition Results

XRD analysis of the cube and fence cathode revealed brucite is more predominant on the top compared to the bottom of the cube cathode, meaning the resistors did have a minimal to no effect on dictating the material properties grown within this set-up (see figure 36). However, XRD of the white material deposited on the fence cathode reveals both limestone and brucite are present, this establishes a multi-material system is possible using the mineral accretion process, meaning the proposed system requires modification. Additionally, SEM analysis also confirms these results (see figure 37 and 38).

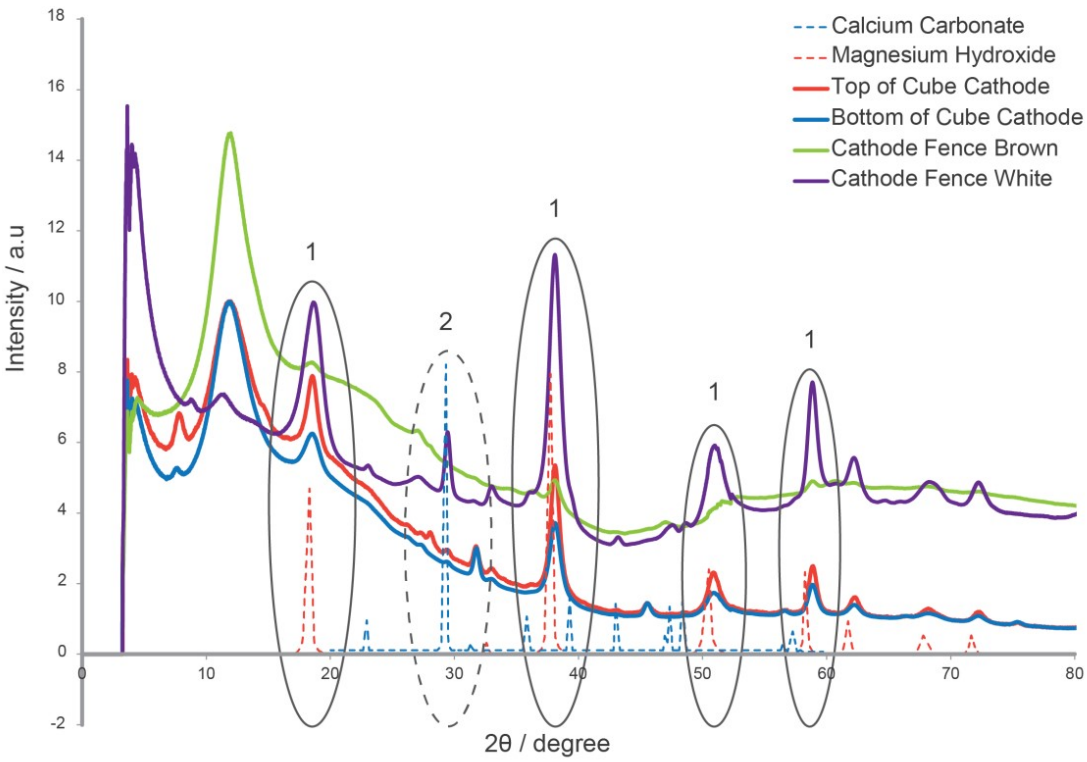


Figure 36: XRD material analysis graph from experiments 01 and 02. The results establish that a multi material system is possible using this material platform. **Micro Results**

The images generated from the SEM analysis (figure 37) in combination with the graphical analysis (figure 38) reveal the impacts of cathode purity. Cathode purity informs the material type deposited, as the purity inform current uniformity. The images highlight various surface textures, which also reveal an emergent, clearly defined shape. Additionally, the images show the various material compositions highlighted by the different crystal shapes, where the needle-shaped ones are limestone and the dandelion shapes are brucite.

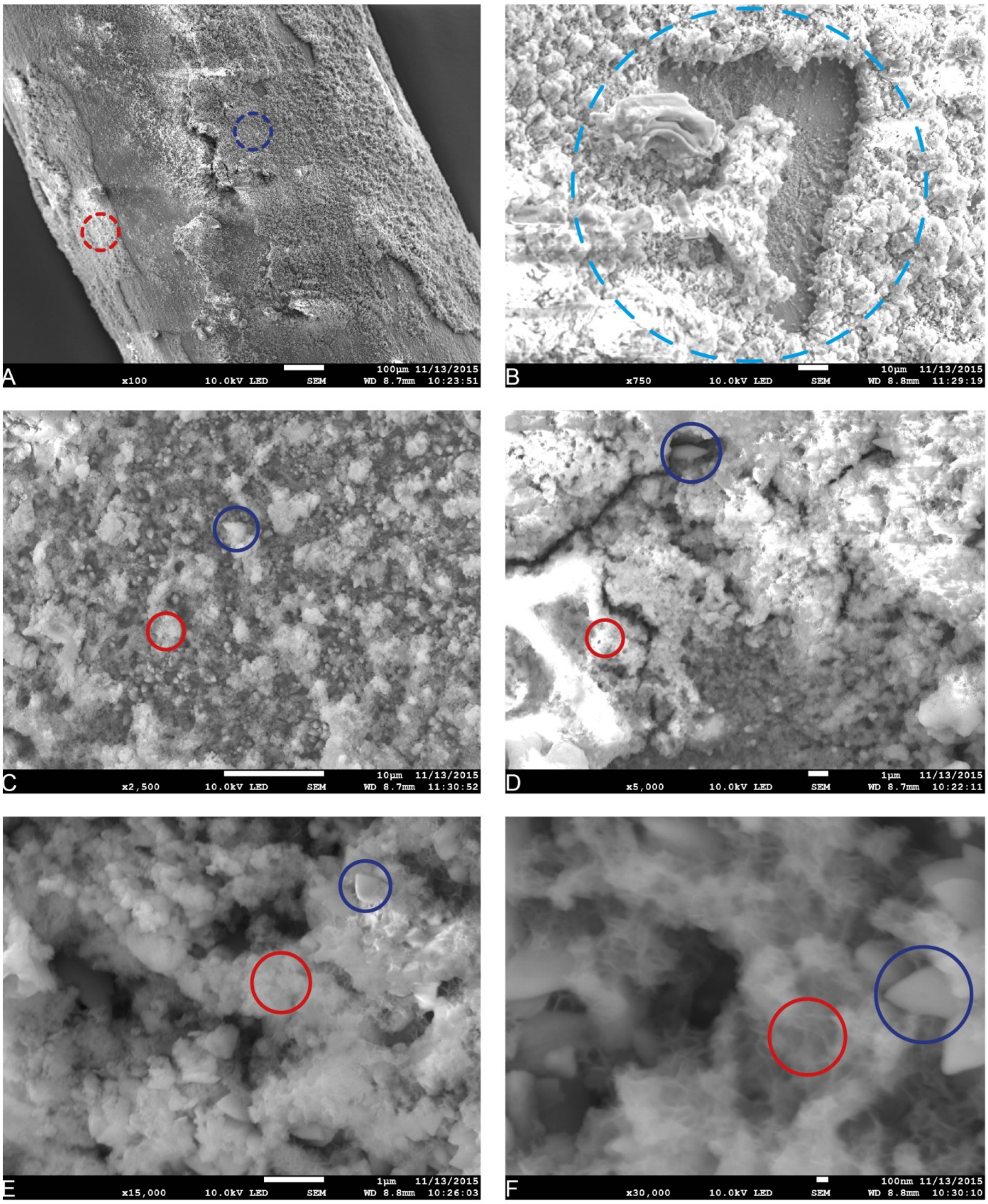


Figure 37: SEM images from experiment 03. The images sequentially increase in magnification. A) SEM revealed effects of the cathodes purity as varying amounts of brucite and limestone crystals depending on analysis locations. Sample location A is highlighted by the central blue circle. Sample location B is highlighted by the lower left red circle. B) Reveals an emergent void space generated in the shape of a 7, which was not controlled. C - F) reveal the varying material compositions, with brucite highlighted with red circles compared to the limestone highlighted with blue circles. 100 x 1mm dia steel wire cathode used the two individual wire cathodes.

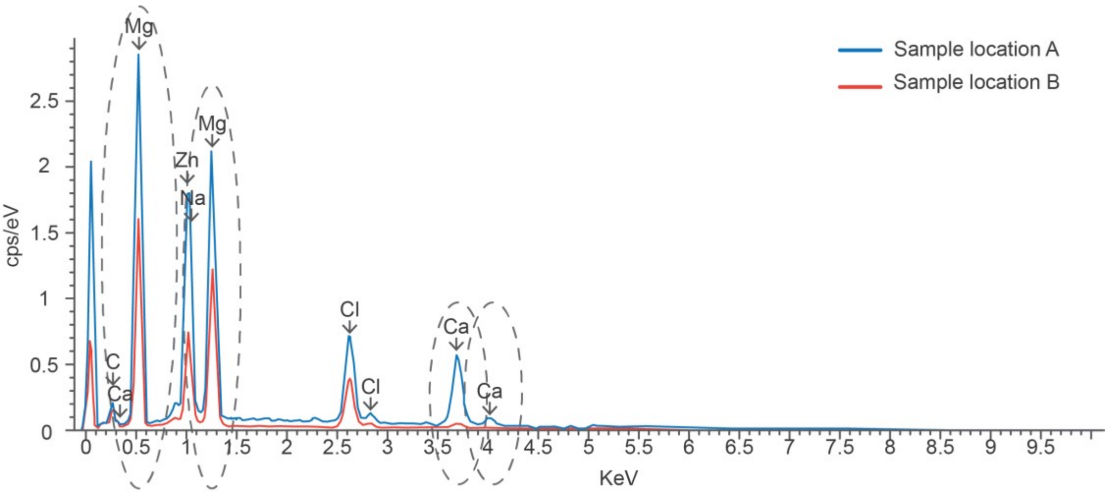


Figure 38: SEM peak value data graph showing the material present. In particular, calcium and magnesium have varying peak values depending on the location of analysis. These variable values establish a multi-material system can be achieved by tuning the voltage supplied.

7.4 Experiments 01, 02 & 03: Conclusions & Discussions

Overall, the initial results from all three of these experiments show promise for using the mineral accretion process to develop an adaptive design and fabrication system, which can manufacture tuneable, adaptive and multi-material structures. XRD analysis of the fence cathode demonstrates that it is possible to create multi-material systems with this approach. SEM analysis shows that varying electrical current controls the material type deposited. The factors required for developing the following experiment are broken down into three sections.

7.4.1 Cathode Typology

These first series of cathodes highlighted two main challenges that need to be addressed in the following iteration of the experiment in order to locally control material properties, these are;

- Modifying the cathode typology requires the cathode elements to be physically separated by an insulating material to enable control over electrical current location and localised material properties. Additionally, localised controlled could be further control be incorporating a form switch to turn off or on the electrical current supplied to individual cathode wires.
- Electrical current can by-pass resistor that is within the cathode due to the seawater solution. Meaning, variable resistors for example potentiometers (analogue or digital) can be placed within the circuit outside of the solution to vary electrical current.

7.4.2 Turbulence

Turbulence is needed in the system to counteract the overriding effects of gravity. Counteracting gravities effects was achieved inducing turbulence within the system, in this case by way of agitating the solution. Additionally, inducing turbulence within this developing design and fabrication system be seen as a requirement for creating coevolving interrelationships as well as preventing stagnation. The system induces turbulence by fluctuating environmental conditions creating material adaption. Turbulence ensures the development of robust systems which continually evolve (Kelly, 1994), enabling emergent results that could not be achieved without these mutual relationships.

7.4.3 Proliferation

The undesirable contamination of the solution that occurred due to the anode being dissolved needs to be removed to be able to produce desired material growth. In order to do remove this contamination a material that will not dissolve during electrolysis is needed. Using a carbon anode will prevent this contamination.

This series of experiments, the results and key factors are part of the paper; *Adaptive materials: Utilising additive manufactured scaffolds to control self-organising material aggregation*. The paper was published at the 2015 RDPM conference (Blaney et al., 2015)

7.5 Experiment 04: 2D Grid Cathode. Controlling Localised Material Properties

The next experiment presented is experiment 04, which aims to extend the three previous experiments by: 1) growing a defined heart shape (figure 39). 2) Growing materials and a shaped composed of locally variable properties i.e. grow materials with varying volumes / thicknesses and of varying material type or composition. 3) Prevents solution contamination and proliferation by using a carbon anode.

The aim of the experiment is to further understand and uncover important clues for designing powerful AM technologies of the future that operate via directed self-assembly of materials.

Properties

The 2D grid experiment is a 6 x 6 2D cathode grid. The grid is composed of 72 individual U shaped copper cathode wires. Figure 40 highlights the experiments set-up. Material build-up on the cathode grid is manually controlled by connecting individual elements or multiple elements (via a breadboard) to a bench power supply. The conductive copper wires (i.e. the cathode) are held in place via 36 modular components, which were fabricated in insulating nylon using additive manufacturing technology (Selective Laser Sintering). Figure 41 highlights the fabrication process. The modular supports are used to physically separate the copper wires and allow specific electric currents to be applied across the 6x6 gridded cathode structure (see figure 42).

To test that it is possible to control material properties of resulting structures, different elements within the 6x6 cathode grid were provided with different voltages in order to create a heart shape (figure 39). Half of the heart shape was supplied with 3.0 volts at one time. Once their growth time was complete the other half was supplied with 4.7 volts. The intention of this experiment was to determine whether it is possible to indirectly create a specific shape with varying material thickness and what effect varying voltages has on growth rate when using the mineral accretion process.

To examine growth rate of materials under different conditions (e.g. 3 volts compared to 4.7 volts), one cathode element was disconnected every 3 hours for the supplied with 3.0 volts (Figure 60), and every 2 hours for the half supplied in 4.7. The value of 3 hours was chosen because initial tests found that it takes 3 hours, at 3.0 volts to grow enough material to be visible with the human eye. Once all of the elements that were supplied with 3.0 volts had finished growing, the wires to be supplied with 4.7 volts were connected to grow the other half of the intended heart shape. To determine the effects that varying voltages and currents have on material composition (i.e. percentage amount of limestone compared to other materials present and growth rate), 12 wires were supplied with different voltages, each individual element being supplied with a set voltage for 2 hours (see figure 39).

The experiment ran for a total of 67 hours: 27 hours for the elements supplied with 3.0 volts, 18 hours for the elements supplied with 4.7 volts and 22 hours for the elements supplied with varying voltages. 300g of marine salts were dissolved in 6.5L of water and the 2D cathode grid was then submerged within the solution. Once the first half of the heart shape was grown (3.0 volt elements) the cathode was carefully taken out of the solution, the solution was then agitated for 1 minute and the cathode grid returned and the other half of the heart shape was grown (4.7 volts elements). A new solution was made before carrying out the experiment which supplied elements with varying voltages. Two carbon anodes of radius 6.3mm and length 75.0mm were used because the carbon anodes do not dissolve and contaminate the solution and should not affect the material build-up.

Notably, as discovered in the first experiment, agitation of the seawater solution is important to resist the effects of gravity as materials self-assemble. Consequently, an initial test on the 6x6 grid agitated the solution every 30 minutes using an aquarium wave-maker pump. However, from these tests it was found that agitation of the solution with the grid-shaped cathode structure produced detrimental effects to early growth of crystals, causing grown material to fall off the structure during agitation intervals. To counteract this tendency, this experiment did not use agitation to counteract gravity as material was growing. However, for this experiment, it was believed that the effect of gravity would be less significant because all of the individual elements are within the same plane (i.e. the grid is flat). Interestingly, control of agitation and focusing it on areas during initial growth may be a useful parameter for preventing and even reversing material growth in future work.

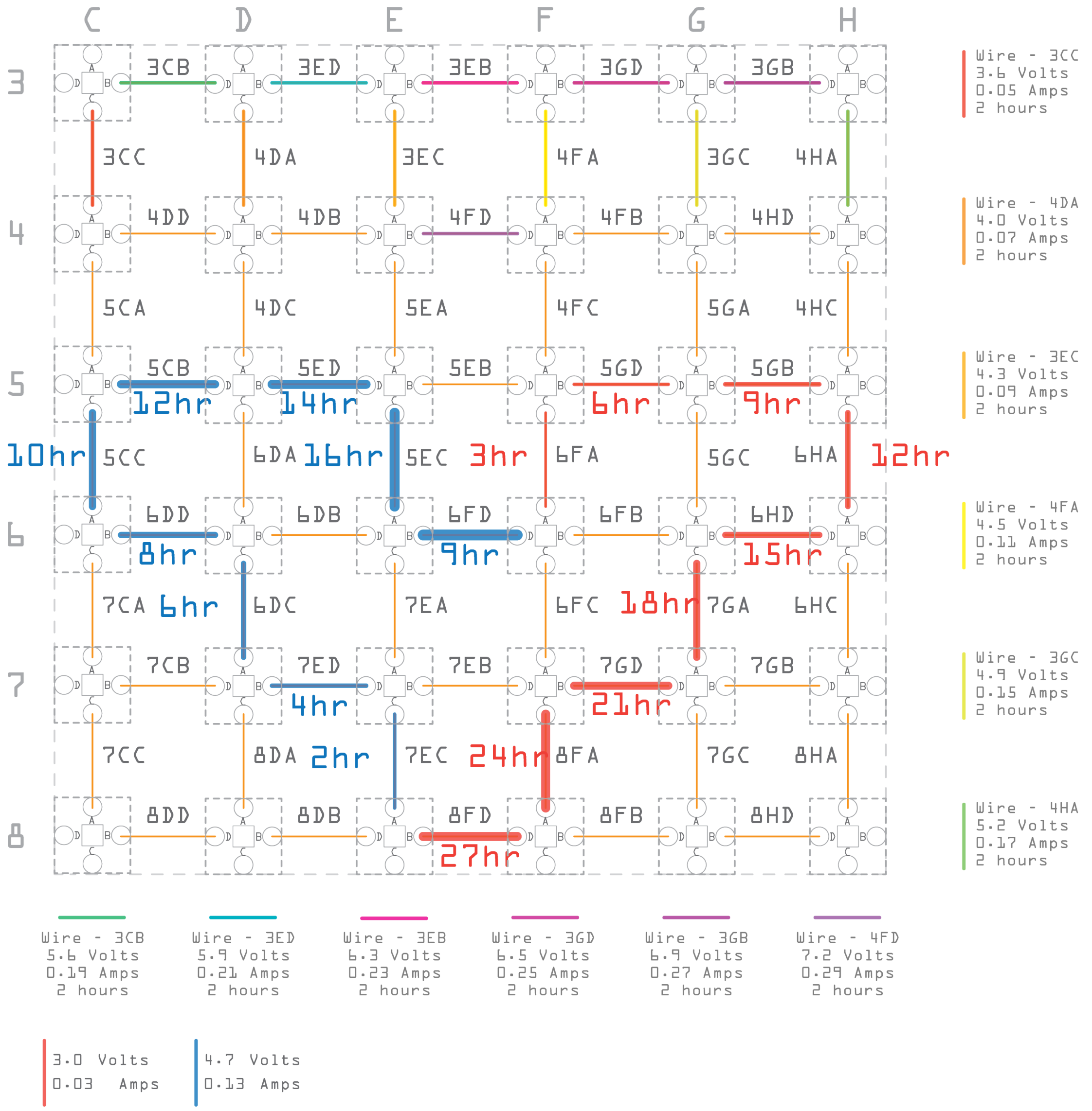
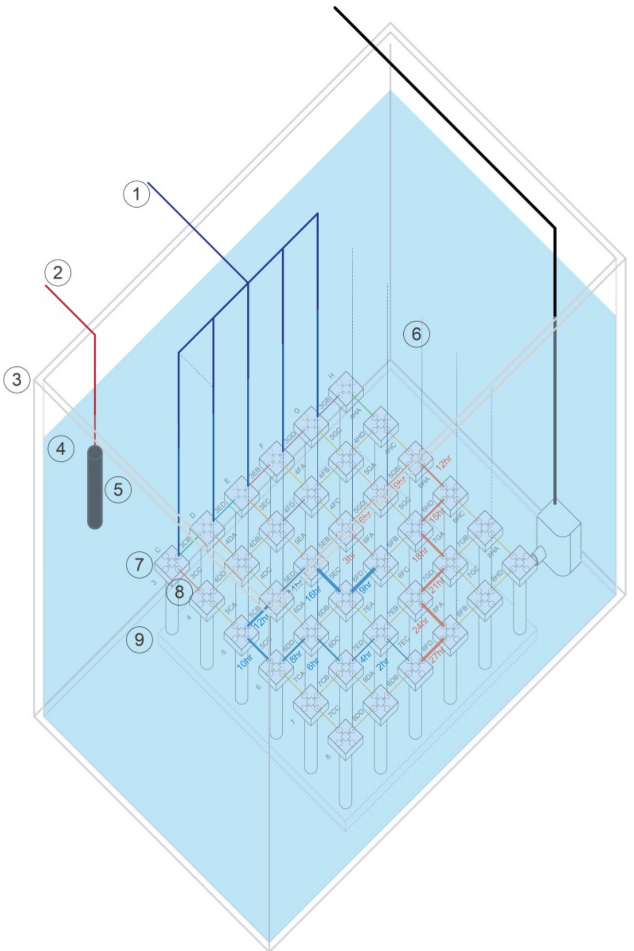


Figure 39: Pixelated heart shape is drawn on the 6x6 cathode grid with the corresponding wire reference to be connected. The heart shape is split in two and supplied with different voltages, each element of the heart is grown for varying time periods. Individual elements are supplied with varying voltages to determine its effects on material composition and properties.



KEY: Wire refernce and voltages supplied

Wire - 3CB 5.6 Volts 0.19 Amps 2 hours	Wire - 3ED 5.9 Volts 0.21 Amps 2 hours
Wire - 3EB 6.3 Volts 0.23 Amps 2 hours	Wire - 3GD 6.5 Volts 0.25 Amps 2 hours
Wire - 3GB 6.9 Volts 0.27 Amps 2 hours	Wire - 4FD 7.2 Volts 0.29 Amps 2 hours
Wire - 3CC 3.6 Volts 0.05 Amps 2 hours	Wire - 4DA 4.0 Volts 0.07 Amps 2 hours
Wire - 3EC 4.3 Volts 0.09 Amps 2 hours	Wire - 4FA 4.5 Volts 0.11 Amps 2 hours
Wire - 3GC 4.9 Volts 0.15 Amps 2 hours	Wire - 4HA 5.2 Volts 0.17 Amps 2 hours
Heart Pattern Right 3.0 Volts 0.03 Amps	Heart Pattern Left 4.7 Volts 0.13 Amps

1) Negative [ground] power supply connection
2) Positive power supply connection
3) Glass tank 198x 300x 200mm
4) Seawater solution - 300g of marine salts dissolved in 6.5 L of water
5) Cardon anode (6 x 106mm)
6) Aquarium pump to agitate solution (300L/hr)
7) 3D printing modular units to hold cathode wires in place (8.5 x 8.5 x 56mm)
8) Distributed grid of U-shaped copper cathode wires (20 x 10mm and 1mm diameter)
9) Acrylic base to hold 3D printed units in place (120 x 120 x 10mm)

Figure 40: Experiment 04 set-up of the 2D distributed cathode network. The experiment is carried out to understand how to control localised material properties and grow a defined

pattern.

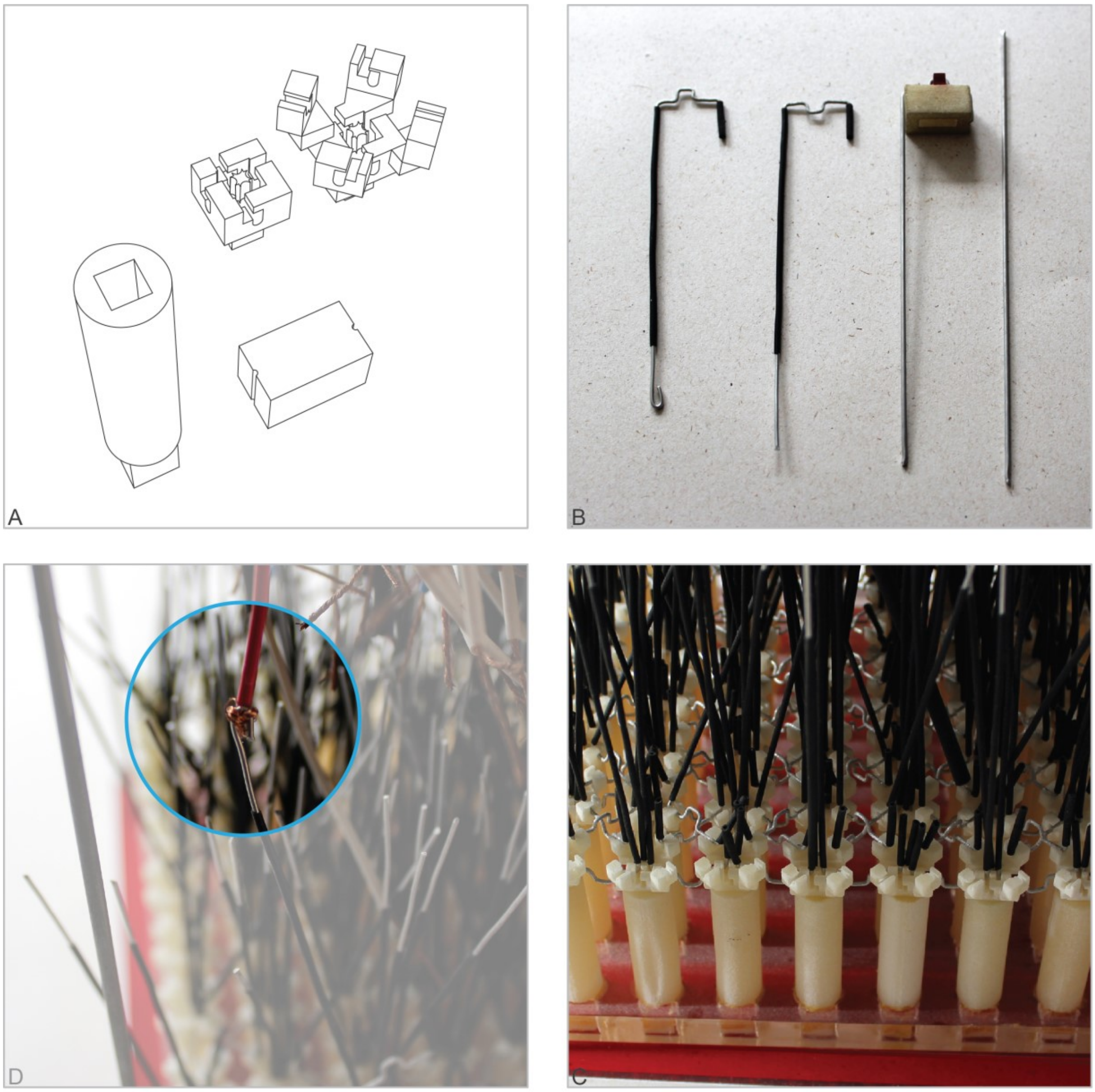


Figure 41: Fabrication process of cathode scaffold for experiment 04. ***A****) Digital design of modular component used to hold the copper / aluminium cathode wires in place. 36 of them were fabricated using selective laser sintering (SLS) a form of 3D printing.* ***B****) Copper and aluminium wire (1mm in diameter), bent around a jig, by hand, to ensure cathode wires were the same dimensions. Copper wires are used in the experiment.* ***D****) Copper wires can be soldered to longer lengths of insulated electrical wiring. Aluminium wires have to be twisted together and fixed with heat shrink tubing.* ***D****) Network of wires placed within the 3D printed head of the components within a square grid.*

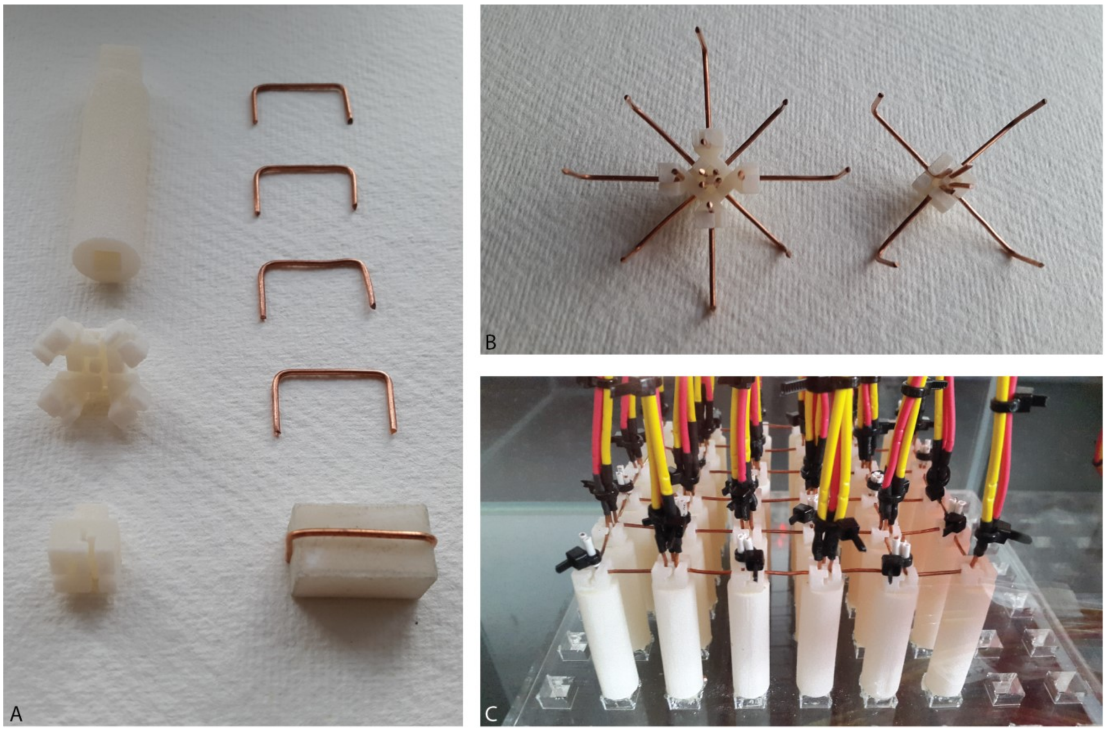


Figure 42: Assembly of 2D grid scaffold (experiment 04). A) AM was used to fabricate modular nodes made to physically separate the cathode elements. B) Two different head were fabricated to increase the resolutions of the grid. C) Final 2D 6x6 grid.

Predictions

Predictions for the 2D grid cathode design is that it should be able to grow a clear heart shape (on the elements supplied with 3.0 and 4.7 volts with different sides of the heart shape growing at different rates and thicknesses. The half of the heart supplied with 4.7 volts is expected to generate a faster rate of material growth, with more material aggregation on elements that are supplied with electricity for longer periods of time.

Analysis

In order to determine material composition / type X-Ray Fluorescence (hereafter XRF) is used to analyse the results of this test. XRF was used as it provides a detailed percentage breakdown of different materials present of the cathode elements. XRF determines the material composition on a small location of the individual cathode elements; as such it may not provide a complete analysis of the whole material composition. XRF analysis was also used as it is much faster than XRD and SEM.

To compare growth rates and final growth volumes, the radius of material aggregation on each element was measured using a digital Vernier at set points.

7.6 Experiment 04: Results

The results from the various methods of analysis used for the experiment are again broken down to discuss what they reveal. *Firstly*, data will be discussed based on anything visible to the naked eye, which is captured via macro photography. *Secondly*, material volume and growth rate analysis will be discussed, which is obtained using digital Vernier. *Thirdly,* material composition results will be discussed obtained via XRF analysis. *Finally,* a series of photographs highlights that material decay occurs within the system.

The factors and the implications of these results mean in regards to design and fabrication processes will be discussed in the conclusion of this section. Finally, challenges are summarised for the next experiment iteration.

7.6.1 Macro Results

This portion of the results is based on observations visible to the naked eye, which have been documented via macro photography. These observations are separated into three main areas: *firstly*, the results of the overall heart-shaped pattern (global properties). *Secondly,* local surface texture qualities and *thirdly,* uniformity in material growth.

Figure 43 reveals the completed growth of the heart shape. Establishing this cathode typology is able to grow an overall defined 2D pattern. Growth is shown here by the lighter material, the darker material being a result of the copper oxidising. Examination of the material growth reveals a clear heart shape was achieved with the half supplied with 3.0 volts, the half supplied with 4.7 volts also predominantly grew where it was intended, which completed the heart shape. However, one cathode element (wire 6DB) had unintended growth occurring on it when carrying out the growth of the 4.7 volt elements. The unintended growth may be due to the material growth occurring on the intended wire contacting a neighbouring wire and inducing unintended growth. If this is the case redundancy is required. Introducing redundancy will be able to reverse material growth which occurs on unintended elements. The unintended growth may also be a result of neighbouring wires contacting one another, which can be addressed by fabricating the scaffolds using AM technology that affords increased tolerances. The elements supplied with 3.0 volts and supplied with electrical current for longer periods of time resulted in increased material build-up. Again, this was also the case for the elements supplied with 4.7 volts apart from the last element (wire 6FD). The anomaly may be a result of material continually decaying away from this cathode element during growth, this would suggest the way the materials fabricate themselves is not linear when voltage / turbulence is increased.

Figure 43 also highlights two other emergent material properties, which are generated at various stages and conditions. The material properties are:

- *Varying surface textures* on the heart shape elements supplied 3.0 volts. A smoother texture was produced on elements supplied with electrical current for longer periods of time, this is compared to an initially granular texture produced from shorter periods of time. A uniform surface texture was created on the of the heart shape supplied with 4.7 volts (figure 43). Control of surface textures can be tuned to increase surface area, which could result in surface ornamentation of architectural structures.

- *Uniform material growth* on the cathode elements was achieved on the 3.0 volts elements that were supplied with electrical current for shorter periods of time (up to 15 hours). On these elements supplied with electrical current for longer periods, material build-up became more predominant at the bends of the cathode elements. *Non-uniform material growth* on the 4.7 volts elements was created as the majority of the material build-up occurred at the bends of the cathode elements. Interestingly this allows an increase in control over localised material properties to emerge on individual cathode elements.

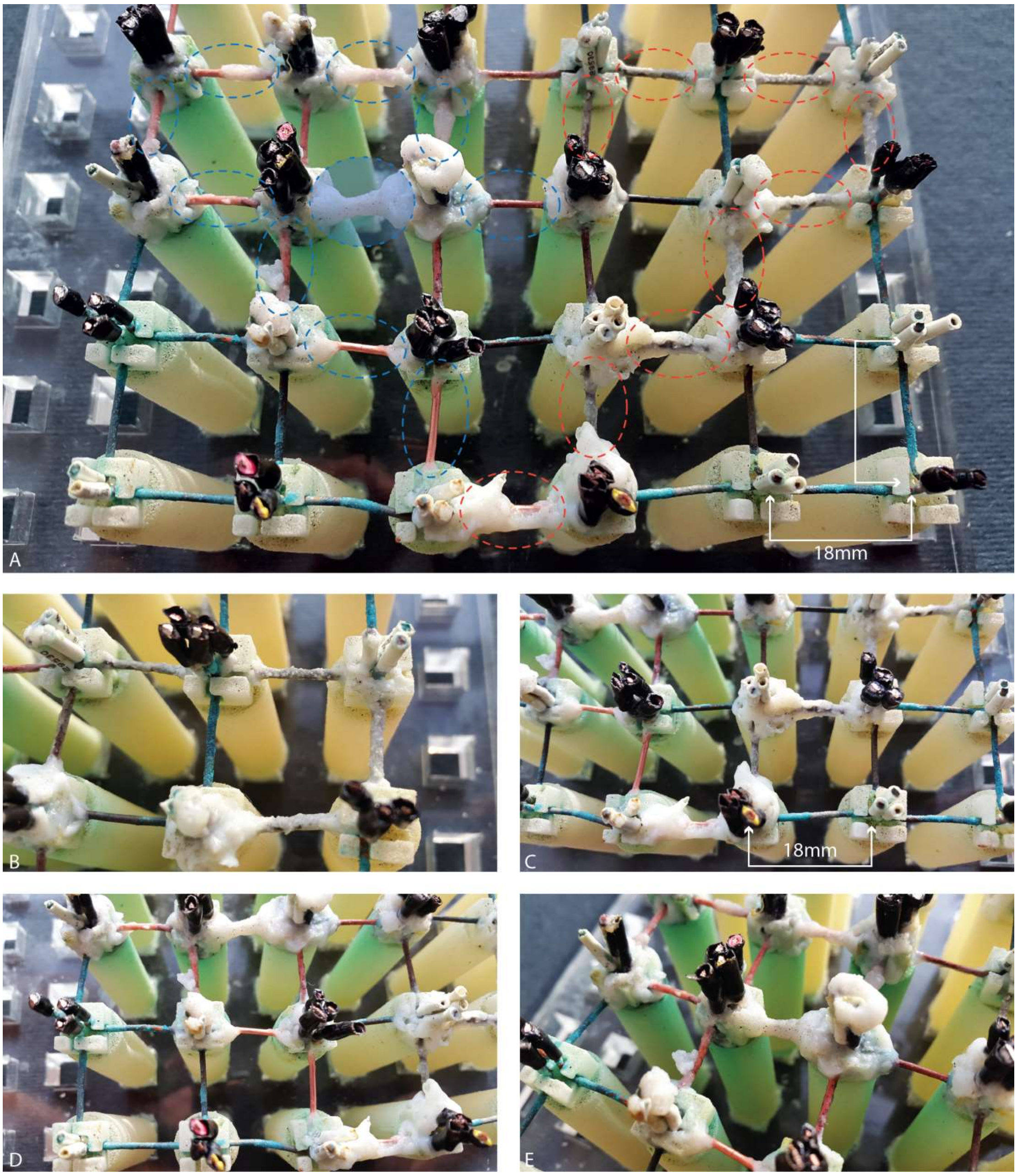


Figure 43: Material results experiment 04. A) The final heart shape growth reveals material growth location and amount can be controlled. B & C) - reveals varying surface textures and varying growth location over time when supplied with 3.0 volts. D & E) reveals a smooth surface texture was produced with initial growth predominating at the bends which became more uniform over time when supplied with 4.7 volts.

7.6.2 Material Volume & Growth Rate Results

Figure 44 show plots of material deposition over time. Figure 44 reveals material deposition increased for both voltage values (3.0 and 4.7 volts) respectively the longer they were supplied with electrical current. The cathode properties in combination with stimulus control establish it is possible to govern the amount of material grown at a specific location. Interestingly more material volume and deposition occurred with the elements supplied with 3.0 volts, which is not the expected result due to the lower voltage. The increased growth volumes at lower voltages suggest that introducing more turbulence during early stages of material deposition has a detrimental effect on growth success. Increased turbulence, in this case, was a result of increasing voltages, which results in an increased amount of hydrogen being produced at the cathodes, which appears to have prevented material deposition. Interestingly the growth rate for both voltages (3.0 and 4.7 volts) is quite similar, which both increase over time (see figure 45).

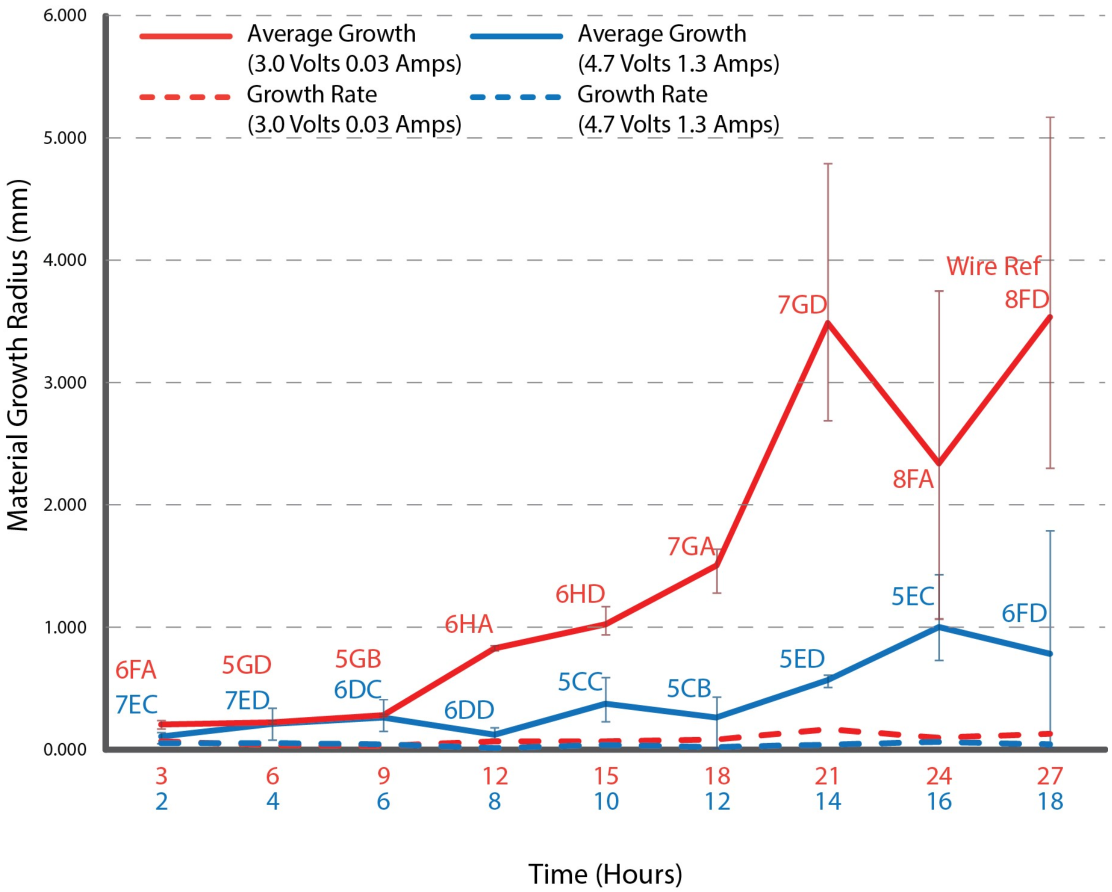


Figure 44: Graph of the growth volume and rate for experiment 04 highlights an increase for both 3.0 and 4.7 volts the longer the cathode element is supplied with electrical current. Error bars highlight the range between average growth and minimum and maximum growth at point on each cathode wire.

The ability to grow increasing amounts of various materials at increasing rates in specific locations enables the structures to adapt at a faster rate regarding material location. Figure 45 shows an initial trend of increasing material growth amount corresponds with increasing voltages between 3.6 – 4.5 volts (0.05 - 0.11amps), this then falls off.

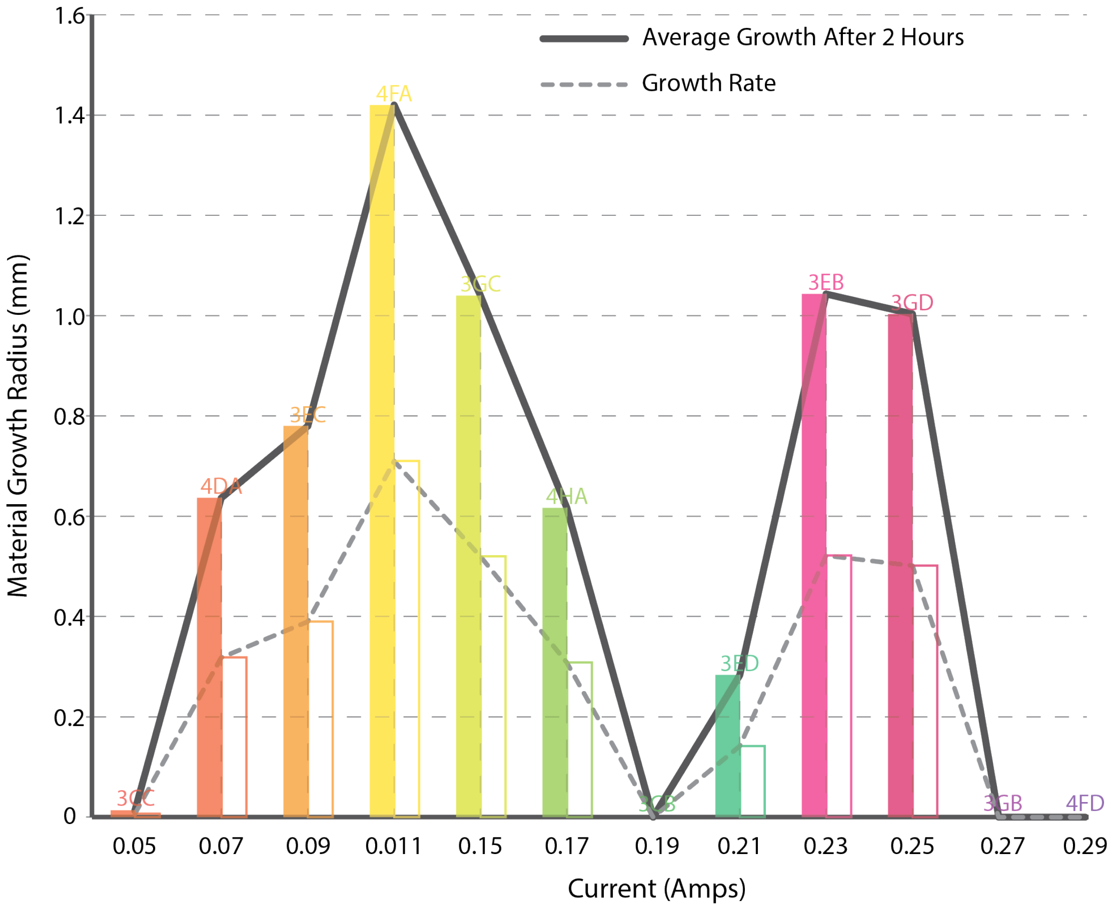


Figure 45: Graph reveals an initial trend that material growth amount and rate increases as voltage / current increases but cannot be sustained due to the materials increasing fragility.

7.6.3 Material Composition & Decay Results

Comparing growth rates (see figure 45) with the material composition graph obtained from XRF analysis (see figure 46) reveals that most material deposition occurred if the presence of chlorine remained below 15%. As Chlorine rose to over a threshold of 15% the material became more fragile, this was determined by reduced or no material deposition being recorded in these samples. Figure 46 reveals XRF analysis of the cathode elements supplied with varying voltages, the analysis highlights that material composition and functionality can be tuned by manipulating the environment (voltage).

Figure 47 highlights *material decay* occurs during and post material growth. Material decay was most significant as the voltages increased; at this point, an increasing amount of material would deteriorate away from the cathode elements and build-up on the base of the jig and tank. The ability to reverse or remove material from cathode elements introduces redundancy within the system, this maintains control of material growth location if material growth produced on one element contacts a neighbouring element and initiates growth. Material decay was hard to document as it occurred due to the poor visibility of the solution, which is a result of the material as it is suspended within the solution. As a result material decay was observed first hand and noted.

Comparing figure 46 with figure 47 reveals *varying mechanical strengths* and compositions are achieved as a result of varying voltages supplied to the cathode elements. As voltage increased the amount of calcium present in the material was reduced resulting in an increasingly fragile material. Elements supplied with more voltage appeared very fragile upon examination (see figure 47). Additionally, this fragility was further revealed as the material deteriorated once it was taken out of the tank as a result of the solutions surface tension. The varying material resilience's and rate of decay establish that varying material qualities and functionalities can be achieved by altering the environment (voltage) as materials grow.

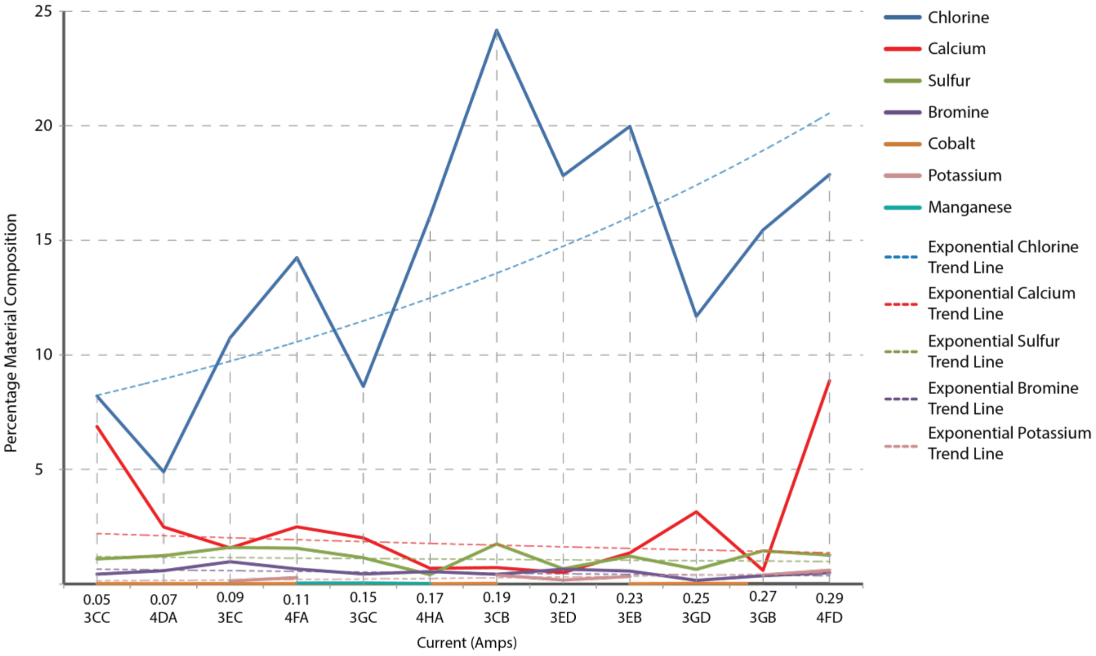


Figure 46: XRF analysis graph for experiment 04 highlights the cathodes supplied with varying voltages reveals that the material composition can be tuned by varying voltages. An increase in voltage results in an increase in chlorine with the reduction of all other materials.

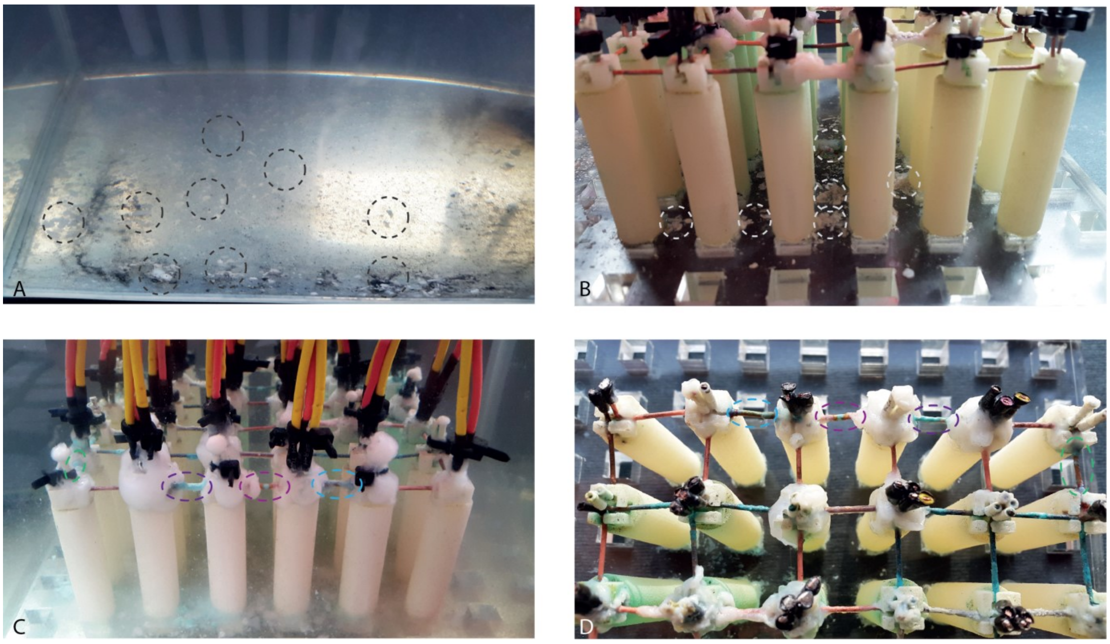


Figure 47: Material decay. A & B) material growth would decay away from the cathodes elements as it grew. C & D) material decay became more apparent as the voltages increased.

7.6.4 Experiment 04: Conclusions

The 2D grid cathode experiment has shown, growing structures through aggregation achieves two major benefits. *Firstly*, the structures can be grown within a 2D matrix scaffold, which can change shape and material properties globally or locally. *Secondly,* the fabrication process is scalable as the material deposited on the scaffolds is based on the materials scale; this is because the molecules that make up the deposited material self-assemble.

The section is now ordered into four topics: *firstly,* cathode typology, which discusses the benefits of the 2D grid. *Secondly,* turbulence and fragility, which raises issues of threshold levels and stimulus during initial or early stages of material growth. Finally, possibilities afforded by this developing fabrication strategy and challenges for the next experiment iteration are discussed next.

7.6.5 Cathode Typology

Significantly these results obtained establish it is possible to grow structures from an abundant base material (seawater). The 2D grid cathode typology is able to locally control variable material properties, such as, shape, location, rate, volume, texture, type and composition, which can be tuned and adapted by imposing and adjusting external stimulus (voltage, pH, solution agitation). Additionally, the smaller-scale material properties, such as surface texture and material volume concentration on the cathode appear to be more sensitive / affected by the stimulus, as these properties change over time. Meaning, they are not fully dictated by the cathode typology. The impact of controlling stimulus points towards being able to control subtle material properties. Imagine, being able to fine-tune the surface texture of a building's facade, such as increasing its surface texture and porosity as a way to capture rainwater and purify it. Additionally, variable material textures could be used to enhance aesthetic qualities.

7.6.6 Turbulence, Material Fragility & Decay

Turbulence in the form of solution agitation was not needed in the system to counteract the overriding effects of gravity in this system as the orientation of the cathode elements are all in the same planes. Significantly, inducing turbulence within the material system at early stages highlights exceeding a threshold amount resulted in the prevention of material growth as it decayed away from the cathode. Intruding or locally focusing turbulence early on could perhaps be used as a means of: 1) preventing local growth, 2) preventing proliferation of a condition from occurring, or even 3) used as a means of guiding self-assembly which is not restricted to cathode scaffolds.

7.7 Experiment 04: Development & Discussion

Again the experiment is analogue in regards to how the heart shape pattern was generated as well as how the stimulus was controlled to grow the shape. In order to address these issues and build towards a system that can create interrelationships between digital design tools, fabrication and material properties, the stimulus must be via hardware, which can be controlled by a digital design tool. For this reason, the following experiments will incorporate Arduino microcontrollers with data or design tools to induce and ultimately monitor stimuli and its resultant effects, which will automate the fabrication process.

Automating the fabrication process may enable: 1) logic from digital designs to be instilled within the fabrication process and resultant physical structures as it's data / instructions can be used to inform the stimuli induced. 2) Adaptive, flexible and tuneable capacities of design simulations to be physically instilled within the structures. For example, structures fabricated within the constraints of a 3D cathode matrix could change shape and material properties. 3) Increasingly complex structures could be fabricated by imposing multiple design demands, which results in integrated structures (Wiscombe, 2012) and multi-functional materials (Oxman, 2012) being created. Notably, the experiments aim to show proof-of-concept that material properties (material volume and surface textures) can be tuned over time through environmental manipulations (voltage), based on digital design tool augmentations. 4) A continual discourse between design, fabrication and materials could be achieved in real-time, which extends the role of '*persistent modelling*' (Ayres, 2012b) by guiding material scale self-assembly.

The 2D grid experiment, its results and key factors have been published in the journal IJRM 2017: *Directing self-assembly to grow adaptive physical structures* (Blaney et al., 2017). Additionally, the materials' adaptive abilities and the development of the system to able to begin to enable feedback have been published at the A-Life conference 2016: *Coupling self-assembling materials with digital designs to grow adaptive structures* (Blaney et al., 2016).

7.8 Experiment 05 & 06: Grown by Data & Parametric Matter

A key limitation of parametric design is that 3D objects can only benefit from the capacity to reconfigure and adapt to changing inputs when they are in a digital format. That is, once the final physical models are manufactured using traditional processes, the parametric designs' data, parameters and relationships are fixed and can no longer be modified. A root cause of this is due to traditional fabrication process, which; A) utilise inert materials or B) imposes form upon materials, removing materials computational abilities. A research agenda, which has challenged this fixation of physical designs, is termed "Persistent Modelling" (Ayres, 2012b). In persistent modelling, the relationships between the representational mediums of the designs processes (sketches, models, digital models) and final physical objects are emphasised. The relationships between the two allows time to be accounted for so change can occur, enabling feedback between design and physical structure (Ayres, 2012b). The two experiments within this section attempt to extend the role of *persistent modelling.* They do so by employing stimulus to connect digital parametric design tools with material scale self-assembly to grow desired volumes.

The reconnection between digital model and physical model / materials enables two factors that could potentially lead to novel physical abilities;

- *Time* – by varying an external stimulus (e.g. voltage) over time it is possible to tune and adapt both the *materials properties* (e.g. composition, surface texture, highlighted in experiments 01 - 03) and the structures 2D/3D *global shape* (e.g. location of material, volume, rate and aesthetics, highlighted in experiment 04) of stimuli sensitive materials via processes of self-assembly, in this case the mineral accretion process.
- *Complex material behaviour* - the ability to deform a materials global shape by imposing a force (e.g. compression, tension) can produce emergent results and complex behaviours. These emergent effects are due to the interactions between the material's fundamental make-up. i.e. the structures / materials constituent parts (atoms, molecules) (DeLanda, 2004, DeLanda, 2015). The process of fabricating structures via self-assembling mineral accretion processes occurs at the scale of molecules; consequently, structures are highly granular. Meaning, they are generated from bottom-up process, which leads to emergent results that could be highly desirable.

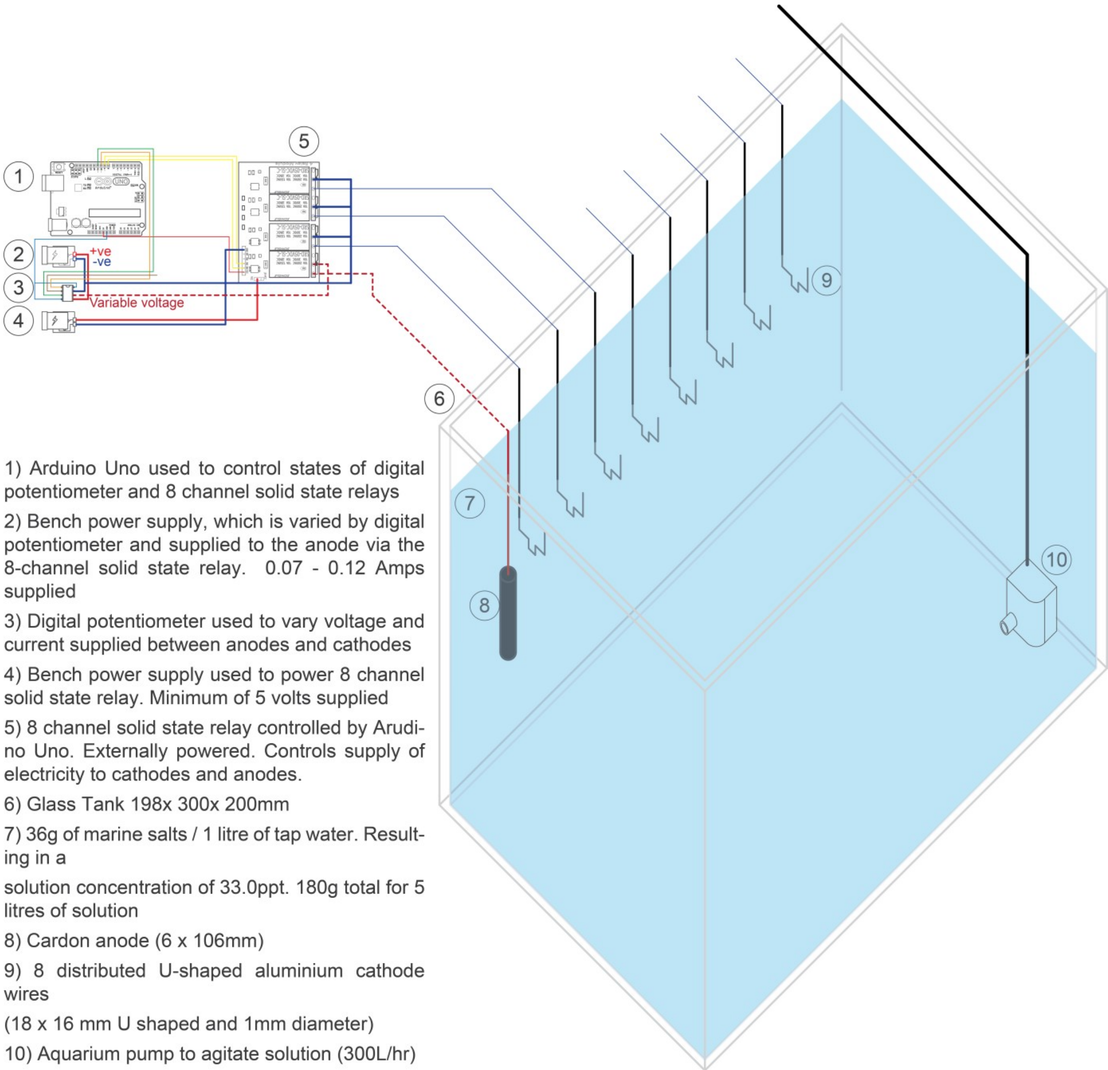
The experiments discussed in this section are experiments 05: *Grown by Data* and experiments 06: *Parametric Matter*. Both extend the previous iterations by automating the induced stimuli's parameters /growth process to an extent. The parameters of voltage, such as inducing voltage, its magnitude and the duration are automated. The main question for these two experiments is; *using the mineral accretion process, how can digital parametric design tools be used to guide material scale self-assembly?*

Exploring this question and examining the experiment's results leads to the idea of creating a design and fabrication methodology based on *interrelationships*. These interrelationships arise from and play a crucial role in forming *'tuneable environments',* which utilised as a means of guiding the interactions between material scale self-assembly.

7.8.1 Generic Experiment Properties

Figure 48 documents the set-up for experiment 05 where the cathode wires and carbon anode are submerged within 5 litres of seawater. The seawater solution was made using 36g of marine salts / 1 litre of tap water, this created a solution concentration of 33.0ppt. For experiment 06: *Parametric Matter,* a second fresh solution was made to carry out the second 'run' of material growth. The solution was agitated but for less than 1 minute durations at random intervals (between 2 and 8 hours). A submersible aquarium Pump (AQC-200) is used to agitate the solution. The pump is set to its lowest speed setting.

Figure 49 documents the fabrication process for both experiments 04 and 05. The jig which physically separate 8 individual aluminium cathode wires was created with 3mm acrylic, which was laser cut into layers and glued together. The 8 individual cathode wires are physically separated, equidistantly, within a laser cut jig. This highlights if a faster and lower-cost fabrication method comparative to 3D printing can be used to fabricate cathode jigs. Additionally, the aluminium's surface was roughed, by rolling it on 200 grit sandpaper. Roughing the wires surface texture is an attempt at increasing surface area to try and support material growth and reduce material decay as witnessed in the 2D grid experiment (experiment 04). Additionally, in order to focus growth at the centre of the U shaped aluminium cathode wire a nodule was bent at its' centre using a jig. Again a carbon anode was used to prevent solution and growth contamination. The dimensions for the cathodes and anodes are noted in figure 50.



1) Arduino Uno used to control states of digital potentiometer and 8 channel solid state relays

2) Bench power supply, which is varied by digital potentiometer and supplied to the anode via the 8-channel solid state relay. 0.07 - 0.12 Amps supplied

3) Digital potentiometer used to vary voltage and current supplied between anodes and cathodes

4) Bench power supply used to power 8 channel solid state relay. Minimum of 5 volts supplied

5) 8 channel solid state relay controlled by Arudino Uno. Externally powered. Controls supply of electricity to cathodes and anodes.

6) Glass Tank 198x 300x 200mm

7) 36g of marine salts / 1 litre of tap water. Resulting in a

solution concentration of 33.0ppt. 180g total for 5 litres of solution

8) Cardon anode (6 x 106mm)

9) 8 distributed U-shaped aluminium cathode wires

(18 x 16 mm U shaped and 1mm diameter)

10) Aquarium pump to agitate solution (300L/hr)

Figure 48: Experiment 05 set-up of eight individual wire cathodes used in experiment 05: grown by data. The experiment automates the growth process using arudino to control hardware that induces the stimulus upon the system. The arduino controls the systems stimulus / hardware components based on the solar systems planetary data.

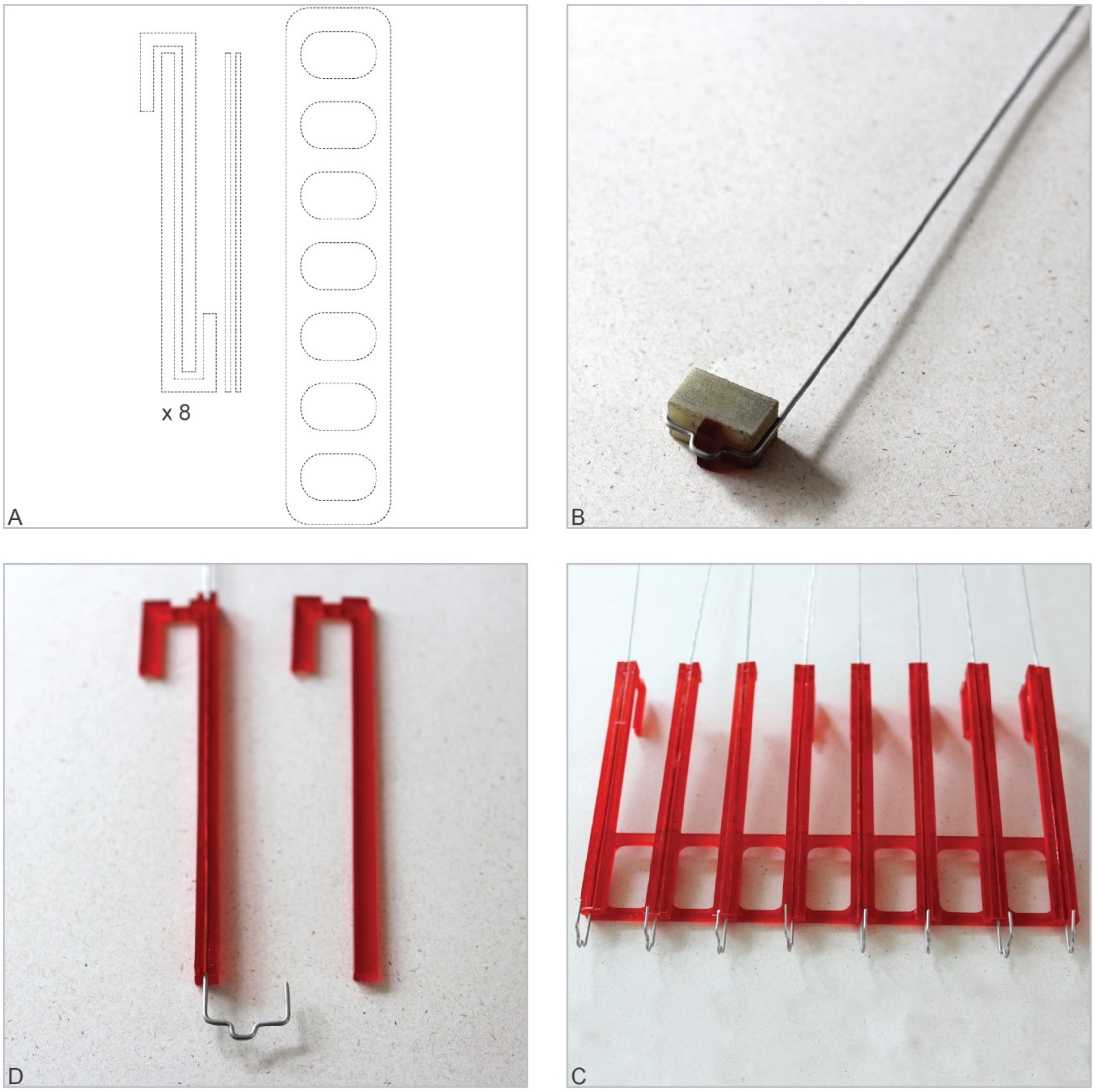


Figure 49: Laser cutting cathode jigs for experiment 05 and 06. ***A****) Components designed in illustrator and laser cut.* ***B****) Aluminium wires rolled on sand paper to roughen up its surface as well as straighten the wire. Roughened end then shaped around a jig by hand to ensure all 8 cathode wires are the same dimensions.* ***C****) The individual cathode wires are then insulated using electrical heat shrink tubing up to 15mm of the shape cathode wire to prevent growth on those areas. Cathode then placed in the jig, which is then glued together.* ***D****) Jig components holding the cathode are then spaced equidistant apart from one another. Aluminium wire total dimensions 8 x 250mm x 1mm diameter.*

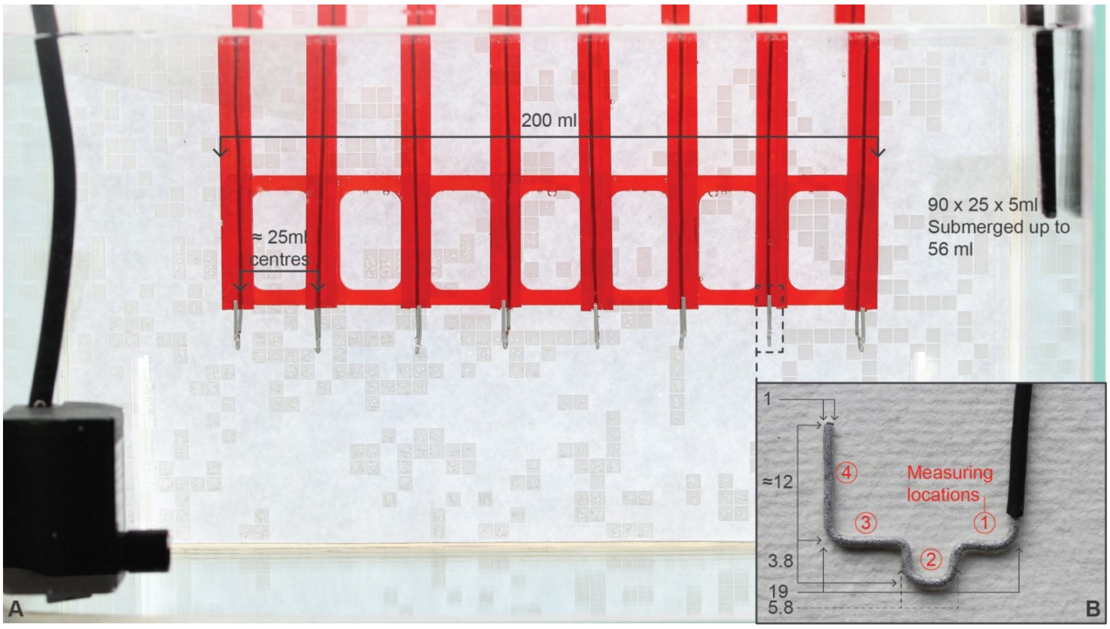


Figure 50: Experiment 05 and 06 set-up. A) 8 U shaped aluminium cathode wires suspended within 5 litres of seawater solution. The cathode wires are equally spaced by containing them within a laser cut jig. B) Surface texture and modified U-shaped cathode wire to focus material growth. Locations of growth measurements also noted.

In order to explore the question of automating the growth process, both experiments incorporate an arduino microcontroller to govern hardware, which induces and controls the parameters of voltage. The hardware components and the circuits / connections are documented within their respective set-up figures.

Critically, both experiments growth durations are based on preliminary results data i.e. preliminary data is used to determine the amount of time required to supply voltage to grow a desired amount material (see figure 51 and 52). In order to control if voltage is supplied to the individual cathode wires a 5V 8 channel relay module, which can physically switch on or off electrical current to be supplied to individual wires. In this case, the relay module is used to control if material growth occurs, by turning on or off electrical current, the volume of material grown and the location of the material grown, as each cathode wire is referenced to a particular relay unit. A digital linear potentiometer is used to control the magnitude of the voltage / current supplied, therefore controlling the type and rate of material growth. However, for each experiment, the arduino is programmed or interacted with differently, which dictates the duration of voltage supply and its magnitude. For experiment 05: *Grown by Data* the arduino is *'hardcoded'* with values to govern voltage. For experiment 06: *Parametric Matter* the arduino controls voltage based on real-time data / instructions received from a digital parametric design tool, which was created in processing. Significantly, these experiments will demonstrate the data or design tools can inform material scale self-assembly and for part of the system interrelationships.

How growth durations and volumes are predicated will now be explained for each experiment separately along with each experiment's result. Finally, key factors and issues for development will be discussed together.

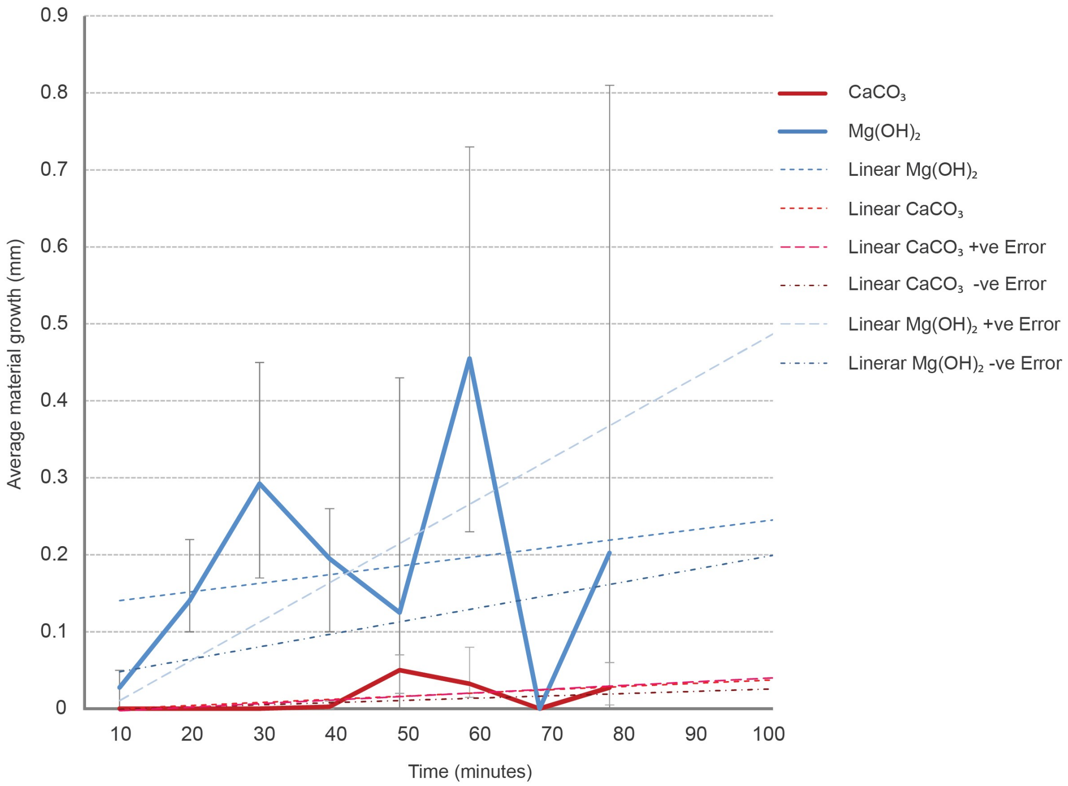


Figure 51: Preliminary results for growth volumes over 80 minutes. The data is used to predict growth durations in both experiment 05 and 06.

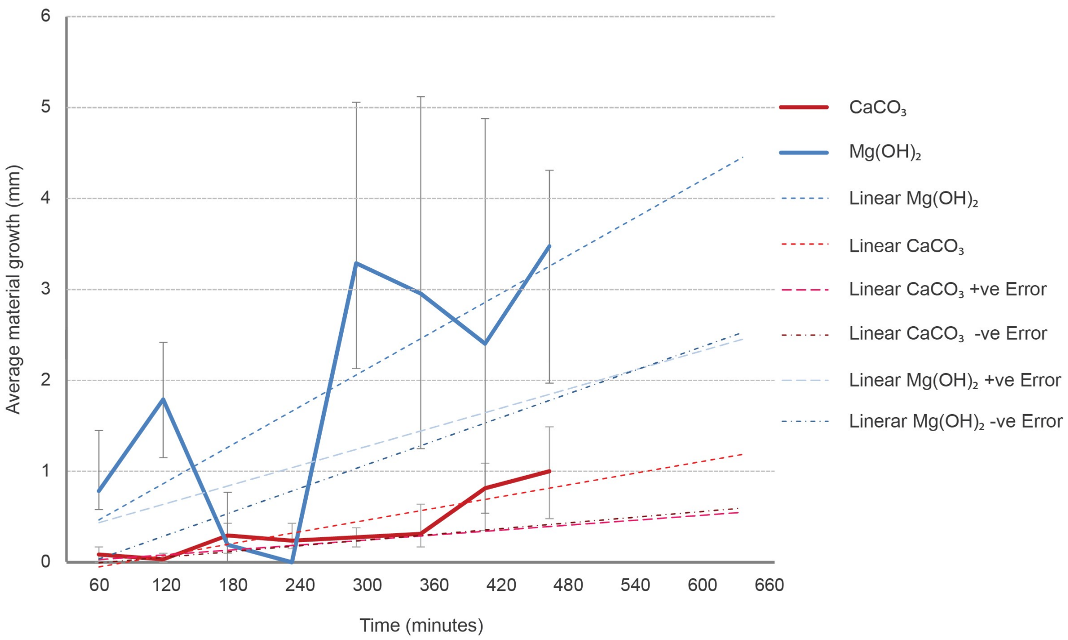


Figure 52: Preliminary results for growth volumes over 8 hours. The data is used to predict growth durations in both experiment 05 and 06.

7.9 Experiment 05: Properties and Data Values

To test if material scale self-assembly can be automated, experiment 05: Grown by Data explores how crystal structures can be grown based on data. The data relates to the planets in the solar system, where their relative size to Earth to inform growth duration and the planet type informs the material composition (see figure 53). For example, the planets Mercury to Mars are rocky planets, so the material to be grown will be the harder limestone. The 4 cathodes representing these planets will be supplied with 0.07 amps. The planets Jupiter to Neptune are large gas planets, so the material to be grown will be the more brittle brucite. The 4 cathodes representing these planets will be supplied with 0.12 amps. The current is controlled by the digital potentiometers. Again the duration each cathode wire is supplied with voltage is determined by preliminary experiments. Figure 54 projects the required durations to grow the desire volumes to represent each planet. These data values are hardcoded and loaded onto the arduino microcontroller.

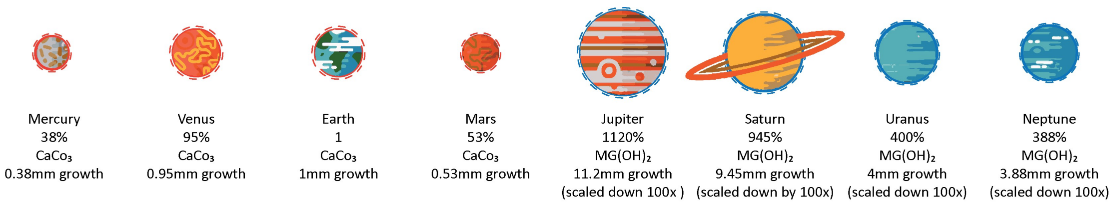


Figure 53: Data based on the size of each planet in the solar system relative to earth and their composition.

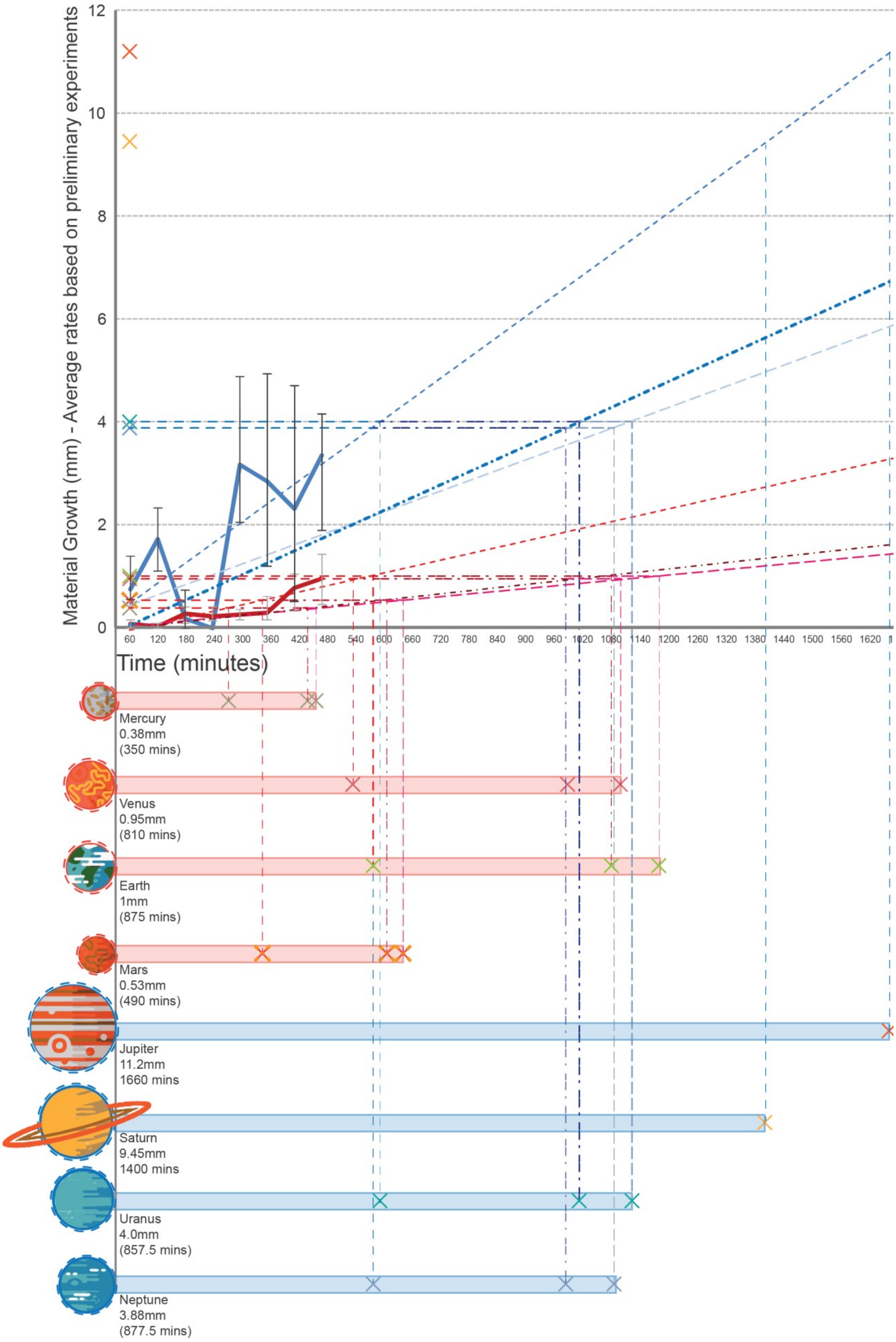


Figure 54: Predicting planet growth times based on the linear projections of preliminary experiments.

7.9.1 Experiment 05: Results. Material Volumes & Growth Rate Results

The results have established that materials can be grown by data. The data used informs the hardware components which induce environmental stimulus (e.g. voltage). These stimuli enable control over localised material growth, governing the rate and volume.

Figure 55 highlights multiple points;

- *Firstly,* that the volume of material grown can be governed by the amount of time the relay is switched on for. The volume of material grown increases over time expect for wire 6, which represents Saturn.
- *Secondly,* it highlights an increased rate in material volume growth, which is governed by the digital potentiometer. The digital potentiometers are used to alter electrical resistance and can govern the electrical current supplied to each wire.
- *Thirdly,* the volume of material growth appears to reach an upper limit at 6.93mm. The limit may be due to several factors: **A**) the cathode wire shape or size being unable to support material growth after this threshold volume. Additionally, material decay was again witnessed as the materials were growing, which increased with cathodes supplied with higher voltages. **B**) The insulating properties of the material grown. As the material grows the electrical current reduces, as a result, the material growth rate reduces. In order to offset this adverse effect, the voltage can be monitored, and this data used to inform the digital potentiometers resistance levels. Interestingly, the resultant and contrasting effect of material growth insulating electrical current could be used to develop feedback between induced stimulus and material properties. **C**) The material resources (e.g. solution salinity) that enable growth are depleted over time and need to be maintained over time, this is due to the closed system. The salinity before growth was measured at 33.0 ppt and after all the planets were grown the salinity was approximately 21 ppt (measured using an analogue fluval sea hydrometer). The reducing salinity means the cathodes metabolise the material resources within the environment and results in material growth slowing or stopping if all the resources are depleted. The material growth at higher voltages is also less materially efficient due to the increased decay.

Table 5 highlights error percentages and the accuracy of material volume grown. Predicting the time based on linear projections to grow a volume is not an accurate strategy. This is highlighted by the average material growth for Mercury - Mars, Uranus and Neptune, which is above the required volume compared to that of Jupiter & Saturn, which is below the required volume. However, the range between the errors for Mercury – Mars is small (2.46 - 28.53). Additionally, table 5 documents the various emergent textures and material properties generated from material growth. Figure 56 highlights these various surface textures via macro-photography. Typically, the materials grown at higher voltages predominantly created smoother, more porous and tubular textures compared to the more granular textures created at lower the voltages. Significantly these varied surface textures are manufactured by the materials themselves, which highlights possibilities of creating functional textures that can be tuned to meet demands. For example, more porous materials being grown and tuned over time to insulate buildings in cooler climates.

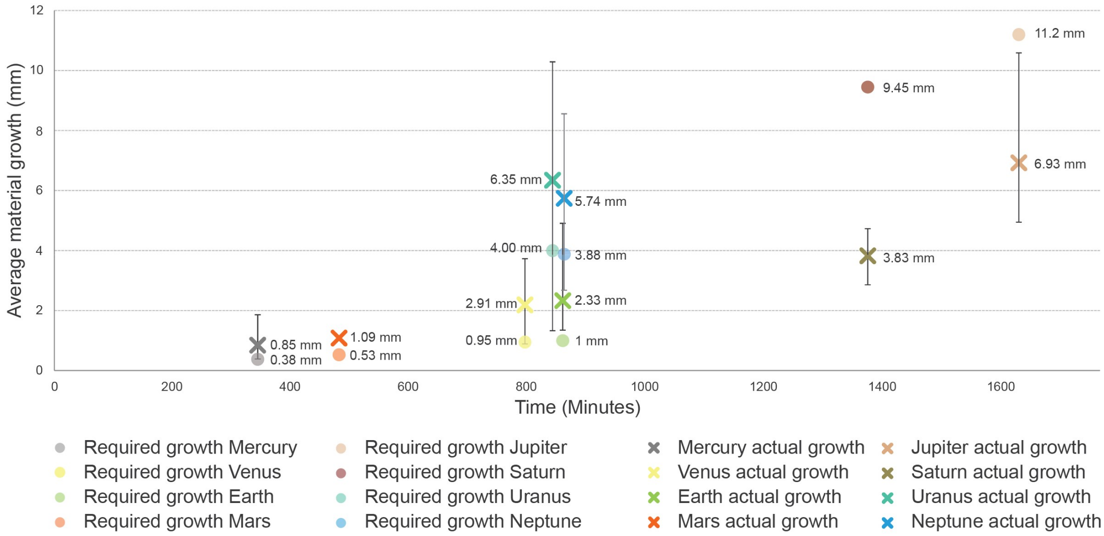


Figure 55: Growth volume graph from experiments 05: grown by data. The results highlight the required planet volumes compared to the actual growth results. Digital Vernier are used to measure material volume grown.

Table 5: Grown by data results. Texture key – S = smooth, P = Porous, G = Granular, T = Tubular

Wire Reference	Growth duration (minutes)	Required growth (mm)	Av growth volume (mm)	Growth rate (mm / minute)	Error %	Texture
1 - Mercury	350	0.38	0.85	0.0024	123.03	G
2 - Venus	810	0.95	2.19	0.0027	130.79	S,T,G
3 - Earth	87	1	2.33	0.0027	133.25	S,G
4 - Mars	490	0.53	1.09	0.0022	104.72	G
5 - Jupiter	1660	11.2	6.93	0.0042	38.17	S,T,P
6 - Saturn	1490	9.45	3.83	0.0027	59.50	S,T,G
7 - Uranus	857.5	4.0	6.35	0.0072	58.63	S,P,T
8 - Neptune	877.5	3.88	5.74	0.0065	48.00	S,P,T,G

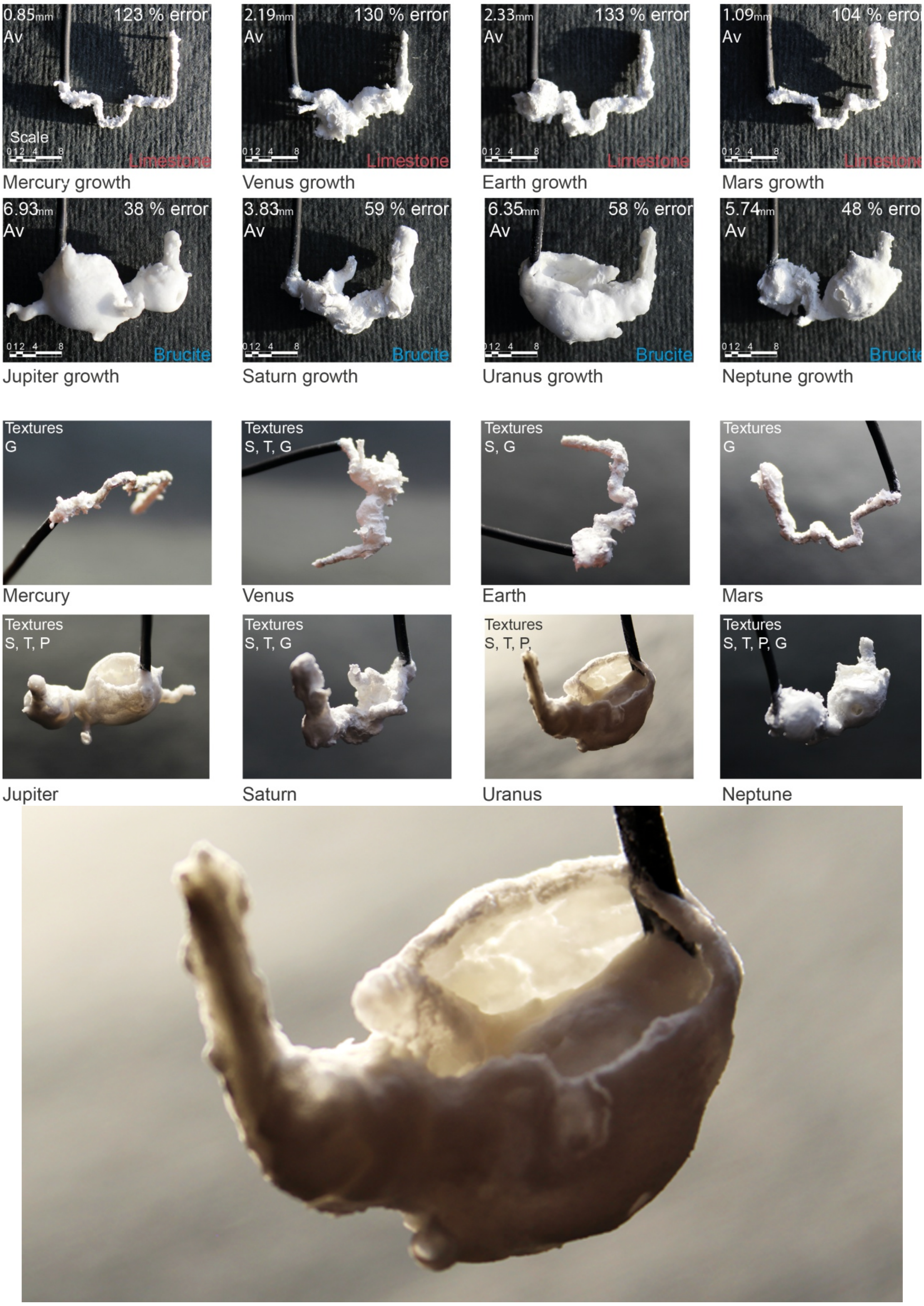


Figure 56: Emergent material properties generated. The first two rows of photographs highlight the various growth volumes achieved, which generally all increased with longer durations. The final two rows highlight the diverse range of emergent surface textures being generated. Interesting, the Jupiter - Neptune cathodes have more porous structures in comparison to the Mercury - Mars cathodes. The images demonstrate data can be used to guide properties material scale self-assembly.

7.9.2 Experiment 06: Properties and Data Values

A second experiment to grow materials governed by a parametric design interface was carried out to investigate if data generated from design tools could be used to govern physical material properties of self-assembling materials (e.g. location, volume, type). The ability to guide material scale self-assembly with stimulus via a digital parametric design tool would extend the abilities of persistent modelling. Figure 57 highlights experiments 06 set-up while figure 58 highlights how the digital design represents corresponds to the physical representation. The experiment looks to extend the grown by data experiment by three main objectives;

- *Firstly,* if a discourse and relationships between digital parametric design, fabrication and material scale self-assembly can be established through induced stimuli.
- *Secondly,* if the time required to grow a desired material volume can be based on average growth rates. The time is determined by the diameter created using parametric tool divided by the average growth per minute of the material at 0.007 and 0.12 amps. The average growth rate was based on the preliminary and grown by data experiments.
- *Thirdly, if* the volumes and material textures could be tuned and altered after the first instance of material growth. To do this the volumes and currents are altered using the parametric tool after the first growth and carried out a second time (see figure 58).

The experiment set-up remained the same regarding the solution and hardware components as the grown by data experiment. The solution was changed after the first period of growth. The parametric design tool determined how the hardware components were governed and induced stimulus. The parametric design tool is used to represent and control: 1) the volume of the material to be grown, which is represented by the circles' diameter and can be continually altered by a slider. The diameter informs the duration the relay is switched on (see figure 58). 2) The type of material to be grown is determined using the buttons, which governs the digital potentiometers resistance value.

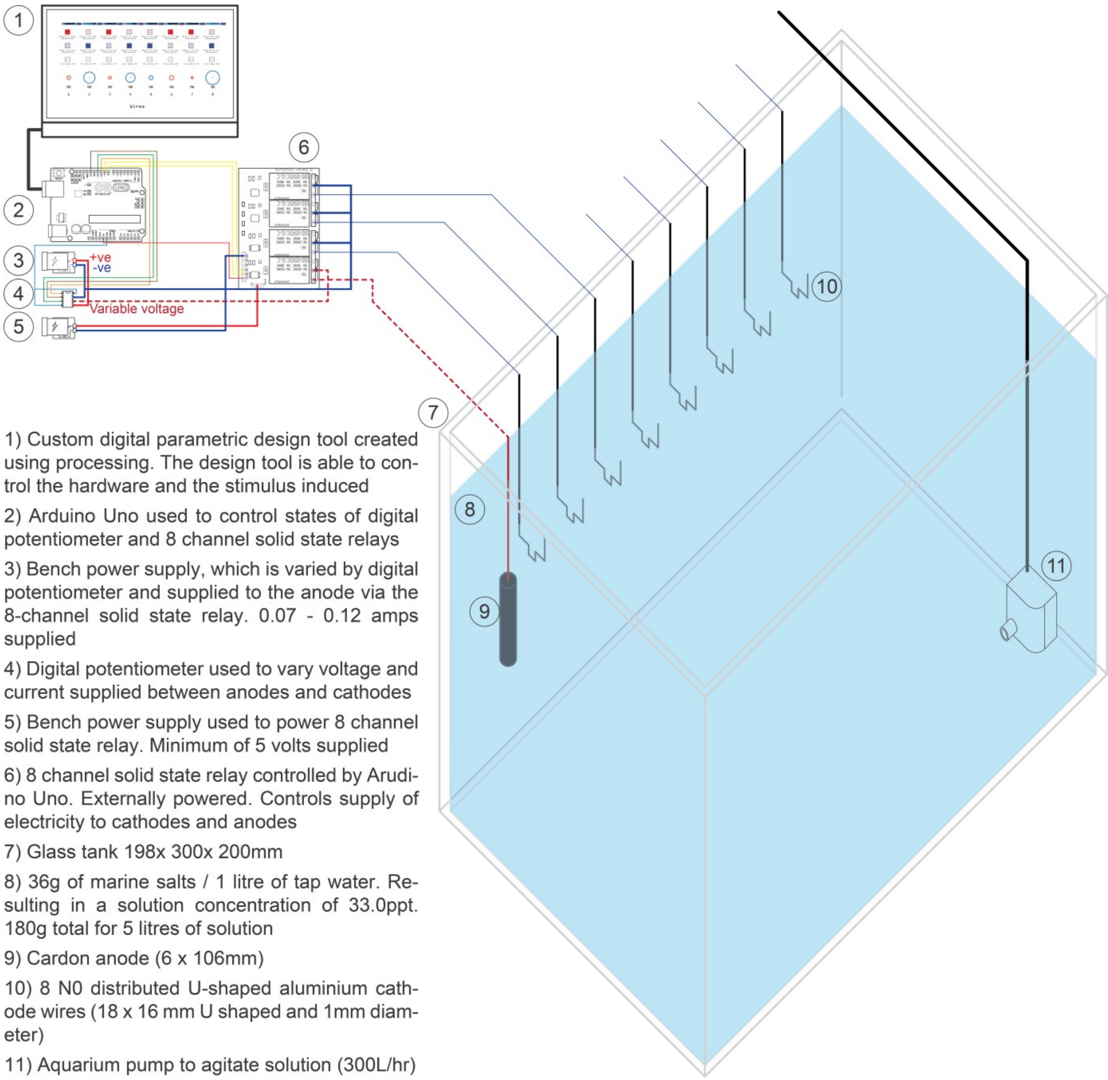


Figure 57: Experiment 06 set-up of eight individual wire cathodes used in the experiment parametric matter. The experiment automates the growth process using arudino to control hardware that induces the stimulus upon the system. The experiment controls the hardware via a digital parametric design tool created in processing.

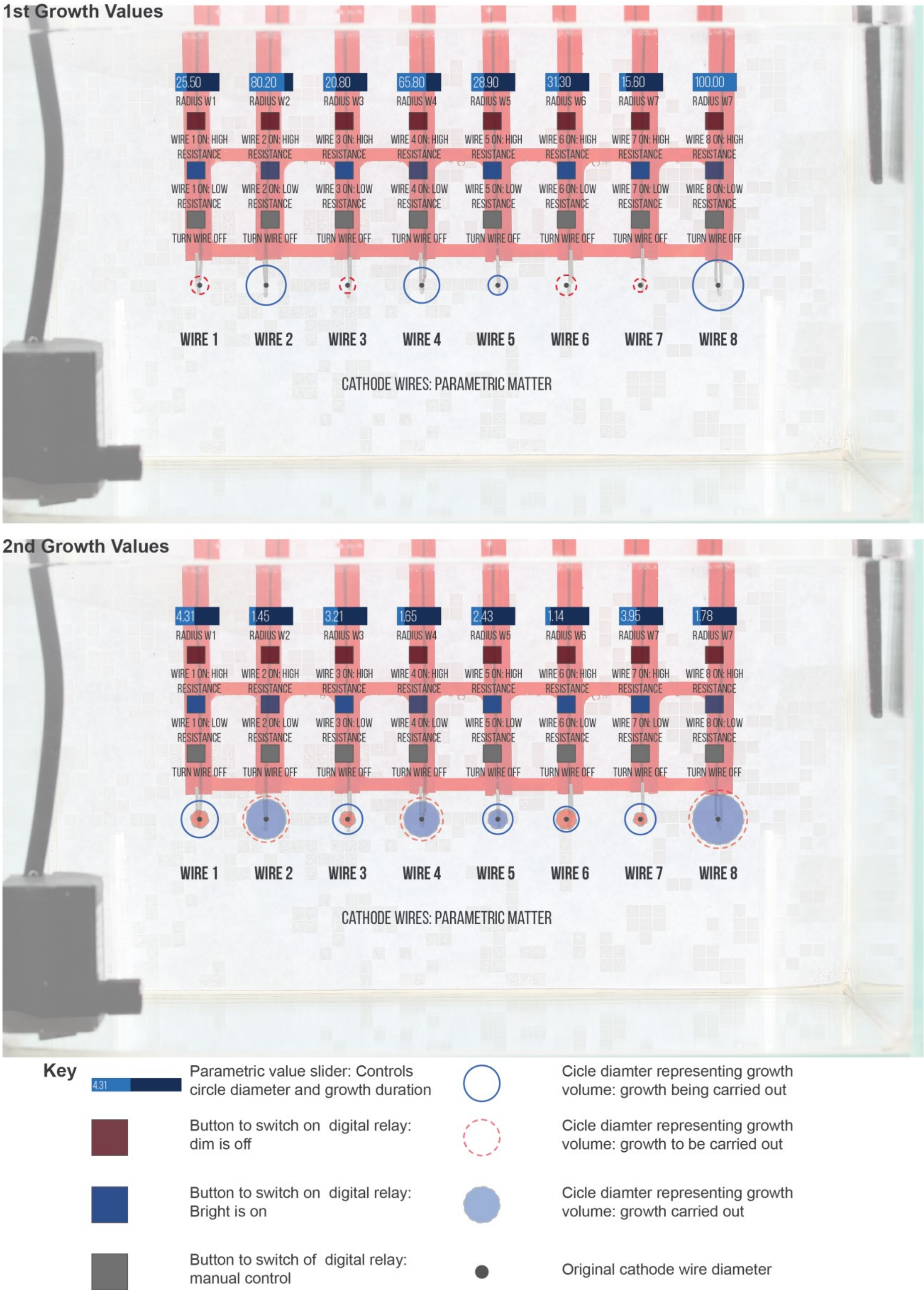


Figure 58: Digital parametric design interface used to govern material growth overlaid on the cathode jig set-up. Circle diameters represent the desired volume to be grown. The red coloured circles represent limestone with the blue colour representing brucite.

7.9.3 Experiment 06: Material Volumes & Growth Rate Results

Experiment 06: *Parametric Matter* establishes that relationships and a discourse between digital design tools, fabrication and material self-assembly can be achieved by controlling and mapping relevant parameters of a stimulus. As a result, the shape-changing capacities and relationships present within digital models and tools can be instilled within the physical material. However, the reliability of the volumes grown is not very accurate. Additionally, un-intended material decay can occur when the volume is intended to be increased. Perhaps, the decaying of material could be utilised as a mechanism to ensure only robust material growth 'survives' at larger scales and volumes. Figure 59 and table 6 document the discrepancies between desired material growth and actual material growth for both instances of this experiment.

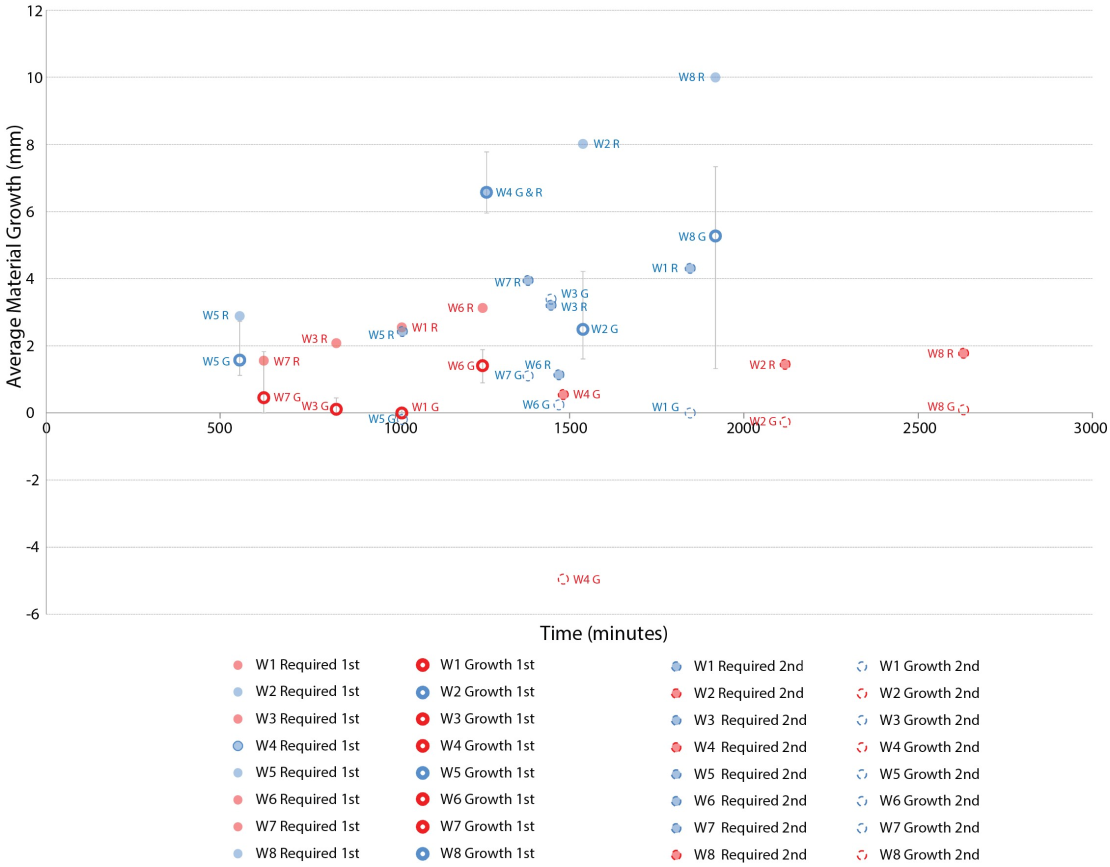


Figure 59: Graph of material growth volumes governed by a parametric design tool. Digital Vernier measured material volumes.

The following findings will be broken down to easily highlight the multiple factors discovered and the importance they could have in relation to adaptable structures;

- Figure 59 reveals the reduced growth rates of limestone during the first growth period. The reduced growth rate was a result of growing the brucite first. Meaning, material resources within the solution were depleted resulting in a slower limestone growth rate.

- Figure 59 - 61 also reveals the ability to instil the shape-changing capacities present with digital design into physical material because of the altered material volumes grown.
- Figure 59 and table 6 highlights the fact material volumes increased and decreased (as a result of decay) as a result of the second growth period. The decay highlights the material fragility of brucite. Material decay occurred on the wires that had grown brucite first, indicating it is not a suitable *'foundation'* material for increasing material growth volumes. The increase in material volumes during the second growth period is at a lower growth rate because of the insulating properties of the material grown.
- The significant decrease in material on wire 4 after the first growth was due to the wire being destroyed. Wire 5 was also destroyed after the first growth. Both these wires first grew brucite. The reason for this may be due to the aluminium wire oxidising at more extreme voltages. The destruction of the cathode wire itself will create anomalous results in determine corresponding material growth volumes with dropping current values. This is a factor that needs to be explored further and may require a more robust scaffold material, such as carbon.
- These changes in volumes establish materials can be tuned and controlled by a parametric tool but without removing material the changes become less apparent and slower. In order to combat this more extreme stimulus may need to be induced.
- The accuracy of growth volumes was improved using average growth rates. Table 6 highlights lower error percentages in particular for wire 4 on the 1st growth and wire 3 on the second growth. The error range, however, is still very large meaning that time based average growth rates are not accurate.
- The table 6 and figures 60 and 61 also highlight the emergent surface textures. Significantly the second growth period demonstrates the surface textures can be tuned. The materials tune their volume and surface textures more dramatically with higher voltages. Additionally, lower voltages could be used to finely tune a materials surface texture.
- The lower voltages during the second growth tuned the granular materials and changed them to smoother textures. The ability to govern these textures could enable them to become functional, which can be informed by and now accommodate design demands that fluctuate.

Table 6: Parametric matter results. Texture key – S = smooth, P = Porous, G = Granular, T = Tubular

Wire reference	Growth duration (minutes)	Required growth (mm)	Av growth volume (mm)	Growth rate (mm / minute)	Error %	Texture
1 - 1st Growth	1019.16	2.55	0.00	0.00	255.0	Na
2 - 1st Growth	1538.67	8.02	2.50	0.0016	31.11	S,G
3 - 1st Growth	831.32	2.08	0.11	0.0001	94.59	G
4 - 1st Growth	1262.40	6.58	6.57	0.0052	0.11	S,T,P
5 - 1st Growth	554.46	2.89	1.58	0.0028	45.42	S,G
6 - 1st Growth	1250.97	3.13	1.40	0.0011	55.19	S,P
7 - 1st Growth	623.49	1.56	0.46	0.0007	70.67	S,G
8 - 1st Growth	1218.54	10.00	5.67	0.0030	43.35	S,T,P,G
1 - 2nd Growth	826.89	4.31	0	0	431.0	Na
2 - 2nd Growth	579.52	1.45	-0.27	-0.0005	-81.4	G,T
3 - 2nd Growth	615.85	3.21	3.39	0.0055	5.6	G,T
4 - 2nd Growth	659.46	1.65	-4.95	-0.0225	-300	G,P
5 - 2nd Growth	466.21	2.43	-0.19	-0.0004	-92.2	S
6 - 2nd Growth	218.71	1.14	0.24	0.0011	79.0	G
7 - 2nd Growth	757.82	3.95	1.11	0.0015	71.9	S,P
8 - 2nd Growth	711.42	1.78	0.09	0.0001	95.0	S,T,P

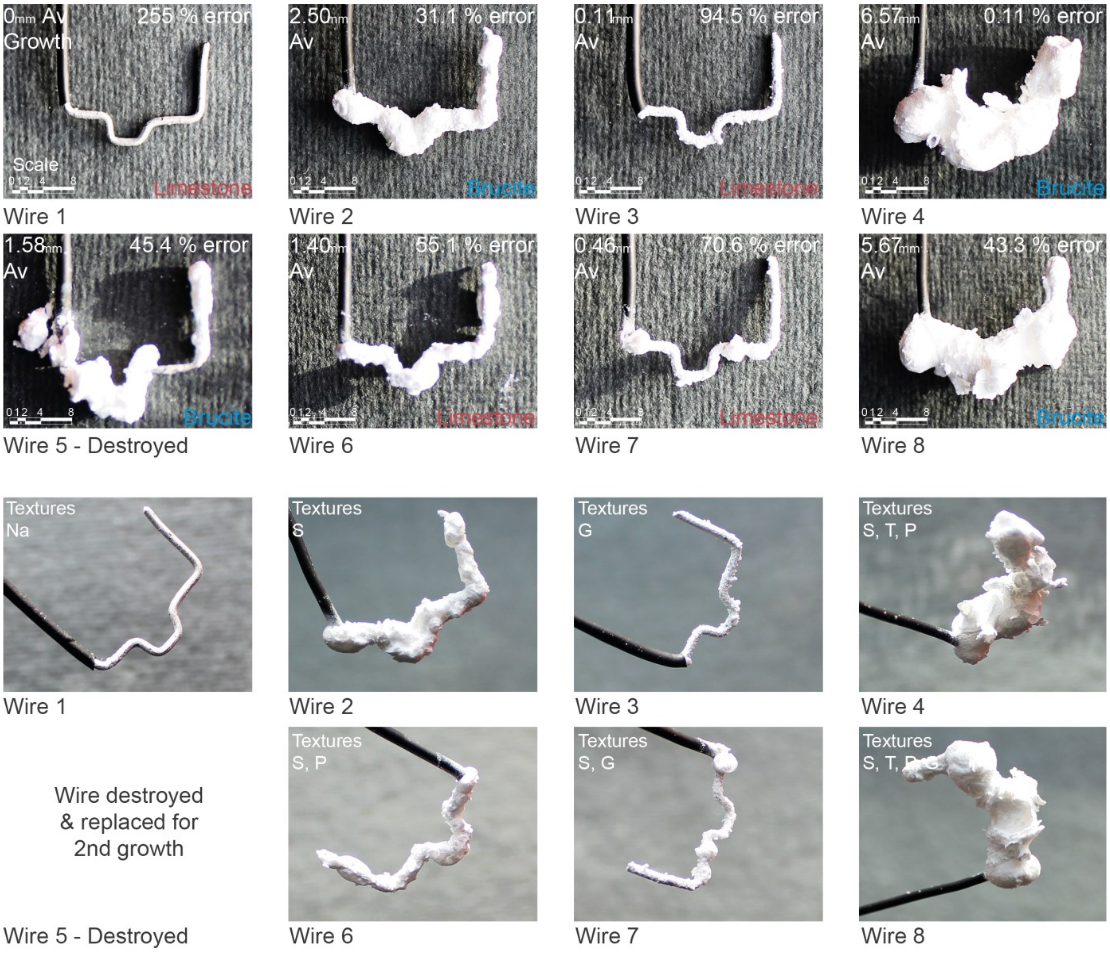


Figure 60: Emergent material growth results from experiment 06. The first two rows compare growth volumes. The last two rows highlight the varied and emergent textures generated.

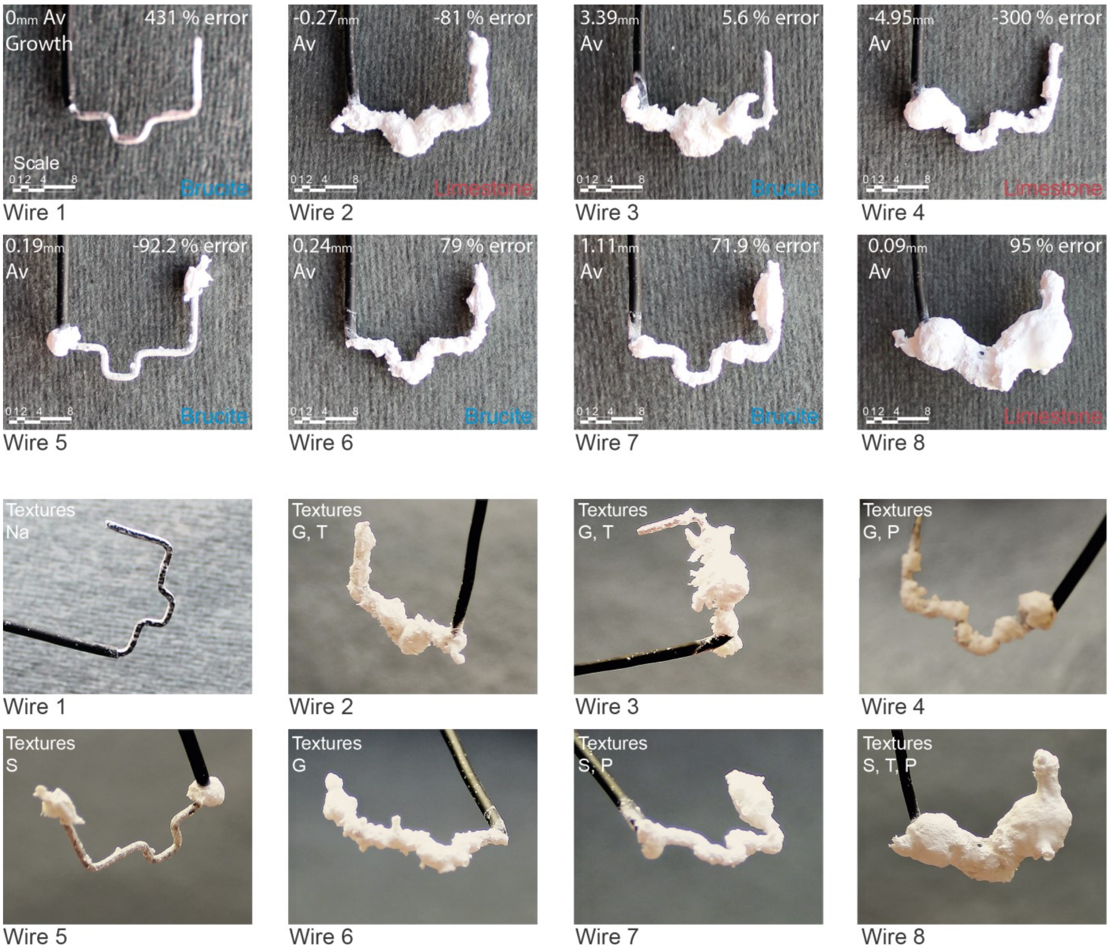


Figure 61: Growth results of experiment 06 after second growth. The first two rows compare growth volumes after second growth instance. The last two rows highlight the varied and emergent textures, which have be altered and tuned compared to the first.

7.10 Experiment 05 & 06: Conclusions

Both experiments 05 and 06 demonstrate the significant potentials made possible as a result of growing materials, where the process has been automated using hardware. In particular, the ability to physically adapt and tune material properties guided by a digital parametric design tool. The experiments results reveal a major benefit of growing materials by inducing environmental stimulus, which is, that material computational processes are produced and engaged within during the fabrication process as well as throughout the structures lifetime. In this case, the material computational abilities are: 1) self-assembly, 2) self-reconfiguration (volume changes) and 3) surface alterations. Additionally, inducing stimuli within this system makes it possible to maintain and develop interrelationships between digital design representations, fabrication processes and material properties. Finally, fabrication processes that are based on growing materials that can be informed by data, which can be generated from complex design models, such as material based computation (Oxman et al., 2015), may make it possible to leverage and reproduce desirable properties and capacities present within biological structures such as, self-healing, increased material efficiencies and adaption. Imagine structures created from materials that can adapt to design demands. For example, a buildings walls being able to increase its materials volume, mass and structural capacities, which could increase the buildings structural loading and insulating abilities. These multi-functional material abilities could address increasing issues of housing demands through adaptive high-rise buildings, which change in size. Additionally, these buildings could have improved climate control strategies, during seasonal changes, by using means that are more passive i.e. do not require mechanical cooling or heating systems. Architectural structures composed of adaptive, viable self-assembling materials could lead to future decarbonisation of buildings and cities if they energy demands the materials require are low and can be generated using renewable means in-situ i.e. within the building itself.

The issues and challenges that are currently limiting the system's, adaptive abilities are, the accuracy / reliability of growing desired volumes without understanding feedback mechanisms within the system. For example, what conditions changes within the solution that can be monitored as material volumes grow and increase, which can be associated to design and fabrication parameters. Possible feedback mechanisms within the system will be discussed in separate headings but significantly, they all inform one another due to the mineral accretion process being based on interrelationships between various stimuli generated, the various material properties produced, and the resultant conditions generated. The sections discussed are, *firstly,* defining interrelationships between design, fabrication and material properties based on mapping material parameters between induced stimulus, resultant environmental conditions and relevant design properties. *Secondly,* reliability in regards to the system being able to accurately grow desired volumes by using sensors to monitor conditions via sensors that correspond to material volumes grown. *Finally*, determining if interrelationships can be associated to design parameters by utilising live data generated from sensors to establish possible feedback mechanisms that can enable a *closed-loop control system,* which incorporates design tools, fabrication. Stimulus, material properties and resultant conditions.

7.10.1 Interrelationships

In order to develop more accurate growth volumes and textures, future work will require interrelationships to be defined and discovered. Interrelationships need to be defined between induced stimulus, resultant environmental conditions and material properties. For example, the experiments have highlighted that the solutions salinity and material resources required to grow materials reduces over time within the closed system. As a result, solution salinity must be maintained to sustain material growth. Additionally, if the solutions' salinity reduces so does the electrical conductivity of the solution. Meaning inducing a stimulus generates a *resultant condition* within the solution. Additionally, *conditional changes / contrasting effects* occur locally at the cathode due to material properties being grown. Hilbertz demonstrates that increasing material volumes can be monitored by incorporating multiple sensor directly around the cathode, due to material growth encasing each sensor wire and insulating them against an electrical signal sent them (Hilbertz et al., 1977). Critically, this demonstrates a *contrasting effect* generated from the material in relation to the stimulus induced (voltage) and can be used as a mechanism to establish feedback between design parameters, stimuli parameters and material properties.

The experiments carried out up to this have lacked these feedback mechanisms to understand the systems interrelationships, which additionally, can also be used to establish feedback. With these feedback mechanisms in mind they have helped to reframe previously known parameters of the mineral accretion process highlighted by Hilbertz et al, Goreau and Streichenberger (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Streichenberger, 1986, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996, Goreau, 2012). The following two sections will now discuss how these interrelationships can be determined and implemented within the final experiments that use the mineral accretion process.

7.10.2 Reliability

Predicting growth rates based on time resulted in un-reliable results as there are too many variables that also alter within the system that impacted drastically upon material growth properties. As a result, material growth is non-linear. Additionally, the decay of material from the cathode wires was not accounted for because it was predicted that when voltage is supplied then material will grow and increase in volume. In order to address these issues among others, sensors are required to monitor *resultant conditions* occurring within the solution as well as *conditional changes / contrasting effects* that occur locally upon the cathode, which have a significant impact upon material properties, for example, increasing material volume. The intention of monitoring resultant conditions and conditional changes that are generated during the mineral accretion process is to understand the parameters that can guide material properties more reliably but can also be associated to material properties and establish feedback between stimulus and design parameters. It has been highlighted that a contrasting condition to the voltage supplied is the insulating properties as the material volume increases on the cathode (Hilbertz et al., 1977, Goreau, 2012), which can be monitored using an electrical current sensor. How this is achieved along with a break-down of the other conditions that can impact on the current sensor readings is given below. These sensors and hardware used and the role they play in the system are based on previous experiments within this research along with literature surveyed. The parameters monitored, offset, maintained and via sensors and hardware are;

- **Maintaining a consistent solution by monitoring *resultant conditions*:** The solution in which the materials grow must have its parameters maintained, these are: 1) ***solution salinity***: this can be maintained by using an electrical conductivity probe, which informs if an additive solution needs to be dosed into the solution to maintain these levels. 2) ***Solution pH:*** again, maintained using a pH probe, which informs if an additive solution needs to be dosed into the solution to maintain these levels. pH levels rise during material growth, with pH levels greater than 9 (Hilbertz et al., 1977) / 9.5 (Streichenberger, 1986) promoting brucite growth. 3) ***Solution temperature***: solution temperature impacts on the solutions' conductivity (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996) with lower temperatures and lower pH levels promoting limestone growth (Hilbertz, 1979). Solution temperature will be monitored via a temperature probe and maintained at a consistent level via an aquarium heating element. 4) ***Solution volume***: solution evaporation occurs over time which impacts on the solution's salinity i.e. as water evaporates the solution can become more concentrated again giving anomalous readings. The solution's volume can be maintained using an aquarium auto top-off pump and or an ultrasonic sensor, which could switch on a dosing pump. The solutions volume could be monitored via an ultrasonic sensor for arduino.
- ***Associating localised conditional changes / contrasting effects: relationships between electrical current and material volumes.*** Hilbertz established that electrical current consumption decreases over time as material grows and increases (Hilbertz, 1979). Monitoring this conditional change / contrasting effect in combination with the solutions resultant conditions can be done via an electrical current sensor, which is incorporated into the circuit externally i.e. non-invasive. The electrical current sensor will be used to determine if the contrasting effect of increasing material volume growth reduced electrical current readings can be used establish feedback between material properties (e.g. volume) and parameters of induced voltage (time and magnitude). However, these resultant current values must correspond to a library / database of material growth volumes.

- ***Time-lapse photography***, preliminary experiments will record material volume growth using time-lapse photography in order to establish what material volumes correspond to electrical current sensor values as well as pH, temperature and salinity values of the solution.
- ***Cathode deterioration***, during the experiment 05 & 06 the cathode wires themselves deteriorated, becoming fragile and prone to breaking. This could impact of the reliability the electrical current readings used to determine is desired growth volumes have been achieved. Carbon cathodes will also be used to address this factor.
- ***Motion capture***, an alternative to electrical current sensor readings to determine growth volumes could be live motion capture data if electrical current sensor readings do not prove to be successful. Live motion capture data is initially not preferred as only material volumes can be detected and not the other material properties generated. For example, how can the same volume of brucite or limestone growth be determined, a property that may be discernible via electrical current sensors. Additionally, motion capture may become redundant when using more complex 3D cathodes as it could become difficult attaining a clear view for lots of cathode wires within 3D space. However, the combination of motion capture with electrical current sensor readings could improve the reliability of desired material growth properties.

7.10.3 Feedback

Feedback between digital design tools / models, fabrication, stimulus and material properties will be established based on the above interrelationships and the live data recorded from the sensors that monitor resultant environmental conditions. The primary form of feedback within the final experiment of this chapter will be based upon the supposed contrasting and reducing electrical current readings, which will correspond to a data library of material volumes recorded via time-lapse photography. Associating these various sensor values with material volume can be used to enable an adaptive design and fabrication i.e. a *closed-loop control system* because the stimulus (control action) induced via the controller (digital design tool) is informed by the desired material properties (process variable). For example, if a material volume is set using a digital design tool and the growth process is started, if a consistent electrical current reading is detected that corresponds to a known and desired material volume the stimulus (voltage) will be switched off. This is the problem with experiments 05 and 06, where voltage duration to grow a desired volume of material of certain type is predicted within a non-linear process.

The ability to induce stimulus and monitor resultant conditions (via sensors) to grow patterns or structures by guiding interactions of self-assembly and generate emergent material properties leads to the notion of creating *'tuneable environments'* as the design and fabrication strategy / methodology. Here structures can be grown and its properties adapted across scales (global shape to local material compositions and organisation) by tuning global environmental stimuli / conditions. *'Tuneable environments'*, are defined as a set of physical stimuli that are adjusted via digital design tools to alter the conditions of a volumetric space that contain self-assembling materials. The idea of tuneable environments will be explored further in the following experiments. Interestingly, *tuneable environments* may also extend the methodology of persistent modelling (Ayres, 2012b) as it can interact with and maintain relationships with material scale properties and material scale self-assembly.

A paper has also been written for the *Grown by Data* and *Parametric Matter* experiments. The set-up, results and key factors from these experiments can be found in the paper titled: *Grown by Data: Designing Parametric Matter.* A second published paper, which documents and annotates the development of the cathode typologies among other factors, can be found within the paper: *Designing Parametric Matter*.

7.11 Experiment 07: Establishing Feedback for An Adaptive Design & Fabrication System

Experiments 07 is the final series experiments to use the mineral accretion process. The aim of these experiments is to establish association and feedback mechanisms between design, fabrication, stimuli and material properties. Essentially, the experiments are used to highlight how a *closed loop control system* can be created.

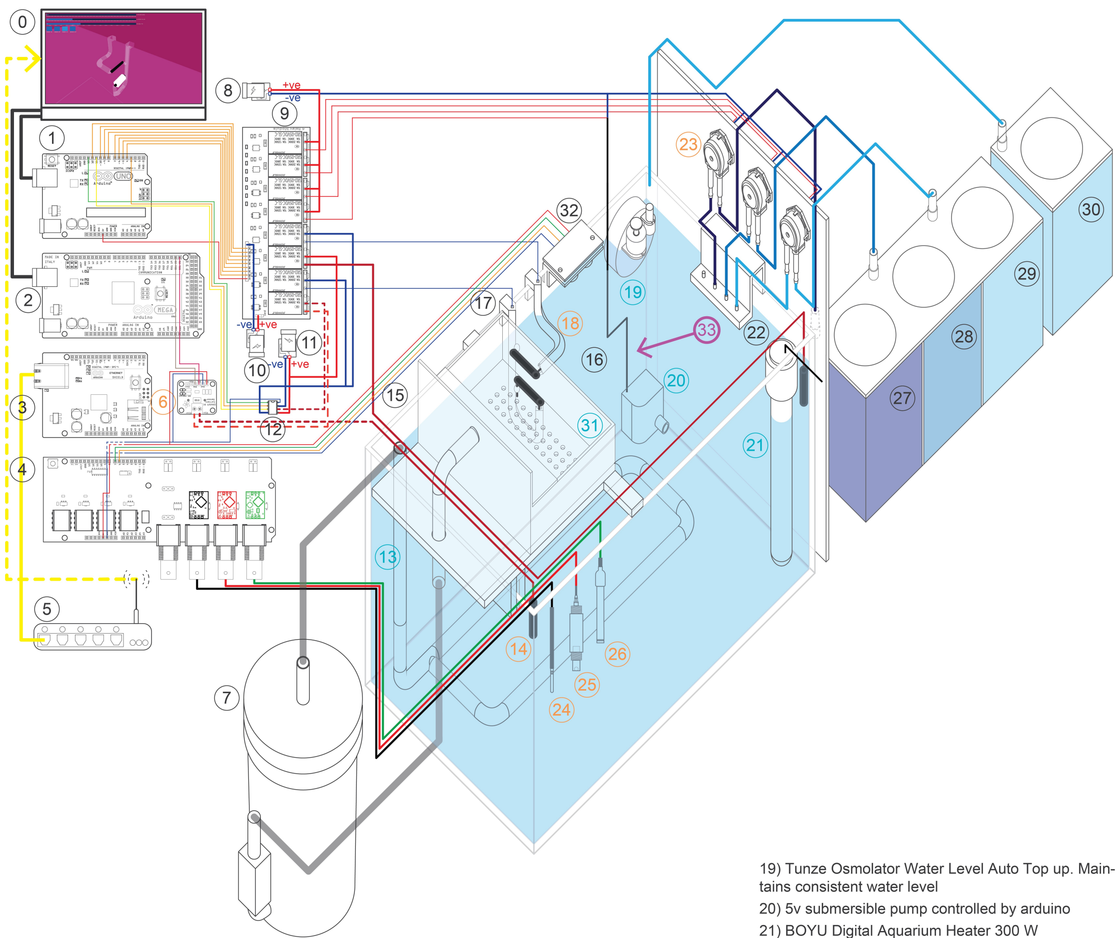
This section and what it discusses is structured as follows: *firstly*, an overview is given for experiment 07, which highlights its set-up properties and fabrication processes used to create the cathode scaffolds. *Secondly,* the generic properties of experiments. *Thirdly,* the specific properties of each experiment that make up experiment 07. *Fourthly,* the methods of analysis and how they are used to determine if material adaption occurs within the system. *Fifthly,* the results of the experiment are presented. Significantly, the results of experiment 07 are used to generate a database of growth volumes relative to electrical current sensor values and solution sensor values (temperature, pH and EC). If the sensor decreases or increase in relation to material volume growth, the values can be used to create association between digital design tool parameters, material properties, stimuli parameters and global resultant conditions / local conditional changes. *Sixthly,* the conclusions from the experiments are discussed. *Finally,* development and challenges are discussed.

7.11.1 Experiment 07 Overview

Experiment 07 is the culmination of all the previous mineral accretion experiments. The aim of experiments 07 is to highlight new potentials of re-thinking design and fabrication processes based on interrelations and growing materials using tuneable environments. If material properties (mainly volume) can be monitored via global resultant conditions of the solution along with local conditional changes / contrasting effects occurring at the cathode it would establish that materials do not have to have form imposed upon them. Instead, monitoring conditional changes and combing them with tuneable environments can begin to enable feedback between the systems interrelationships as well as enabling the tuning and adapting of highly desirable material computational processes, such as self-healing and self-adaptation .

The set-up of experiment 07 is highlighted in figure 62. Experiment 07 is used to generate a database of sensor values relative to material growth volumes. The sensor values recorded that make up the solutions resultant conditions are: 1) solution temperature (°C), 2) solution conductivity (siemens), 3) solution pH. The sensor values recorded that make up the local conditional changes / contrasting effects are: 1) electrical current difference (mAmps), 2) electrical voltage difference (Volts), 3) electrical power difference (mWatts). Significantly, the electrical sensor’s values are used to monitor and determine if material growth generates a conditional change to the stimulus supplied i.e. do the electrical sensors values decrease as material growth increases, whilst the solutions resultant conditions are maintained. The database of values generated will establish if conditional changes can be associated to digital design representation and enable feedback between design parameters, fabrication stimuli, conditional changes and material properties. These conditional changes between the systems components would establish that an adaptive design and fabrication system can be created using stimuli to guide material scale self-assembly. Significantly, the ability to guide material scale self-assembly through stimulus and monitoring conditional changes, which can be controlled and monitored via digital design representations demonstrates the strategy of *persistent modelling* (Ayres, 2012b) can be extended to grow adaptable structures using material scale self-assembly.

The set-up of experiment 07 is highlighted figure 62, which documents the various components and sensors incorporated, which could be used to generate feedback between design and fabrication parameters if conditions changes are detected, which can be used to create a *closed-loop control system.* The conditional changes could have direct associations like those of parametric design tools or non-linear associations, which could be more suitable for determining subtle interrelationships within the mineral accretion process.



0) Experiment 07 generates various sensor data values record to CSV files to determine if conditional changes occur when stimuli is induced that can be associated to parameters of design representations

1) Aruino uno controlling stimulus

2) Arduino Mega for sensor data

3) Ethernet sheild used to send data over wifi router. Stacked on top of Whitebox Labs Tentacle Shield.

4) Whitebox Labs Tentacle Shield with, EZO RTD (temperature) cicuit, EZO pH circuit and EZO Conductivity circuit. Stacked on top of Arduino mega.

5) Wifi router connected to ethernet sheidl.

6) INA219 Current sensor to measure current dropping as material growth increases

7) EF-150 Aquarium external filer pump.

8) Bench power supply used to supply power for dosing pumps.

9) 8 channel solid state relay controlls dosing pumps and voltage supplied to cathodes and anoodes.

10) Bench power supply used to power 8 channel solid state relay.

11) Bench power supply, which is varried by digital potentiometer and supplied to the anodes

12) Digital potentiometer used to vary voltage and current supplied between anodes and cathodes

13) Filer pipe network with 3D printed parts and flexible hosing

14) 2 x Cardon annode (75 x 24 x 4.5mm)

15) Glass tank 50x 300x 300mm

16) 39.5 base solution made using tap water and 1.5kg of marine slata. Chemicals dosed into it to maintain a consistent solution electrical conductivity

17) 2 Nº custom 3D printed cathode jigs.

18) Two carbon cathodes used 1 pair smooth the other pair rough. Smooth dimensions 6.3 x 33.2mm. Rough dimensions 6.1x33.2mm. Cathode 01 is the top cathode, which has it's electrical values measured. Cathode 2 is the bottom cathode

19) Tunze Osmolator Water Level Auto Top up. Maintains consistent water level

20) 5v submersible pump controlled by arduino

21) BOYU Digital Aquarium Heater 300 W

22) Jig to hold dosing tubes

23) Peristaltic dosing pumps controlled by arduino sensor values. Used to maintain solution salinity / conductivity and pH

24) Whitebox labs PT-1000 temperature probe

25) Whitebox labs industral pH probe

26) Whitebox labs conductivity probe K1.0

27) Reef fusion 2 mainains calcium and alkalinity levels

28) Reef fusion 1 raises calcium levels

29) Reverse osmosis water

30) Reverse osmosis water

31) Filter tank containing 5-30 micron filter paper to remove decayed material and keep solution clear

32) Ultrasonic sensor to monitor solution volume / evaporation

33) Camera position to record growth data. The camera recordd growth from above

Figure 62: Experiment 07 set-up. Experiment 07 is used to monitor growing volumes in relation to real-time sensor value, in particular electrical current sensor values. The aim is to generate a database of values that highlight if conditional changes occur relative to material growth increasing. These conditional changes can be used to establish feedback between interrelationships of material properties and stimuli, which can then be related to digital design tool parameters. Significantly, the sensors are external to the materials / cathodes this is done to determine if material scale self-assembly can emit signals that can be monitored to establish feedback.

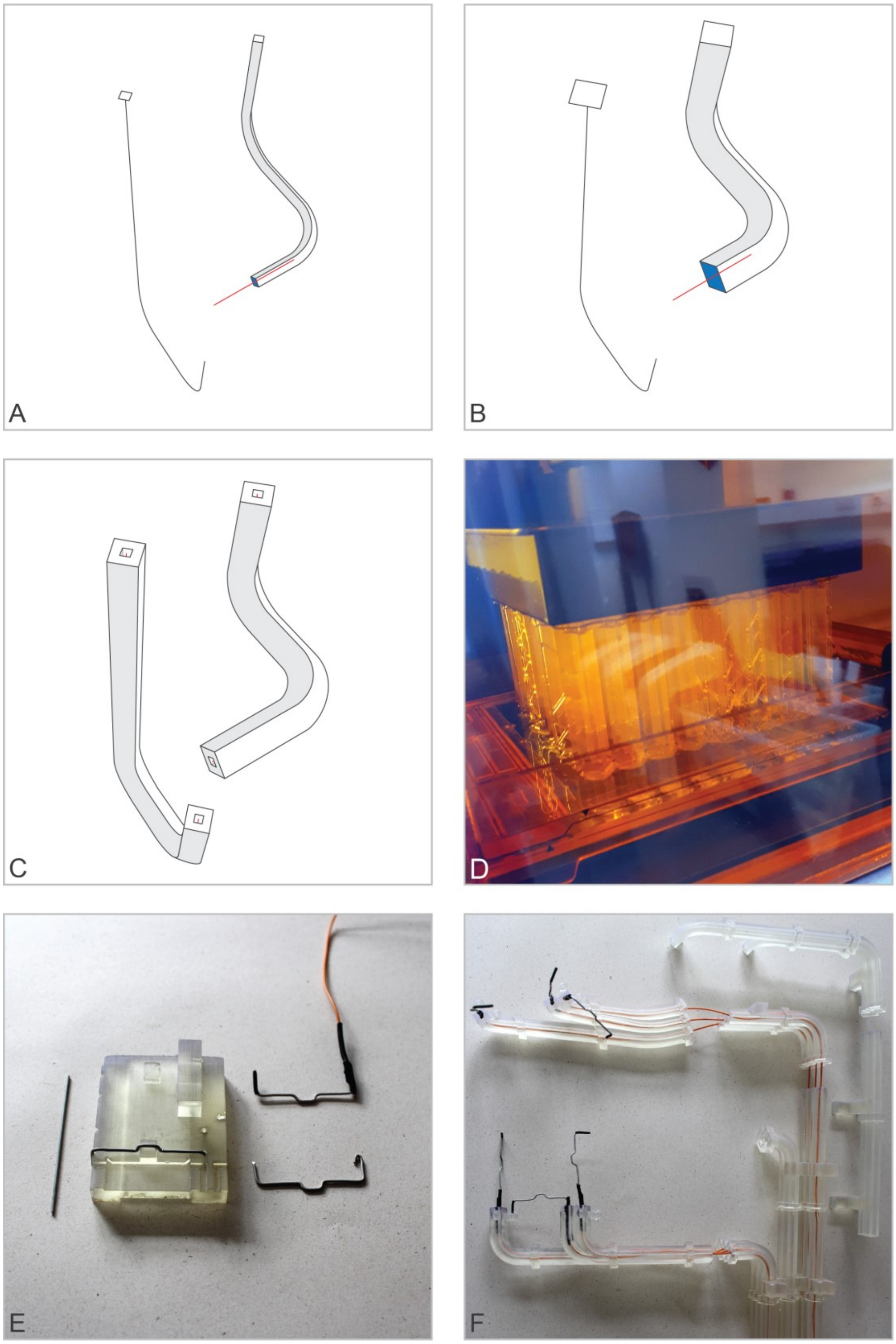


*Figure 63: 3D printing cathodes using single material stereolithography (STL). **A**) 3D model created within sketch-up. Hollow internal paths are created pulling a diamond shape along desired network of paths using the 'follow me' tool. **B**) The same process is repeated for the external surfaces using a large diamond shape. **C**) The two shapes are then combined. **D**) The digital model exported and 3D printed using the Form 2 3D printer. **E**) Aluminium wires are formed around a 3D printed jig to ensure they are all the same dimensions and connected to insulated electrical wire. Cardbon cathodes were cut by hand then wrapped with copper wire, which is then soldered to insulated electrical wire. **F**) Wires fed through the 3D printed sections, which are then glued together.*

7.11.2 Experiment 07 Properties

This section will outline the role each component, stimuli and resultant effect will play in the experiment 07 and how they can be used to build towards an adaptive design and fabrication system in relation to guiding parameters of mineral accretion process. Significantly, the sensors incorporated are external to the materials / cathodes this is done to determine if material scale self-assembly can emit signals that can be monitored to establish feedback.

There are three main means of inducing / creating a stimulus to accrete minerals upon cathode scaffolds*: 1) concentration gradients, 2) ionic attraction and 3) electric migration* (establish a direct electrical current / voltage between electrodes) (Hilbertz, 1978). These experiments only deliberately induce voltage / direct electrical current as the stimulus to guide material properties (volume and location) of the mineral accretion process. Significantly, as material grows upon the cathodes it insulates against electrical current (Hilbertz et al., 1977, Goreau, 2012). Meaning, material growth is a conditional change or contrasting effect to the induced voltage / electrical current used to grow increasing amounts of material. It is these types of conditional changes that can be used to establish feedback within the system and determine if the desired volume of material has been grown, which could be set using a digital design tool. Electrical current, voltage and power will be measured using electrical current sensors to establish if a voltage / electrical current value corresponds to a certain volume of material grown. An electrical current sensor is incorporated externally within the system between the cathode and anode of cathode 01 (the top cathode in figure 62).

Ayres establishes the ability of design tools to induce stimulus upon physical materials and monitor its effects enables relationships to be established between design representations and physical representations (Ayres, 2012b). Significantly, developing and utilising a digital design tool to control the parameters of voltage (duration, magnitude and location) in this system would establish relationships between digital representations and physical representations. However, inducing a stimulus (voltage) to grow material volumes upon a cathode via the mineral accretion process results in multiple interrelationships being generated as highlighted by Hilbertz et al and the pervious experiments of this research. The various parameters, hardware components and interrelationships within the system and how they inform the material properties generated are now discussed individually.

Location of material growth: voltage can be supplied to a specific cathode to grow material where it is desired if the cathodes are physically separated as demonstrated in experiments 04 onwards. Experiments 5 and 6 established that an 8 channel solid state relay can be used to physically switch on or off the voltage to a specific cathode element within a separated network. Enabling control over the location of material growth and can be automated.

Volume of material growth: the amount of time voltage is supplied between the electrodes primarily governs the volume of material grown. The 8 channel solid state relay can be turned on or off at any time either based on manual control, predicated times or sensor readings.

Experiment 07 will generate a database of electrical current sensor readings that correspond to volumes of material grown, which can then be used to stop material growth when the desired certain average sensor reading has been recorded multiple times.

Reversing material growth: A double pole double throw relay can be used to switch the polarity of the voltage supplied i.e. the cathode could become the anode and visa versa. Incorporating this piece of hardware would enable material build on a cathode to be completely removed from it, which would further enhance the shape-changing abilities of the shape cathode in regards to where material is grown and also removed from. However, this would require the cathode to be made from a non-perishable material like carbon to prevent solution contamination and cathode deterioration.

Type of material growth: governing the material type grown is predominantly based on the magnitude of the voltage / electrical current supplied (Hilbertz, 1978, Hilbertz, 1992). However, there has not been a specific threshold of voltage and electrical current stated in which a specific material type predominates. For this reason and based on previous experiments, the first instance of experiment 07 will supply 4.00 volts between the cathodes and anodes using a bench power supply unit. 4.00 volts initially results in 0.108 amps being recorded from the bench power supply unit's display when one cathode is supplied and 0.187 – 0.193 amps when two cathodes are supplied. The intention is to carry out experiment 07 for 12 hrs. However, the voltages and duration will be reviewed after each experiment that make up experiment 07 especially if: 1) no significant sensor values are recorded. 2) If no significant material growth is produced. Extending experiment 07 and carrying it out using various voltages and durations could highlight if higher or lower voltages and the material type generated result in greater contrast in conditional effects. Resulting in improved resolution of feedback mechanisms. A bench power supply unit is used to supply a fixed voltage during each iteration of experiment 07. A bench power supply enables less electrical current / voltage variations, which could ensure more reliable data-base values are created. In order to grow a combination of limestone or brucite, the voltage / electrical current supplied between the cathodes and anodes could be controlled using a digital potentiometer, where higher resistance reduce the voltage / electrical current and would predominantly grow limestone and visa versa. The ability to control voltages by incorporating a digital potentiometer was established in experiments 05 and 06. Within experiments 07 a digital potentiometer will not be used to alter electrical current / voltage values.

Although voltage / electrical current plays a significant role in guiding the self-assembling material interactions of the mineral accretion process, several other stimuli arise during the process as well as other factors that can impact on the material properties generated. These factors, resultant stimuli and the components used to monitor, maintain and offset them are;

Cathode location: two separated cathodes are used, which are positioned vertically in-line with one another (one above the other) to examine the impacts of material growth occurring on cathode below has on the one above as hydrogen bubbles are generated at the cathode's surface. This will inform how a 3D network of cathode needs to be spatially organised. Within experiment 07 two cathodes are separated and mean the set-up does not have the resolution to grow a global shape. This is done to establish if self-assembling materials can be guided by stimulus and can then be adapted when using the simplest set-up.

Number of anodes, material, locations and distances between cathodes: Two rectangular carbon anodes are used (75 x 24 x 4.5mm). The anodes are placed in the corners of the glass tank to ensure a maximum and set distance away from cathodes (≈355mm). The distance between anode and cathode(s) impacts on the material type grown, where brucite predominates at locations where the cathode is closest to the anode (Hilbertz, 1979). Experiment 07 will use two different cathode materials, which all have differing properties. The cathode material types used are carbon and aluminium. Carbon is used as the aluminium wires apparated to deteriorate and disintegrate in experiments 05 and 06. The cathodes material properties, dimensions and surface are highlighted in figure 64 and table 7.

Cathode wire connections: Numerous cathode connection wire to the power supply should be spaced evenly to achieve more uniform growth (Hilbertz, 1976). However, as the cathodes are individually separated and relatively small in comparison to the size of cathodes used by Hilbertz. The single wire connection to each cathode has typically produced uniform growth in previous experiments in this research, with growth volume initially developing and being greatest at the bends and ends of the cathode wires, as this focuses electrical current (Goreau, 2012). These properties were predominantly witnessed in experiments 04 onwards.

Solution volume and composition: 39.5 litres of tap water will be used and held within a glass tank (302 x 500 x 298mm). The tap water will have 1.5kg of materine salts dissolved into it, which forms the base solution of the experiments. In order to maintain a consistent solution electrical conductivity (hereafter EC) and pH during the mineral accretion process chemicals will be dosed in based on sensor values and defined thresholds. How the values and volumes of chemicals are dosed is discussed further down. Tap water is used as it is readily available. The solutions volume will evaporate over time so its volume is maintained via an aquarium auto-top off system (tunze osmolator), which will pump in reverse osmosis water (hereafter RO) to maintain a specific volume. Additionally, an ultrasonic sensor will measure the water levels, which will also inform a dosing pump if small amounts of RO water need to be added to maintain a set volume of base solution. The variation in solution volume will alter its concentration levels of chemicals, which are used to maintain consistent pH and EC levels so these values and the volume of liquid need to be constantly monitored via pH and EC sensors. RO water is dosed in to maintain a solution volume as is EC value is minor comported to tap water so it won't affect the solutions EC values significantly when added.

Solution pH: Solution pH also impacts on the type of material growth as anything greater than a level of 9.0 - 9.5 results in brucite growth predominating (Hilbertz et al., 1977, Streichenberger, 1986). Furthermore, during the mineral accretion process, the solution's pH is increased (alkaline) at the surface of the cathode and reduced at the surface of the anode (acidic) (Goreau and Hilbertz, 2005). Overall the net effect of pH should be cancelled out, but this could be based on having comparatively equal surface areas the cathodes and anodes. The surface areas of the various cathode types compared to the carbon anodes are noted in table 7. However, in order to maintain a consistent solution pH level, a pH sensor will be used to monitor these levels, which will inform a dosing pump to add chemicals to maintain an intended solution pH level between 8.0 – 9.1. Being able to govern pH levels of the solution could be an additional condition used to dictate and potentially enhance / accelerate the growth of a particular material type.

Solution salinity / conductivity: The base solution will have chemicals added to it to maintain a consistent solution salinity / electrical conductivity, which directly affects material growth properties (rate and type) occurring upon the cathodes as well as the electrical sensor readings taken from the cathode to measure growth. The solutions salinity / conductivity will be maintained using an electrical conductivity probe. The readings from the EC probe will be used to control the actions of a peristaltic dosing pump to maintain consistent solution conductivity. For example, if the solution falls below a threshold value of 25000.0s a small amount of concentrated solution will be dosed in to offset the falling salinity / conductivity levels of the base solution as a result of the mineral accretion process. The conductivity of the base solution decreases during the mineral accretion process as it removes (precipitates) the dissolved ions that grow the materials from the solution at the cathodes and anodes surface (Hilbertz, 1979, Hilbertz and Goreau, 1996, Goreau and Hilbertz, 2005). Significantly, if the base solution's composition (among other conditions) is not maintained the solution's conductivity reduces, which would produce anomalous and unreliable results from the electrical current sensor, which are used to determine material growth volumes. Additionally, solution evaporation and temperature also significantly impacts the base solution conductivity.

Temperature: fluctuations in temperature affect the solution's conductivity (Hilbertz et al., 1977, Hilbertz, 1978, Hilbertz, 1979, Hilbertz, 1981, Hilbertz, 1991, Hilbertz, 1992, Hilbertz and Goreau, 1996). In order to maintain a consistent solution conductivity to ensure more reliable current sensor readings, the solution will be maintained at a temperature of 22.5-26°C using an aquarium heating element. Additionally, the solution's temperature will be monitored via a temperature sensor (see figure 62).

Solution agitation: In order to maintain a homogeneous solution when chemicals are dosed into the solutions as well as counteract the effects of gravity, which causes the solutions ions to sink, a 5V submersible pump is used to agitate the solution. The pump will agitate the solution for 2 minutes every time chemicals are dosed into the solution to maintain salinity and pH, as well as after a 30 minute interval for 2 minutes if no chemicals have been added within that time. Additionally, an aquarium filter pump will also agitate the solution(see figure 62). However, the filter pump is controlled manually and at random times. It is incorporated to filter the solution to maintain a clear solution by counteracting the build-up of material decay being suspended in the solution, making the solution cloudy and was witnessed in all the previous experiments. Filtering the solution aims to keep it clear so improved photography can be achieved, which provides the live material volume growth data.

Time: Over time, it has been demonstrated the material that has been grown, which is composed of brucite and limestone changes composition. Where the percentage composition of brucite is reduced and replaced by an increase in limestone, without inducing voltage (Hilbertz, 1992). This material composition state change will not be accounted for within the experiments 07.

Hardware and Communication: The sensors and electrical components used within the experiments are documented in figure 62. Two arduinos are used in the experiment. The first arduino is used to control the actuators (relays for voltage, dosing pumps and agitation pump). The arduino can be communicated with via the digital design tool to inform parameters of the stimulus. The second arduino is used to record the live sensor readings (temperature, pH, solution electrical conductivity and voltage / electrical current). In order to prevent arduino to computer connection and communication issues, the design tool sends instructions (strings) to the first arduino via USB. Sensor information from the second arduino is sent to the design tool via an Ethernet shield. Based on preliminary tests, communicating over two separate means (USB and Ethernet) resulted in improved communication reliability. Additionally, combining the sensor shield and sensor circuits with the relay devices resulted in the sensor circuits not working and prevented sensor readings being taken. As mentioned above the main sensor used to monitor conditions, which establish feedback between and have a significant effect on and material properties within the system, are: 1) an electrical current sensor, 2) a solution EC sensor, 3) a solution pH sensor and 4) a solution temperature sensor. These sensors are very sensitive and as a result can generate a range of fluctuating readings (bar the temperature sensor), which could result in unreliable results and system actions. In order to maximise the benefits of the sensor's accuracy and address fluctuations several strategies are employed;

Sensor Calibration: Both the pH and electrical conductivity (hereafter EC) sensors used to measure the solution's properties and maintain them are calibrated manually prior to the experiments. The pH and EC sensors are manually calibrated via a 3 point method. **Sensor Value Averages:** A challenge arises with sensor reading fluctuations that occur due to high sensitivity of the pH, EC and electrical current sensors. In order to address the fluctuations and generate more reliable readings, the readings are averaged based on 8 sensor readings per sensor before dictating what action is carried out within the system. For example, if the solution's conductivity falls below a reading of X based on the average EC values the system will then switch on a dosing pump to does in 2ml of a solution. The solution is then agitated for 2 minutes via a pump and then the solutions EC values are taken again after 5 minutes to determine if the solution is within an acceptable threshold rage. **Base Solution Threshold Values and Ranges:** Threshold values for the base solutions pH and EC are determined prior to inducing material growth to produce base-line values. The base solution is initially made by dissolving 38.2g of marine salts per litre of tap water (1.5kg for 39.5 litres). The initial values and threshold ranges for each of the experiments are highlighted in table 8. Recording the initial pH and EC values of the base solution are important as they inform the actions of the system (see figure 66).

7.11.3 Experiment 07 Specific Properties

There are two properties to experiment 07: *firstly,* the intention is to run experiment 07 for a total of 12 hours but this will be determined with the volume grown over this duration generates significant enough electrical current readings that correspond to material volume grown. The sensor readings will be recorded at set intervals of 10 seconds, with an average sensor value from every 10^{th} minute from each sensor will then be compared to time-lapse photography. A photograph will be taken every minute with every 10th photograph being used to record growth volumes. Over 12 hours 72 photographs will be used to generate corresponding live growth volume data with live sensor values. *Secondly,* the experiment will determine if carbon cathodes can sustain material growth and produce reliable sensor readings without deteriorating.

Cathode materials, shape and texture: Experiment 07 uses three different types of cathodes and their properties are documented in figure 64 and table 7. The shape, material and surface textures of the cathodes used in experiment 07 will determine three factors: 1) what effects the material type have on conditional changes and resultant effects within the system. 2) Can associations be made between sensor readings and material volumes grown. 3) Does material type and properties (e.g. geometry, texture, materiality) have an impact on being able to initiate growth and support it for long durations.

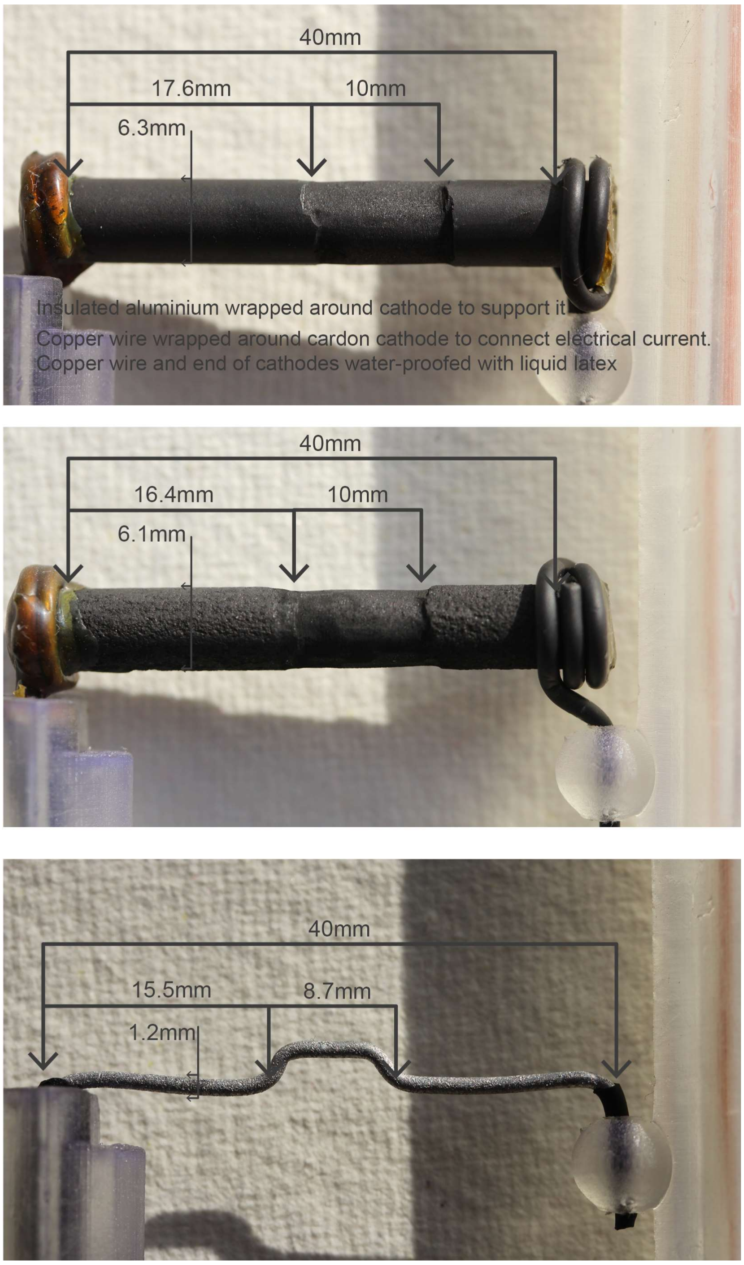


Figure 64: The three types of cathodes used in experiment 07 explore the impacts of surface textures and material type on material growth and current sensor readings. The material types are: Top - smooth carbon, middle - rough carbon, Bottom rough aluminium. Additionally, the carbon cathodes have their ends water proofed and insulted by coating them in silicone and liquid latex.

Table 7: Cathode properties and ratios to anode surface area

Cathode Type	Dimensions (mm)	Cathode Surface Area	Anode Surface Area	Surface Area Ratio
Carbon Smooth	6.3 x 33.2	719.44mm^2	8361.6mm^2	1:11
Carbon Rough	6.1 x 33.2	694.68mm^2	8361.6mm^2	1:12
Aluminium	40 X 1.2	310.64mm^2	8361.6mm^2	1:27

Table 8: Experiment 07 base solution properties. Values taken before each experiment.

Experiment	BPSU vals	Solution Temperature	Base solution starting pH	Base solution starting EC	Base solution threshold pH ranges	Base solution threshold EC ranges
07A: Carbon Smooth	4.00V 0.193A	23.6	8.5	24490.0	>8.1 <9.0	>24000.0 <25000.0
07B: Carbon Rough	4.00V 0.204 A	25.8	8.8	34381.0	>8.1 <9.0	>34300.0 <34700.0
07C: Aluminium Wire	4.00V 0.194A	22.7	8.9	42041.0	>8.1 <9.0	>41900.0 <42200.0

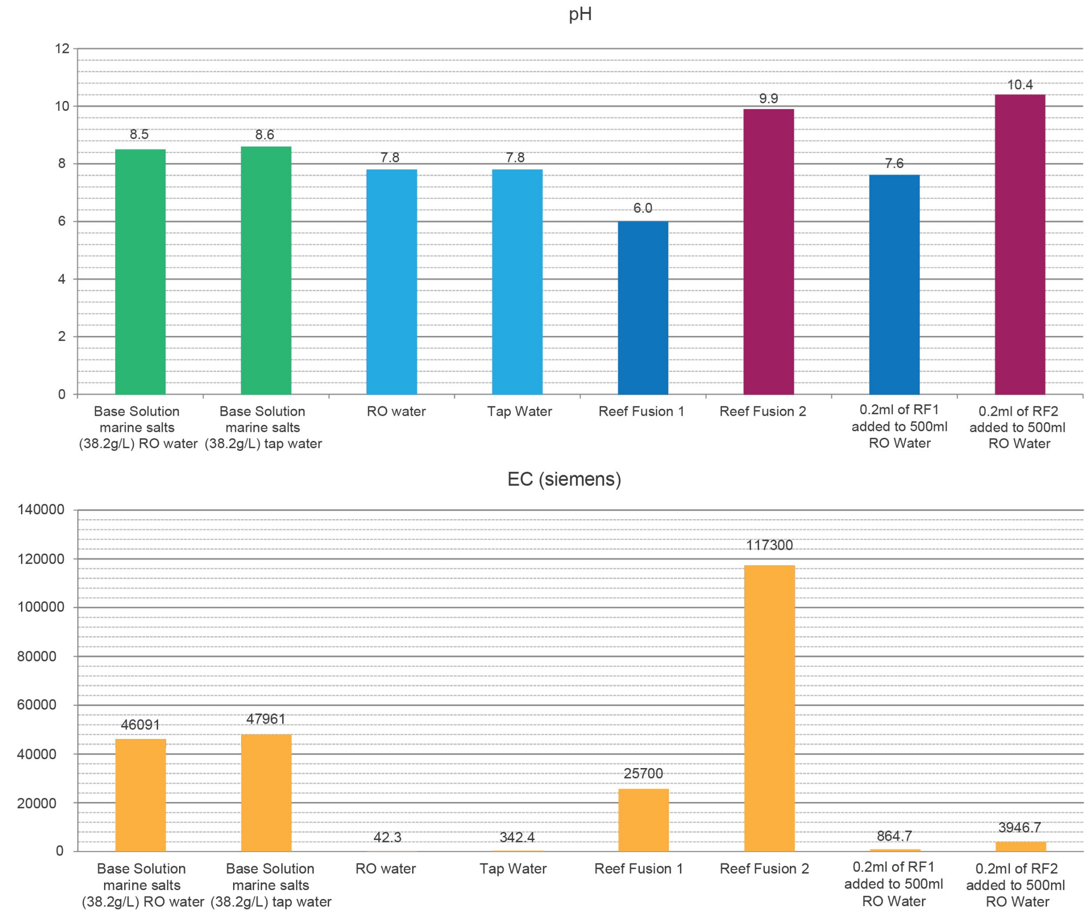


Figure 65: Graph of the various chemical and base solutions pH and EC values. These values will inform threshold values and actions of the system. Base solutions values created with 500ml of RO water or Tap water with measurements taken at temperatures between 24.5 and 26.0 °C.

7.12 Experiment 07 System Actions

The overall logics of the system that governs what or if any actions are carried out based on threshold sensor values are highlighted in figure 66. These system logics are predefined and will have an impact on the interrelationships generated, for example, if the electrical conductivity of the base solution is below 25360.0 s and the pH is low (less than 8.1) and no actions have occurred within 5 minutes then switch on dosing pump 2 to does in 2ml of reef fusion 2. If liquids have finished being dosed switch on agitation pump for 2 minutes to mix the solution. Essentially these are the same logics used to govern each dosing pump action. Additionally though, if not dosing pump actions occur the agitation pump is turned on for 2 minutes every 30 minutes to prevent ions sinking to the bottom of the tank due to gravity. The temperature sensor do not inform any of the system actions and the filter pump will be controlled manually, which will be switched on and off at random intervals and for random durations.

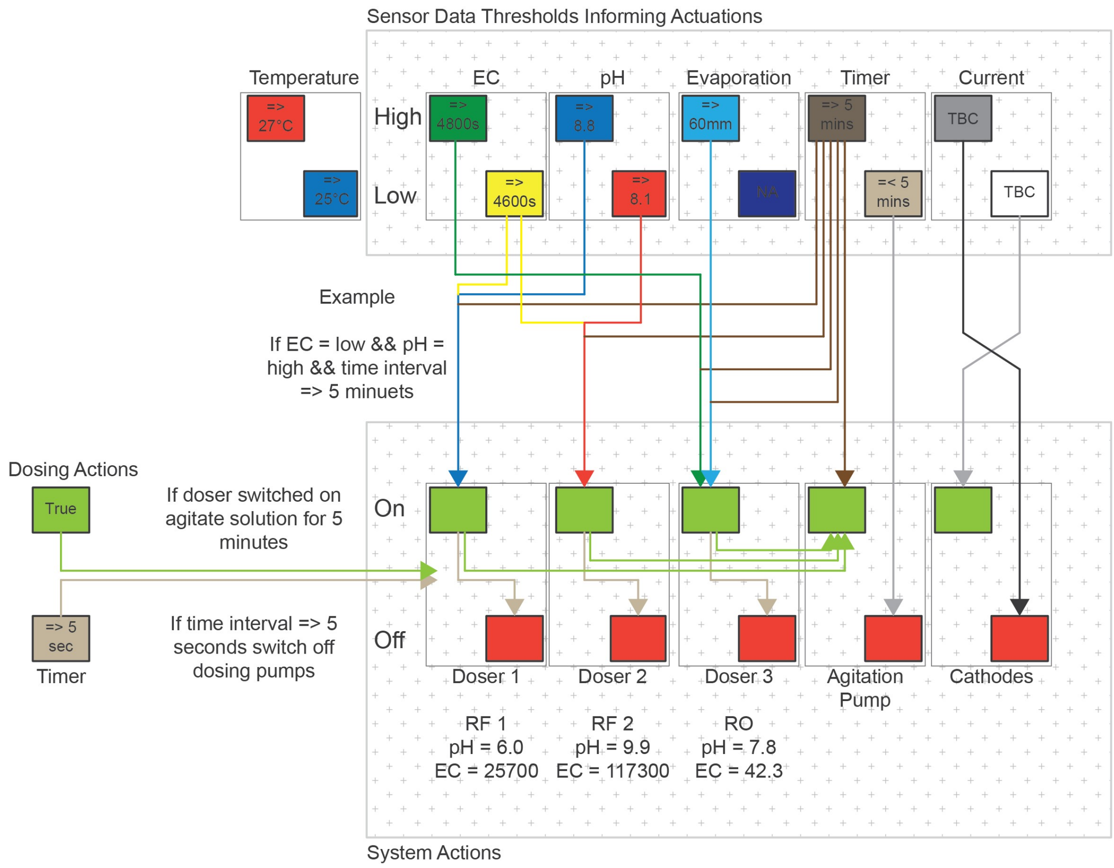


Figure 66: Overview diagram of the system logics for how defined threshold values inform what actions are carried out. Additionally, in order to prevent a large number of actions being carried out constantly single actions can only be carried out every 5 minutes.

7.13 Experiment 07 Analysis

The analysis and results generated from experiment 07 will be based on combing real-time data generated from several sensors (pH, temperature, salinity and electrical current sensors) and compared with time-lapse photography if sufficient material growth has occurred. The sensor data and time-lapse photography can be compared as they will have corresponding time stamps. Time-lapse photography will provide data on the volume on material grown, which will be measured relative to a known dimension within the photograph. In this case the diameter of the cathode. In order to achieve reliable photographic analysis for growth volume data, the cameras positions and experiment set-up will not be moved.

7.14 Experiment Results

The results establish how an adaptive design and fabrication system can be developed based on determining global resultant conditions variations of the solution and local conditional changes of the cathode relative to material properties generated, which highlights several significant factors that need to be addressed in order to develop an adaptive design and fabrication system when: 1) employing tuneable environments to guide material scale self-assembly and 2) utilising material platforms that have inherent interrelationships. Additionally, these results highlight a converging challenge of design tools representing physical materials and also extend the parameters and design principle for enabling material self-assembly in a design context.

7.14.1 Experiment 07 Results: Database of Material Volume, Growth Rates & Corresponding Sensor Values

Firstly, the data generated from the sensor values and photographs are presented, which are combined into graphical data if enough material volume has been grown to allow comparative analysis. *Secondly*, the key principles of the result from each are discussed. *Finally*, overall conclusions are discussed that highlight various design principles and issues when developing an adaptive design and fabrication system that is based on stimulus, interrelations, material scale self-assembly and incorporates sensors externally to the materials.

Table 9: Experiment 07A: sensor values relative to material growth volumes.

Time (mins)	Av Material Volume (mm)	Av Current (ma)	Av Voltage (V)	Av Power (mW)	Av Solution EC (µS)	Av Solution pH	Temperature (°C)
10	na	86.00	1.03	88.0	24461.25	8.5	23.6
20	na	86.57	1.02	88.0	24443.75	8.5	23.6
30	na	86.74	1.05	87.38	24483.75	8.5	23.6
40	na	87.21	0.95	79.50	24408.75	8.5	23.6
50	na	86.89	1.03	88.50	24441.25	8.5	23.6
60	na	86.85	1.03	86.63	24395	8.5	23.6
70	na	87.51	0.78	71.13	24287.5	8.5	23.6
80	na	86.91	1.02	89.50	24246.25	8.5	23.6
90	na	86.95	1.03	89.75	24250	8.5	23.6
100	na	86.95	1.03	89.75	24180	8.5	23.6
110	na	86.95	1.03	89.75	24158.75	8.5	23.6
120	na	86.95	1.03	89.75	24083.75	8.5	23.6

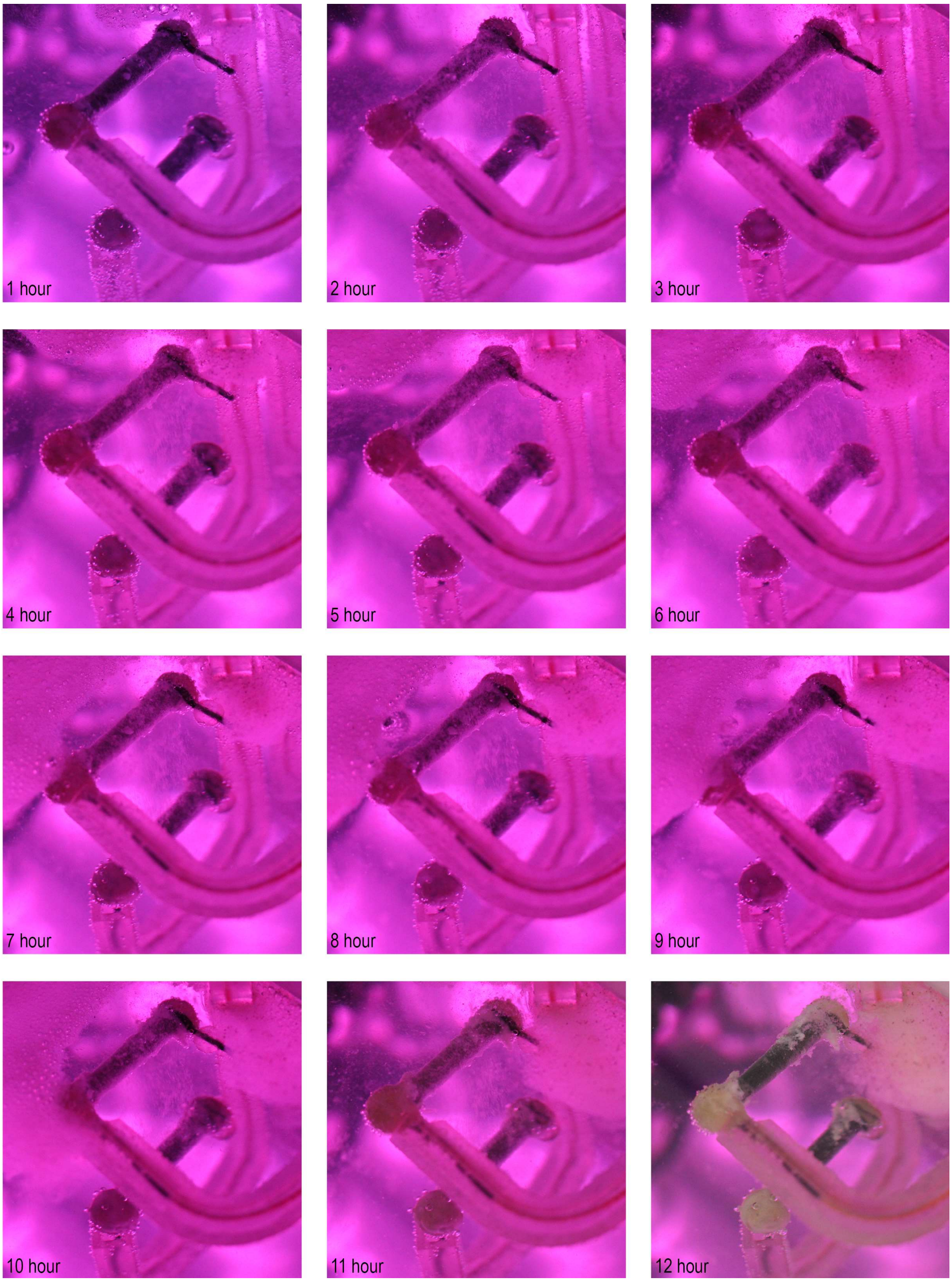


Figure 67: Series of images highlight the limited material growth that occurred within experiment 07A (smooth cathode) over a 12-hour duration. The last image reveals small amounts of material growth predominantly occurring at the ends of the cathode but also along the cathode's length. Highlighting that a smooth surface texture does not impact growth. Link to time-lapse video: https://vimeo.com/user12085005/review/380364588/5d86943f8c

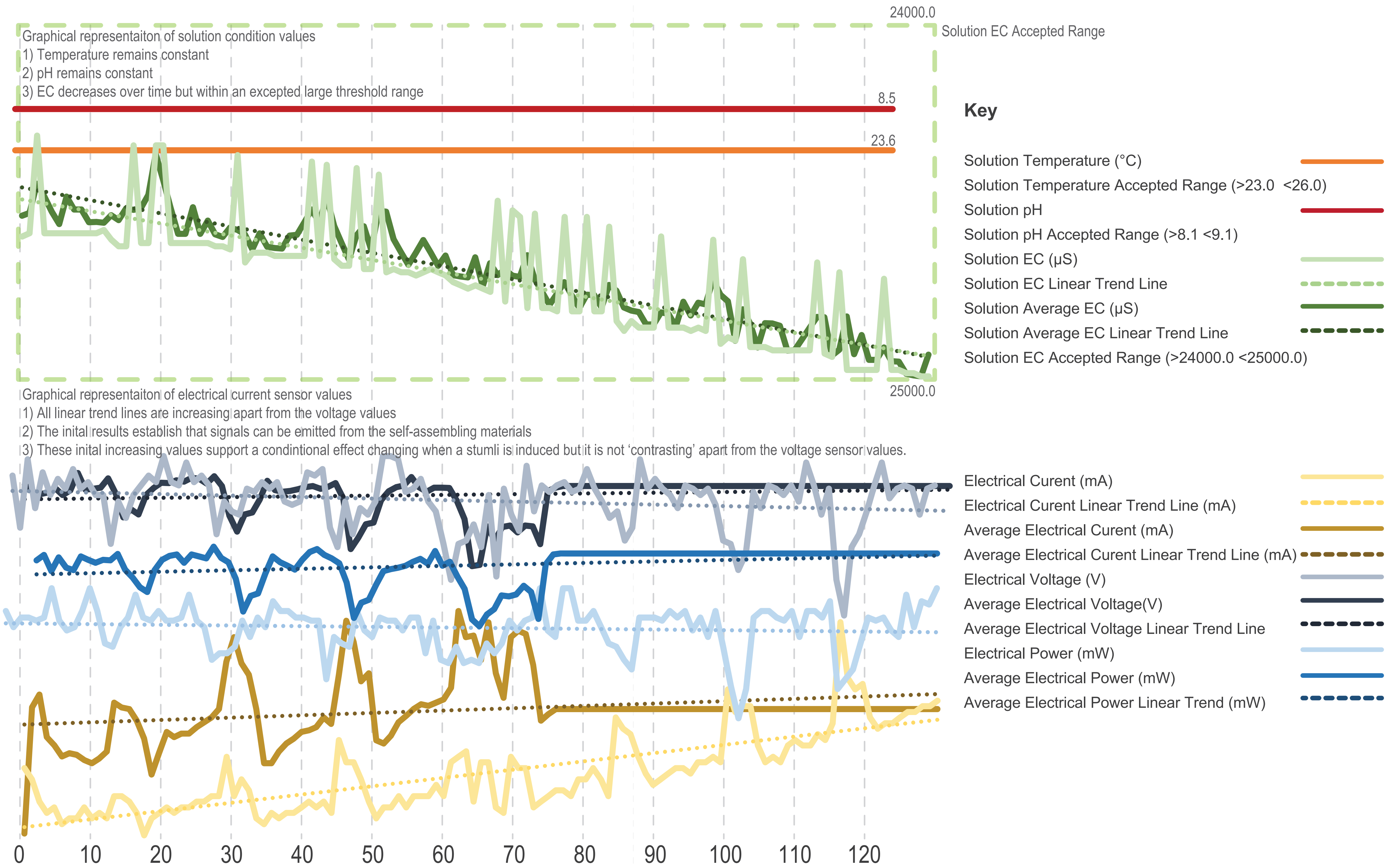


Figure 68: Graphical representation of sensor data for experiment 07A (smooth cathode). Material volume growth is not included as not significant amount was grown over 12 hrs. The sensor values also terminated after 2 hours due to a communication fault that occurred unexpectedly. However, these initial results highlight that electrical current sensor values generall increase overtime apart from voltage values, which do not contrast with the stimuli but support a condintional effect changing when a stumli is induced.

Table 10: Experiment 07B: sensor values relative to material growth volumes.

Time (hrs)	Av Material Volume (mm)	Av Current (ma)	Av Voltage (V)	Av Power (mW)	Av Solution EC (µS)	Av Solution pH	Temperature (°C)
0	na	0.00	0.06	0.0	34401	8.9	25.8
1	na	98.34	0.70	19.1	34349.8	8.9	25.6
2	na	99.00	1.04	101.6	34539.8	8.9	25.2
3	na	99.40	1.35	89.8	34526.0	8.9	25.5
4	na	99.31	1.01	71.5	34677.3	8.9	25.3
5	na	99.31	1.01	71.5	34694.8	8.9	25.9
6	na	99.31	1.01	71.5	34823.5	8.9	25.7
7	na	99.31	1.01	71.5	34938.5	8.9	25.7
8	na	99.31	1.01	71.5	35126.0	8.9	25.2
9	na	99.31	1.01	71.5	35137.3	8.9	25.7
10	na	99.31	1.01	71.5	35242.3	8.9	25.8
11	na	99.31	1.01	71.5	35296.0	8.9	25.1
12	na	99.31	1.01	71.5	35347.3	8.9	25.6

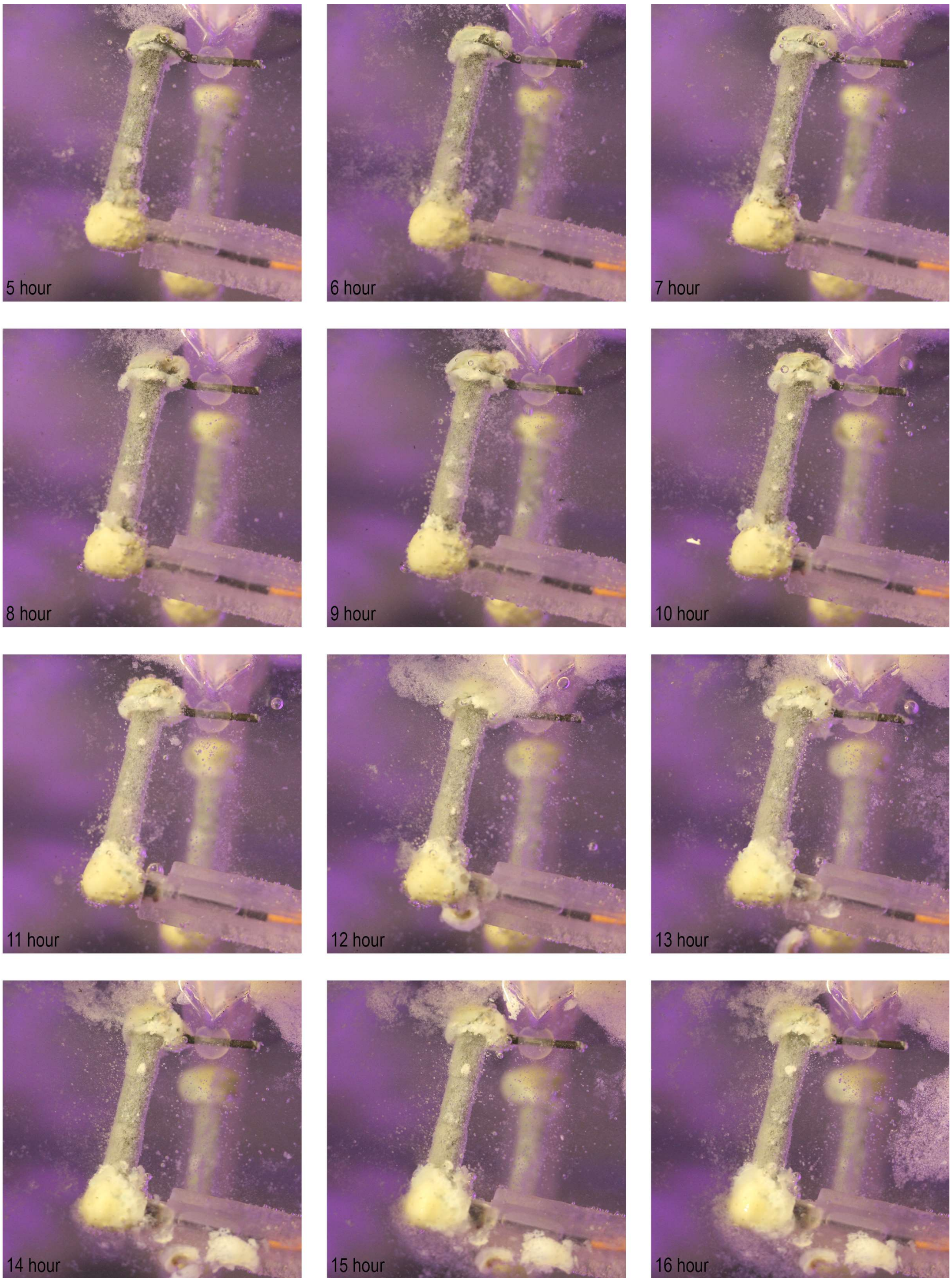


Figure 69: Series of images highlight the material growth that occurred within experiment 07B (rough cathode) over a 16-hour duration. The images highlight that over 16 hours minimal material growth occurs. The growth that does occur focuses at the ends of the cathode where the electrical wires are connected. This demonstrates that the cathodes material acts as a foundation and had a significant impact on facilitating and then supporting material growth. The inability of the carbon cathode to initiate and support growth irrespective of surface texture is highlighted by the largish chucks of material breaking away from 14 hours onwards. Link to time-lapse video: https://vimeo.com/user12085005/review/380372447/9f83e6d0bb

Figure 70: Graph combining real-time sensor data values and growth volume photographs for experiment 07B (rough cathode). Again, insufficient material volumes were grown to compare again sensor values. The electrical current sensor values show initially large fluctuations, but then average become steady after 3 hours. The solutions conditions remain somewhat constant apart from solutions EC which appear to increase almost linearly overtime. The linear increase of solution EC matches the steady linear increase in the voltage sensor values.

Table 11: Experiment 07C: sensor values relative to material growth volumes.

Time (hrs)	Av Material Volume (mm)	Av Current (ma)	Av Voltage (V)	Av Power (mW)	Av Solution EC (μS)	Av Solution pH	Temperature (°C)
0	na	96.63	0.31	74.3	42022.25	8.8	22.7
1	na	96.40	1.39	111.4	42061	8.8	23.2
2	na	93.23	0.47	46.8	42037.25	8.8	23.4
3	na	93.23	0.47	46.8	42063.5	8.8	23.4
4	na	93.23	0.47	46.8	42213.5	8.8	23.4
5	na	93.23	0.47	46.8	42249.75	8.8	23.4
6	na	93.23	0.47	46.8	42292.25	8.8	23.5
7	na	93.23	0.47	46.8	42354.75	8.8	23.7
8	na	93.23	0.47	46.8	42426	8.8	23.9
9	na	93.23	0.47	46.8	42496	8.8	24.1
10	na	93.23	0.47	46.8	42522.25	8.8	24.1
11	na	93.23	0.47	46.8	42519.75	8.8	24
12	na	93.23	0.47	46.8	42577.25	8.8	23.8
13	na	93.23	0.47	46.8	42646	8.8	23.7
14	na	93.23	0.47	46.8	42754.75	8.8	23.6
15	na	93.23	0.47	46.8	42781	8.8	23.5
16	na	93.23	0.47	46.8	42848.5	8.8	23.5
17	na	93.23	0.47	46.8	42928.5	8.8	23.4
18	na	93.23	0.47	46.8	43022.25	8.8	23.4
19	na	93.23	0.47	46.8	43039.75	8.8	23.4
20	na	93.23	0.47	46.8	43124.75	8.8	23.4
21	na	93.23	0.47	46.8	43567.25	8.8	23.4
22	na	93.23	0.47	46.8	43667.25	8.8	22.8
23	na	93.23	0.47	46.8	43844.75	8.8	24.2
24	na	93.23	0.47	46.8	43931	8.8	25.5

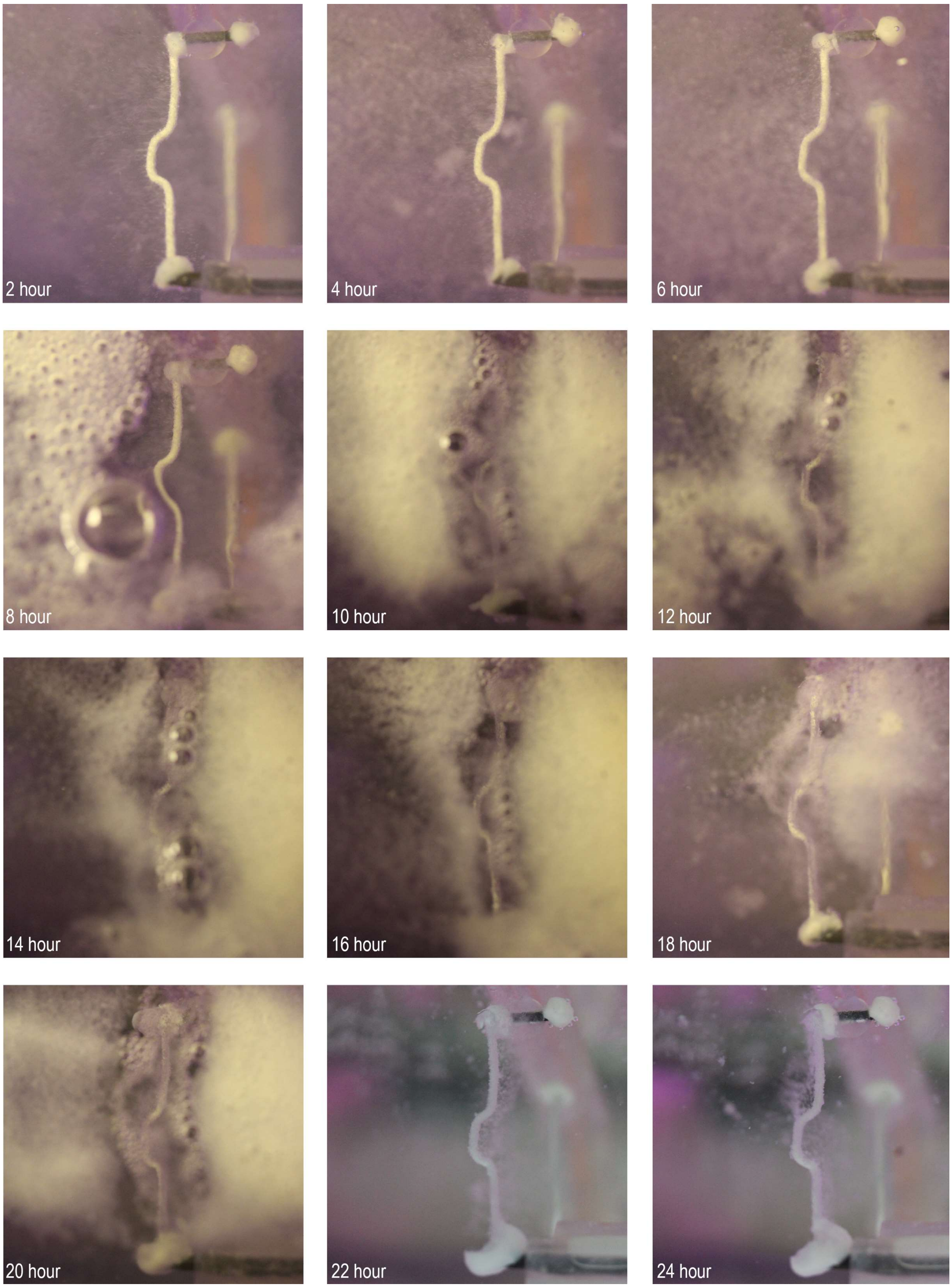


Figure 71: Again, over a 24-hour duration, insufficient material growth has been created to determine associations between senor readings and material properties generated. This highlights the significant role material assembly rate plays in being able to determine associations and informs possible applications of the materials potential adaptive abilities. The lack of material growth over all three experiments establishes that the design and fabrication process must centre around ensuring favourable conditions in order to grow materials, which means only inducing stimulus / energy doesn't strictly generate material self-assembly. Link to time-lapse video: https://vimeo.com/user12085005/review/380528892/37b9e051f6

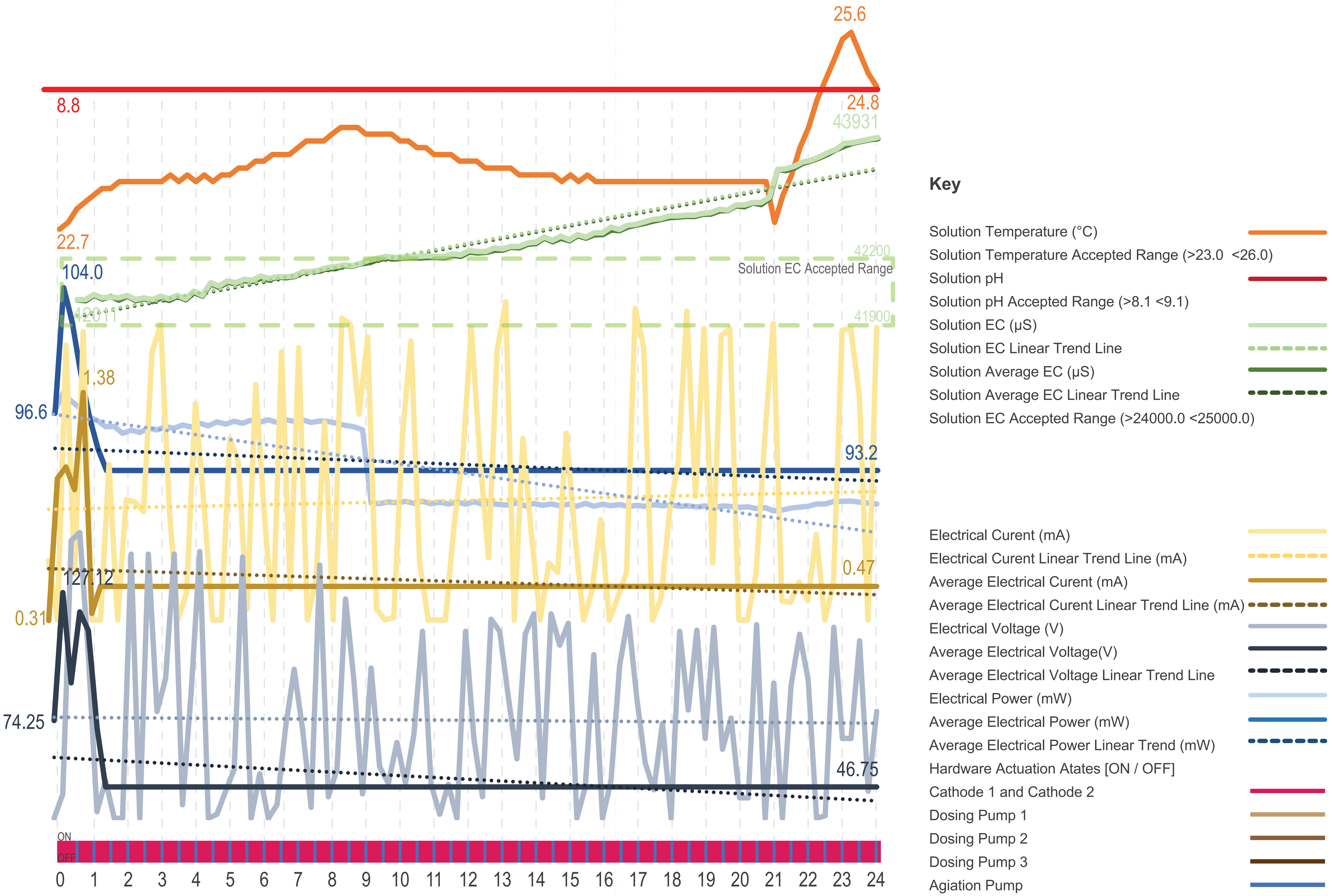


Figure 72: Graphical data representing real-time sensor data values for experiment 07C (aluminium cathode). The data highlights all electrical sensor values reduce as solution electrical conductivity increases, which is outside of the accepted range. The reducing electrical sensor values further highlights the impact the foundation / substrate material has on informing interrelationships within the system as these values are likely due to the aluminium cathode deteriorating as minimal material was grown upon the cathode.

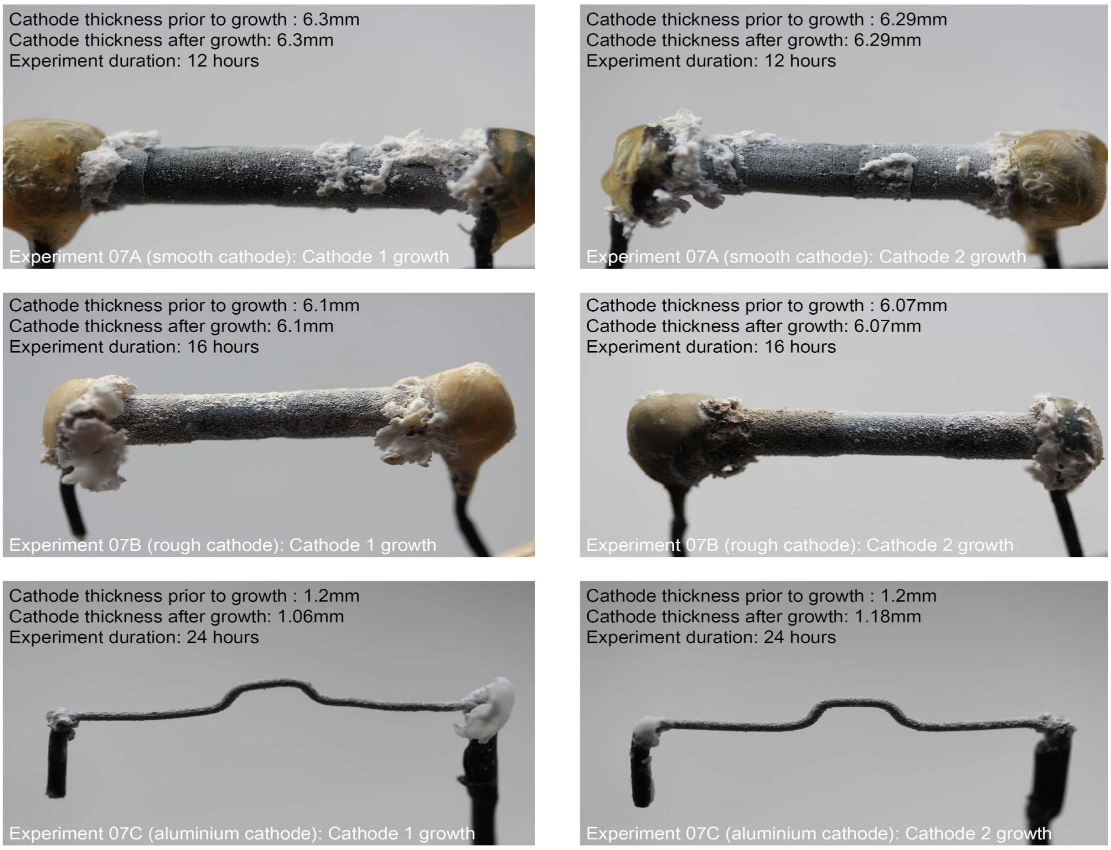


Figure 73: Macro photograph highlighting the very small amount of material grown and varied material properties generated with the various cathode materials. The images establish several factors: 1) that the cathode materials act as a foundational material and have a significant impact on being able to generate material growth, sustaining material growth and producing variable properties. 2) Carbon cathodes (top and middle row) are poor 'foundational' materials for supporting material growth irrespective of surface texture when compared to the volumes grown upon aluminium cathodes highlighted experiments 05 and 06 at similar durations. 3) Most material growth occurred at the ends off all the cathodes due to electrical current being focused at sharp edges or bends. 4) Cathode material composition informs material properties grown. The carbon cathodes have insulating material at the ends of them and significantly, did not fully inhibit material growth. Instead, smaller fine porous layers of material were produced, highlighting that transitioning / variable foundational material properties can be used to grow variable or gradient based self-assembling material properties. 4) Carbon cathodes did not deteriorate at all as their thickness remained the same unlike the aluminium cathodes destroyed in experiment 06 at much short durations and compared to the reduced thickness of the aluminium highlighted in the bottom row of photographs.

The results of experiment 07 are discussed individually in regards to the key factors and issues of each cathode type and sensor values generated. They are then expanded upon in the conclusion section by collectively analysing all of the results and properties, which reveal several possible key design principles and issues required for developing an adaptive design and fabrication system that can resembles a closed-loop control system when incorporating material scale self-assembly and complex interrelationships.

Experiment 07A (smooth carbon cathode): Data results

- Insufficient material growth occurred over 12 hours on the smooth carbon cathode to determine associations between material growth volumes and global variable resultant conditions and or local conditional changes highlighted by figure 67.
- The error in hardware communication resulted in a small sample size (see table 9) but highlights hardware communication must be robust to maintain sensor values throughout the fabrication process in order to monitor conditional changes.
- Based on the small sample size, resultant conditions of the solution electrical conductivity reduce over time but remain within a defined threshold range whilst the solutions pH and temperature remain constant (see table 9 and figure 68) meaning only agitation actions occurred.
- Figure 68 highlights the electrical current sensor values where only voltage values decrease overtime, which highlights only voltage could potentially be associated as a *contrasting condition* to the stimulus.
- Figure 68 highlights average voltage, electrical current, average current, power and average power values all increase overtime, which was not expected, but the increasing linear trend could still be associated to parameters of a design as the vary over time. These increasing sensor values could be termed as *parallel conditions* if associated to increasing material growth volumes.

Experiment 07B (rough carbon cathode): Data results

- Again, insufficient material growth occurred over 16 hours on the rough carbon cathode to determine associations between material growth volumes and global variable resultant conditions and or local conditional changes highlighted by figure 69.
- Table 10 and figure 70 highlights average power values decreasing overtime in this instance. Additionally, power and electrical current values vary drastically but their average values become stable after 3 hours and with the linear value showing a slight increase over time.
- Interestingly, figure 70 highlights both voltage and average voltage values increase as the solutions electrical conductivity gradually increases over time, which did not remain within defined threshold ranges. Highlighting the system requires significant calibration for future work.
- These electrical current sensor values do not have any correlation with experiment 07A, and begin to highlight multiple complex interrelationships.

Experiment 07C (aluminium cathode wire): Data results

- Again, insufficient material growth was generated during the experiment, which highlights the unpredictable nature of the process (see figure 71). Critically, the lack of growth on a cathode type that has previous enabled comparatively large volumes of material have been grown in previous experiments highlights that inducing a stimulus / energy does not solely dictate material scale self-assembly. Instead, favourable conditions must be ensured, which are based on interrelationships.
- Table 11 and figure 71 highlighting diminishing electrical current sensor readings for all of the values of current, voltage and power even as solution electrical conductivity increases outside of the accepted range. Highlighting, the impact the cathodes material has on interrelationships and conditional changes within the system as comparatively, the carbon cathodes electrical values all increased.
- The solutions electrical conductivity was well beyond the accepted range and no system action data was logged to show the dosing pumps preventing this proliferating condition, even though during testing all system actions were initiated if threshold conditions were exceeded. Again, this highlights the system must be robust enough to maintain communication to ensure favourable conditions can be maintained over long durations of time due to how slow the mineral accretion process occurs. Additionally, it also highlights that any component within the system that can induce a stimulus must be accounted for and can be related to one another, which becomes increasingly complex and highlights the limitations of direct associations within this system type.
- From a practical data acquisition point of view, the hydrogen bubbles forming at the surface obscured the view from above and would have made volume and analysis difficult. In order to address this surface must be cleaned of this resultant effect, which was achieved by placing filter pump tubing at this location.

7.15 Experiment 07: Conclusions

Analysing the results generated from experiment 07 has revealed several key design principles and issues required for developing an adaptive design and fabrication system that resembles a closed-loop control system. These principles are:

- **Foundational / substrate material properties**: The carbon cathodes material only enabled minimal material growth when comparing experiments 07A and 07B with experiment 05 and 06, which grew material over similar durations. Highlighting that the cathodes materiality acts as a foundational / substrate material within this system, which has a significant impact on material scale self-assembly.
- **Variable substrate materials**: The carbon cathodes had their ends insulated with silicone but at these locations material growth is focused and generated various material properties, from petal like to almost multiple barnacle like formations (see figure 73). The combination of the conductive cathode and insulating silicone reveal

the possibility to create cathodes with variable material properties, which could provide further control over grow desired material properties at specific locations.

- **Favourable conditions**: must be created in order to support and initiate material scale self-assembly, which is highlighted due to the lack of material growth over all three experiments. This establishes that tuneable environments be used to create favourable conditions and not just used to simply induce stimulus in order to grow materials as stimulus has not generated material growth. Significantly, this extends the energy component of the required ingredients to achieve self-assembly defined by Tibbits (*I - Materials and Geometry; II - Mechanics and Interactions; III - Energy and Entropy)* (Tibbits, 2016) in order to guide material scale self-assembly and material platforms with inherent interrelationships.
- **Maintaining favourable conditions**: Favourable conditions could be controlled more precisely within the system if all components that can induce a stimulus have feedback between one another as they impact on one another as well as the local conditional changes that support material growth and the global resultant conditions created within the solution. This is highlighted by the unintentional temperature increases of the solution, which affects the solutions EC and electrical current sensor readings.
- **Directly integrated sensors vs external sensors:** incorporating sensors externally to monitor local conditional changes for the cathode has resulted in large fluctuations and means a consistent sensor value cannot be used to directly associate it with stimuli parameters or potentially, material properties. Alternately, Hilbertz incorporated sensor directly around the cathode to determine growth volumes produced (Hilbertz et al., 1977) and potentially highlights that in order to accurately determine properties of material scale self-assembly sensors may have to be directly incorporated into the materials, if the materials are inert and or cannot self-sense of self-error correct. However, this could be due to intending to determine direct association between material properties, stimulus and, potentially design parameters. Potentially, exploring digital tools and processes that enable non-linear associations could address this issue and maintain the flexible benefits of incorporating sensors externally to the materials
- **Non-linear associations**: Due to the varied sensors values and lack of material growth generated no associations could be made that could be mapped to possible design parameters. However, experiment 07 highlighted the multiple interrelationships that exist within the system between stimulus, material properties, local conditional changes and global resultant conditions. Meaning, it would be extremely difficult to determine and capture all the complex relationships and creating associations that can map directly onto associative design tools / processes, such as parametric design based on linear associations i.e. cause and effect relationships. Instead, utilising design tools and process that can be based on non-linear associations (Richards and

Amos, 2016) would be more appropriate as they can be used discover complex interrelationships.

7.16 Experiment 07 Future Work

There are three main areas of future work that can be extended based on the experiments up to this point. *Firstly,* incorporating digital design tools to finally create and adaptive design and fabrication system. *Secondly,* exploring 3D / volumetric growth. *Thirdly,* how to begin to move away from the predefined scaffolds structures, which forms the basis for the following experiments explored in chapter 8.

7.16.1 Incorporating Digital Design Representations

The intention was to incorporate a digital parametric design tool to represents the physical set-up of experiment 07 and govern parameters of stimulus by determining if direct association can be made from the results of experiment 07 (figure 74). For example, using a numerical slider to increase a cylinder's radius would represent material volumes to be grown, which would induce the stimulus (voltage) for comparatively longer periods of time until a corresponding electrical current sensor reading was consistently detected, then the stimulus would be stopped. However, the digital parametric design tool was discarded as it was intended to be used to create an adaptive design and fabrication system after reviewing the results of experiment 07. It was discarded due no direct associations becoming apparent within experiment 07 results as: A) no growth volumes were created and B) the electrical current sensor data varied significantly. Comparatively, persistent modelling and the material system used by Ayres enables a direct association, as metal sheets are deformed by expanding them by controlling and monitoring pressure via a digital design representation (Ayres, 2011). However, the direct associations become limited up to a material threshold, where materiality plays a significant role and the design representation and associations cannot account for local material deformations (Ayres, 2012a). These issues highlight a converging factors of resolution of associative parametric design tools becoming limited as they are:1) based on direct associations and 2) are based on boundary representations, which means physical material properties are treated as homogenous (Richards and Amos, 2016). These points highlight a converging problem for the lack of materiality being accounted for within digital representations and design processes based on liner / direct associations between parameters and becomes more apparent if the materials used can self-assemble on the material scale and have inherent interrelationships.

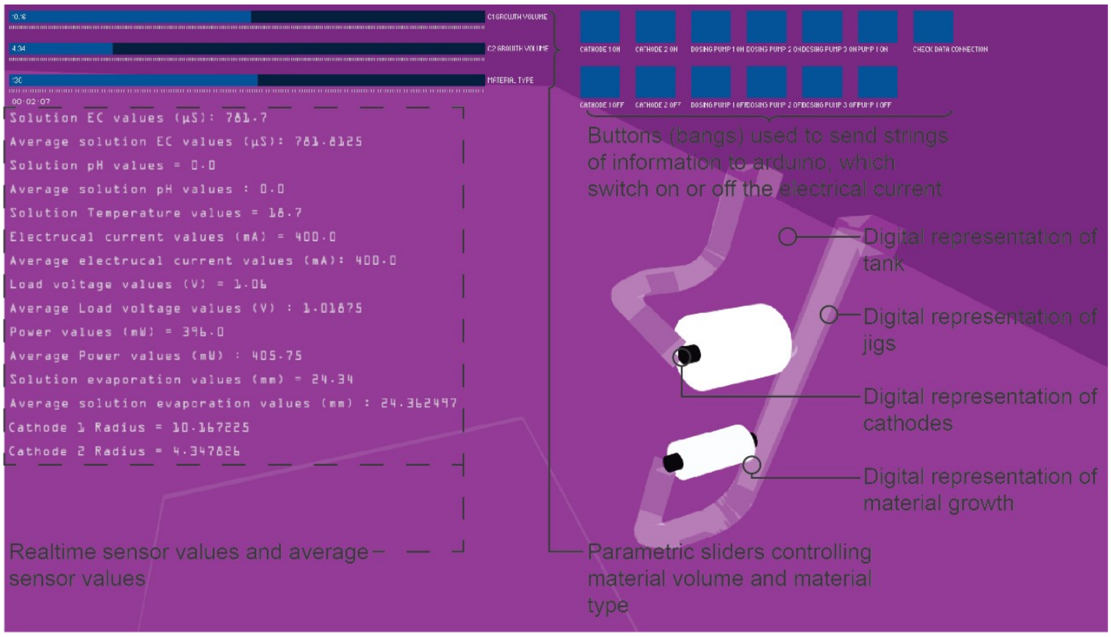


Figure 74: Interface of the proposed digital parametric design tool to be used govern parameters of material growth. The parametric design tool was discarded due to the direct associations required, which are not apparent in the results generated in experiment 07.

In order to address these problems three main strategies could be employed within future work. These are: 1) incorporate hardware that is capable of being incorporated into a system that is based on machine learning, such as the recent arduino nano BLE 33 sense. 2) Incorporate material based computation design tools (Oxman, 2010b, Oxman, 2011b, Oxman et al., 2011, Bader et al., 2016a, Richards and Amos, 2016, Richards et al., 2017), which can account for locally variable material properties as they are not based on boundary representations used within the parametric design tools used in these experiments. 3) Utilise digital design strategies and tools do not require pre-defined relationships or direct associations between parameters i.e. the relationships can be non-linear, enable the system to generate its own associations and interrelations(Richards and Amos, 2016). Meaning, the multiple environmental conditions and the effects could be engaged with and controlled with more freedom but more accuracy in terms of how the guide material properties during the mineral accretion process.

7.16.2 3D Growth

The majority of the experiments carried out within this research using the mineral accretion process have been carried out within 2D predominantly, especially for the experiments using physically separated cathode wires. Meaning controlling variable material properties within a 3D volume has not been defined or explored. Figure 75 documents a preliminary experiment that demonstrates that variable material properties can be controlled within a 3D scaffold.

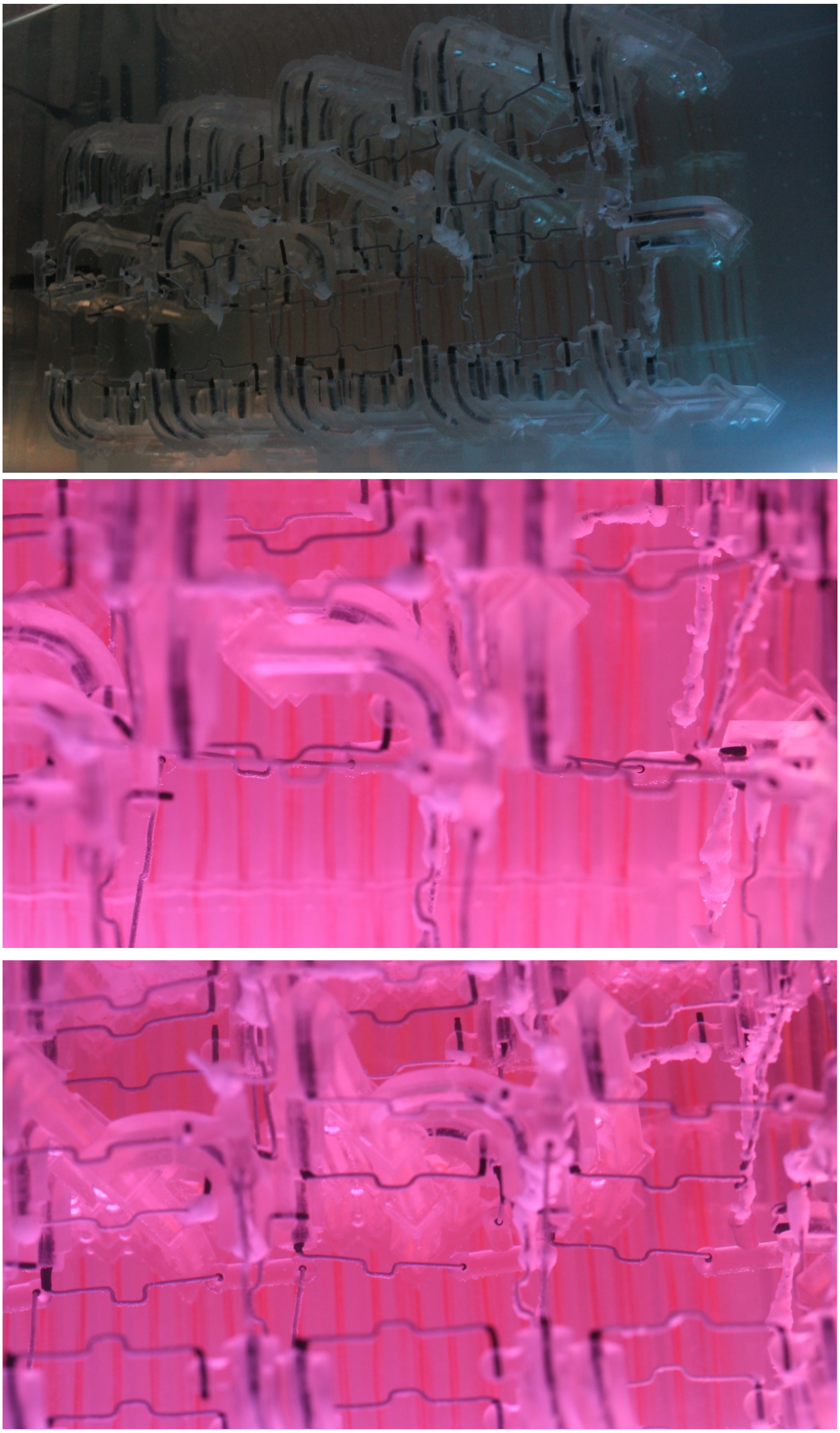


Figure 75: A preliminary experiment establishes volumetric material growth is possible with locally variable properties. The cathode scaffold is made up of 96 aluminium wires.

7.16.3 Challenges: Self-Assembly Without Scaffolds & Rapid Durations

Two major limitations within the series of mineral accretion experiments is the fact the material growth and the global adaption of the shape is restricted to the cathode scaffolds dimensions and resolution as well as occurring over very long durations of time. For example, the pixelated heart shape grown in experiment 04 and the long time durations taken to grow small volumes of material. However, the mineral accretion experiments have established that *tuneable environments* can be used to guide properties of material scale self-assembly. This raises the question; *how can tuneable environments be used to guide other forms of material self-assembly to generate and guide 2D and 3D patterns rapidly and without the need for scaffolds?*

This question is explored in the next three experiments in the following chapter. Importantly, the flowing experiments do not look to determine associations to establish feedback between design representation, material properties, stimuli induced and resultant conditions generated based on inherent mechanism within the material platform. The following experiments explore how patterns can be manipulated over shorter periods of time using *tuneable environments*, in both two and three dimensions, without the need for restrictive scaffolds.

7.17 Chapter Summaries

Key areas points from each mineral accretion experiment section are briefly summarised below.

Cathode Typologies / Properties.

- Physically separated cathode components enable localised material properties.
- Cathodes can be composed of variable materials (from conductive to insulating) to enable greater control over the material properties generated.
- Based on the preliminary experiment it is possibly to grow 3D forms and patterns within a 3D physically distributed cathode network, which could lead to

Open-Loop Control System

- Stimulus enables a discourse between digital design tools, fabrication, material scale self-assembly and material properties
- Parameters of a stimulus mapped to material properties (e.g. stimulus duration informs growth volume) can be controlled via analogue or digital means by incorporating hardware.
- Predicting growth durations to grow desired volumes based on preliminary experiments is not reliable as the process is not linear. Feedback is needed.
- Interrelationships and resultant material effects / properties must be associated in order to build towards a closed-loop control system.

Closed-Loop Control System

- Arduino communication and sensor readings are more reliable when carried out over two separated connections.
- Favourable conditions must be created and maintained in order to initiate and sustain material scale self-assembly, which extends the role energy plays within the required design parameters in order to achieve self-assembly defined by Tibbits (Tibbits, 2016).
- When utilising that material platforms that self-assembly on the material scale and inherently have interrelationships between conditions and material properties direct association become extremely limited as they cannot account for all of the complex interrelationships generated. Making associative modelling processes (design representations) redundant and builds a case for utilising design tools based on non-linear associations.

Development & Future Work

- The design and fabrication methodology of tuneable environments in combination with contrasting effects will be explored in three final experiments to test how they can guide other material platforms and their computational processes.
- Future work could incorporate more sophisticated design tools to determine non-linear relationships between environmental conditions and more delicate material properties so they can be adapted with greater sensitivity, such as surface texture.

8 Contrasting Materials: Moving Away From Scaffolds

The chapter is split into three sections for three separate experiments. The three experiments develop from 2D, into 3D and the material platform is based on either; high flow acrylic paints + additives (e.g. silicone or isopropyl alcohol) or acrylic inks and volumes of various support materials, such as water, oil, sugar syrup or vegetable glycerine. The order of the sections are;

- *Firstly,* Experiment 08: *Generative Recipes* explores how 2D paint patterns are generated based on mechanisms (e.g. gravity, evaporation, displacement) between the recipe's ingredients. The results give rise to the idea of contrasting materials acting as '*semi-rigid scaffolds'*.
- *Secondly,* Experiment 09: *Contrasting Interfaces* is a small experiment which explores how 3D acrylic ink diffusion can be delayed via a contrasting support material interface.
- *Thirdly,* Experiment 10: *3D Ink Diffusion* explores how different volumes of support material (e.g. water, syrup or vegetable glycerine) can inform 3D ink cloud patterns. The support materials are agitated using pumps to manipulate the cloud patterns. The experiment highlights how different support materials generate multiple material properties over a range of times.

The series of experiments within this chapter are used to explore the idea of creating *tuneable environments* to guide material scale self-assembly without the need for rigid scaffolds. Rephrasing this aim as a question; *how can tuneable environments guide material scale self-assembly without requiring constraining scaffolds?* Due to this main aim and the established feedback within the mineral accretion experiments, these paint and ink experiments are not concerned with establishing feedback between; material properties generated, stimuli and design tools. Essentially, all of the experiments and systems developed are *open-loop control systems*. The material platforms (inks and paints) used in the experiments test the robustness, limitations and application potentials of *tuneable environments.* Finally, speculations and possibilities are discussed on how feedback could be achieved between the system's components (digital design tools, stimuli and material properties) and what these freer forms of 3D material scale self-assembly may lead towards.

8.1 Generative Paint and Volumetric Ink Diffusion Overview

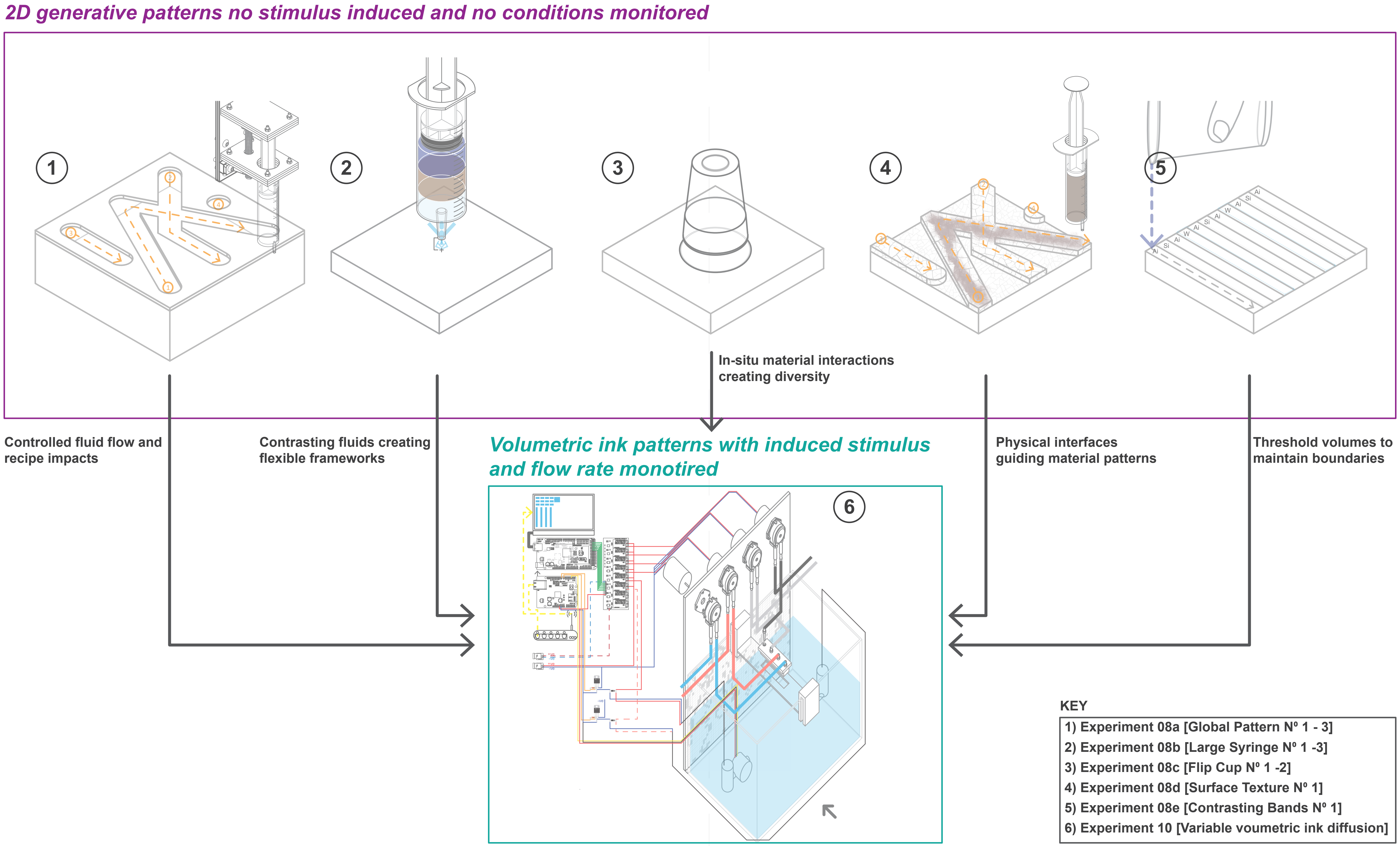


Figure 76: Overview of the multiple 2D generative paint experiment and the 3D ink diffusion experiments.

8.2 Generative Recipes Overview: Moving Away from Scaffolds

The 2D generative paint recipe and 3D ink diffusion experiments are simply explored as a means to understand how to move away from the restrictions of the cathode scaffold structures within the mineral accretion experiments, whilst still examining the role stimulus can play within these material platforms. Both of these experiments are not intended to establish feedback between design, fabrication or material properties.

8.3 Experiment 08: Generative Recipes

The *'Generative Recipes'* experiment proposes to creatively explore material scale self-assembly using tuneable environments via generative 2D paint patterns. The paint patterns are generated by varying the recipes ingredients, which are comprised of various ratios of coloured high flow acrylic paints that have varying densities, flow / pouring mediums (liquitex or floetrol) and additives (silicone or isopropyl alcohol). The ingredients induce material mechanisms (e.g. isopropyl alcohol induces evaporation), which impact on the patterns generated. Additionally the means in which the paint recipes are deposited also impact on the patterns generated. .

Significantly, these paint recipes attempt to explore self-assembling patterns from the perspective of energy in the form of mechanisms that occur between the additives and paints. The experiments will help to understand how stimulus (energy) can be used to induce, guide and tune material mechanisms that inform pattern generation. Notably, Tibbits defines *energy and entropy* as one of the three required ingredient to achieve self-assembly, the other two being: *I Materials and Geometry and II - Mechanics and Interactions* (Tibbits, 2016). The following experiments within this chapter attempt to explore energy and entropies impact on pattern generation as the predominant approach within an architectural research context has focused on the first two ingredients by defining the material units geometries and connection interfaces (Hensel and Menges, 2008, Dierichs and Menges, 2012, Dierichs et al., 2012, Tibbits and Flavello, 2013, Tibbits, 2014b, Angelova et al., 2015, Dierichs et al., 2015, Dierichs and Menges, 2015, Aejmelaeus-Lindström et al., 2016, Dierichs and Menges, 2016, Keller and Jaeger, 2016, Murphy et al., 2016a, Rusenova et al., 2016, Dierichs and Menges, 2017b, Papadopoulou et al., 2017, Murphy et al., 2017a). Additionally, defining the local and global material properties of a structure via 3D printing technologies or material lamination, enables defined responses to environmental conditions, such as bending, twisting and folding up (Raviv et al., 2014, Tibbits, 2014a, Tibbits et al., 2014, Correa et al., 2015, Menges and Reichert, 2015, Reichert et al., 2015, Wood et al., 2016, Dierichs et al., 2017a, Wood et al., 2018).

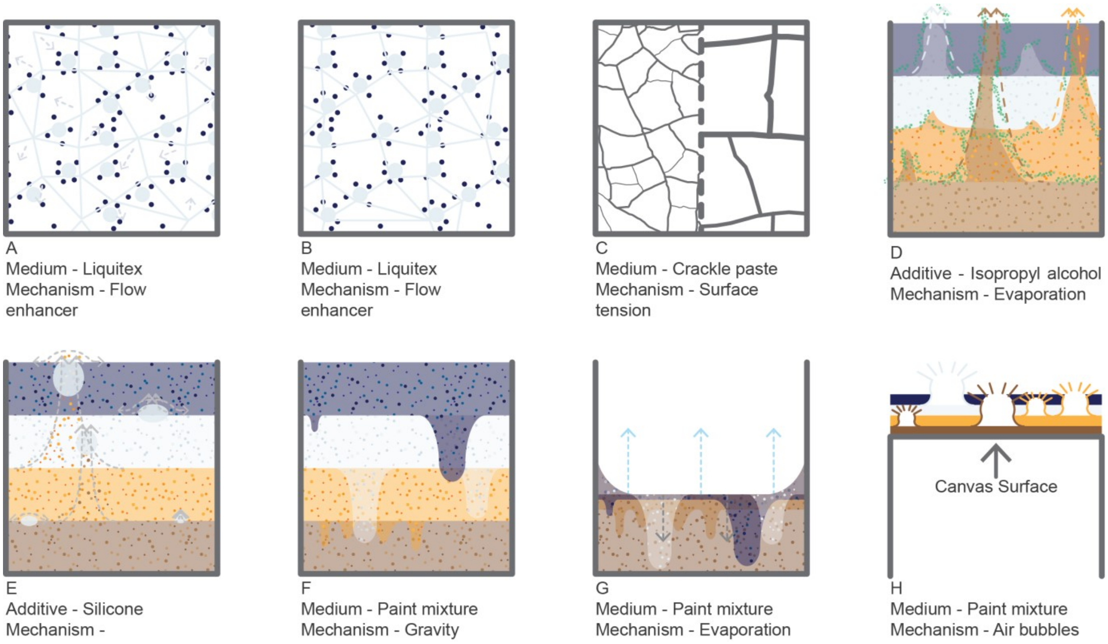


Figure 77: Highlights a occurring between paints, additives, stimulus (evaporation, gravity, air pockets bursting) and interfaces.

These experiments attempt to define conditions and or parameters which form the major factor for generating patterns' local or global properties. This is done by recording and evaluating the patterns and effects generated (via photography and videography) by the recipes. Additionally, these initial experiments can be used to inform what material parameters of the patterns generated could be tuned using the tuneable environments strategy. Understanding these interactions and how they can be guided by manipulating environmental conditions highlights how tuneable environments can be extended without the need for constraining scaffold frameworks. Removing the scaffolds could lead to novel material abilities and technologies, such as extending the layer-by-layer approach of 3D printing technologies by basing them on and manipulating volumetric diffusion of materials. Critically, these material abilities and novel technologies could be leverage by re-thinking fabrication process by engaging with material computational process and mechanisms.

8.3.1 249Experiment 08: Properties

The generative paint experiments will be carried to explore how multiple 2D patterns can be generated by changing the ingredients and ratios within the paint mixture recipe. Essentially, various colours of high flow acrylic paint, which have various densities, are mixed with flow mediums and additives (silicone and or isopropyl alcohol), which make up the recipe's ingredients. The 2D patterns generated will highlight what the effects of the ingredient are as well as the impact of how the paint recipe is deposited on the canvases. Figures 78 - 82 document the various methods in which the paints will be deposited in experiment 08.

The general method for depositing the paints was done by creating a syringe system to ensure a consistent flow / deposition rate across similar paintings that only explored the impacts of the ingredients. The components of the syringe system are described in greater detail within the diagrams. The paint mixtures will be deposited onto 152x152mm deep edge canvas, which will be primed with 2 coats of white gesso to create a smooth surface. The canvases will be levelled using a digital spirit level to try and limit the impact of gravity, which will result in the paint mixture flowing to the lowest level of the canvas. Once all of the paint is deposited the canvas will be handled in a set routine to move the paint across the entire surface of the canvas (if needed).

Various recipes are used for all for the paintings within the experiment in order to understand their impacts, as well as the impacts of how the paint is deposited on 2D pattern generation. Table 12 documents each of the paintings recipes and helps to clarify: 1) the paintings ingredients and properties (volume, paint colour and additives) and order in which the paint mixture is deposited. 2) How the mixture is deposited; either by syringe or by cup. 3) The location and the volume of mixture deposited. 4) The order of the paint layers, which is determined by the paint's densities with the heaviest paints stacked on top of one another so they would sink into each other due to gravity.

Table 12: Generative paint recipes

Experiment 8 Break down	**Ingredients**	**Colour order**	**Deposition Method**
Global Pattern No 1	30ml Fl + 3ml W + 2ml + AP + 1ml Si	BU, TY, TW, PG (9ml per path)	Syringe with template
Global Pattern No 2	25ml LQ + 4ml IA + 4ml W + 2ml AP +1ml SI	BU, TY, TW, PG (9ml per path)	Syringe with template
Global Pattern No 3	30ml LQ + 4ml IA + 2ml + AP	BU, TY, TW, PG (9ml per path)	Syringe with template
Large Syringe No 1	15ml LQ + 2ml AP	TW, PG, TY, BU, IC, 5ml SI (all at once)	Syringe at centre point
Large Syringe No 2	15ml LQ + 3ml IA + 2ml AP	TW, PG, TY, BY, IC (all at once)	Syringe at centre point
Large Syringe No 3	15ml LQ + 3ml IA + 2ml AP	TW, PG, TY, BY, IC (all at once) (@160°C for 60sec)	Syringe at centre point
Flip Cup No 1	15ml FL + 3ml W + 1ml AI + 1ml IA + 1ml SI	All at once - paints deposited into cup	Flip cup at centre point
Flip Cup No 2	30 ml FL + 2ml W + 2ml AP	All at once - paints deposited into cup	Flip cup at centre point
Surface Texture No 1	30ml FL + 3ml W + 2ml AP + 1ml SI	BU, TY, PG, TW (9ml per path)	Syringe + template
Contrasting Bands	8ml FL + 1ml W + 1ml AI	All at once - paints deposited into cup	Cup pour + template

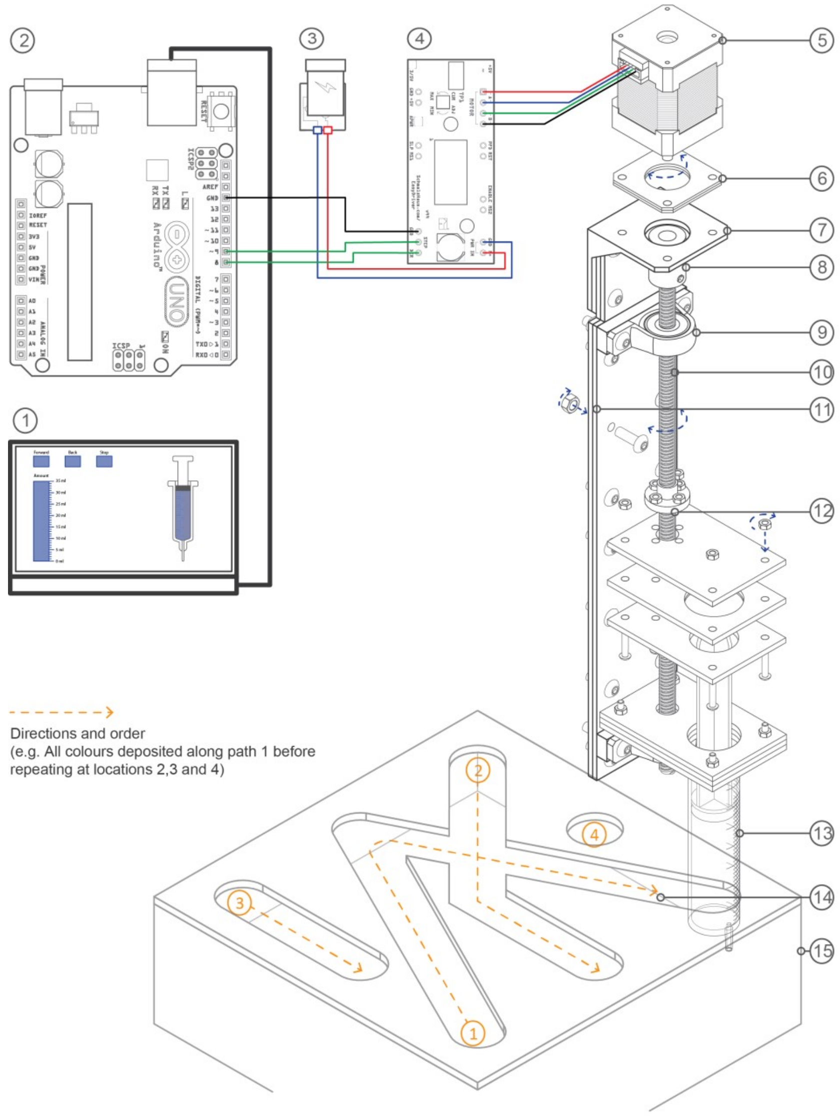
*Tab key: **FL** = Floetrol, **LQ** = Liquitex, **AP** = Acrylic paint, **SI** = Silicone, **IA** = Isopropyl Alcohol, **W** = Water. **Golden high flow acrylic paint colours key**: **AP** = Acrylic Paint, **BU** = Burnt Umber, **TY** = Transparent Yellow, **TW** = Titanium White, **PG** = Paynes Grey, **IC** = Iridescent Copper Light, **MG** = Manganese Blue Hue, **QM** = Quinacridone Magenta. **Liquitex and FW Acrylic Ink**: **AI** = Acrylic Ink, **CB** = Carbon Black, **TW** = Titanium White, **FB** = Fluorescent Blue, **BC** = Birdwing Copper*

In order to further ensure the environmental conditions are the primary contributors to generating the effects several other factors are maintained; A) the recipes mixture is deposited using a syringe system to ensure flow rate is consistent. B) The mixture is deposited onto a level canvas. C) Once all the mixture is deposited the canvas is only tilted (in a set routine) so as to move the paint across the whole of the canvas surface if needed. D) A change in temperature or introducing additional additives in-situ have been used to determine how varying materials or conditions can be used to manipulate resultant textures, patterns and effects.

A brief description is given below for how a selection or each painting is generated along with the various interactions and mechanism the paintings explore;

- **Paintings A - C:** 9ml volumes were deposited in layers using a mechanical syringe system over a global pattern and explore how global patterns are affected by varying recipe viscosities by increasing additive volumes (see figure 78).
- **Paintings D - F:** sucks up each volume of paint then deposits all of them in one go at the canvas centre via syringe. They explore the importance of where material interactions occur and the robustness of the additives (see figure 79).
- **Paintings G - H:** shots of paint are first deposited into a cup at set locations. A video link is provided below several paintings that also highlight the process, the interactions and results. The cup is then turned upside down at the canvas centre. This explores how patterns are generated in-situ when the materials introduced to one another within a volume (cup) by layering them (see figure 80).
- **Paintings I:** is deposited the same as experiments A-C but explores how the varied surface textures guide's material flows (see figure 81).
- **Paintings J,** paint is deposited into a cup the same as experiment G, but then poured along the defined stripes, silicone stripes are created before this. Isopropyl alcohol and water is then deposited in stripes next to the paint to explore how material boundaries interact (see figure 82).

A video link is noted here as well as at the end of the results to help clarify the set-up as well as interactions generated. Video links for several experiments: https://vimeo.com/270687667 https://vimeo.com/270696373 https://vimeo.com/273500850



1) Processing interface used to control stepper motor
2) Arduino connected to laptop via USB for serial communication
3) External power supply (12 volts supplied)
4)A3967 stepper motor controller PCB - v44 Easy Driver
5) Nema 17 stepper motor 59 Ncm (Bipolar)
6) 2 mm nema17 stepper motor anti vibration cork dampers
7) 42 mm L bracket mount for nema17 stepper motor
8) Nut coupling between nema motor and lead screw
9) Shaft bearing mount set
10) T8 trapezoidal lead screw rod
11) 3mm acrylic bolted together
12) Brass flanged round lead screw nut
13) 35 mm syringe (inter-changeable)
14) 152 x 152 mm deep edge canvas
15) Global pattern cut from 3 mm acrylic

Figure 78 Experiment 8a - global pattern. The experiment deposits the paint mixture across a template pattern using the syringe system. 3 different paint recipes are deposited. The paints are deposited in the order of the least dense paint first with the most dense paint last. The paints are mixed in cups. 9mls per path per deposition are sucked up by the syringe system by reversing the motor and then deposited. The direction and amount is controlled using a digital interface created using processing. The experiments examine the effects of paint order and ingredients on global patterns.

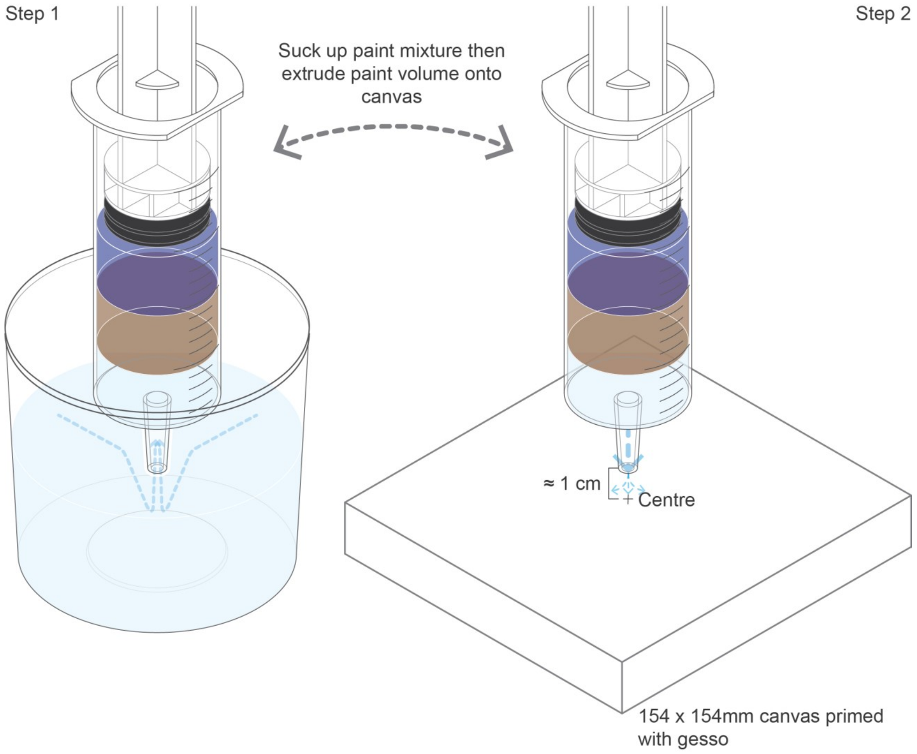


Figure 79: Experiment 8b - large syringe. A large syringe is fitted to the syringe system as it is modular. Similar to experiments 8a paint mixtures a series of paint colours are sucked into the large syringe with the densest paint colour first this time as that will be the colour to be deposited last. 17ml of the mixture is sucked up per colour with a total of 85ml's plus 5ml silicon lastly. All of the mixture is then deposited all at once from the syringe at the centre of the canvas. The experiment examines the impact of how the paint is deposited.

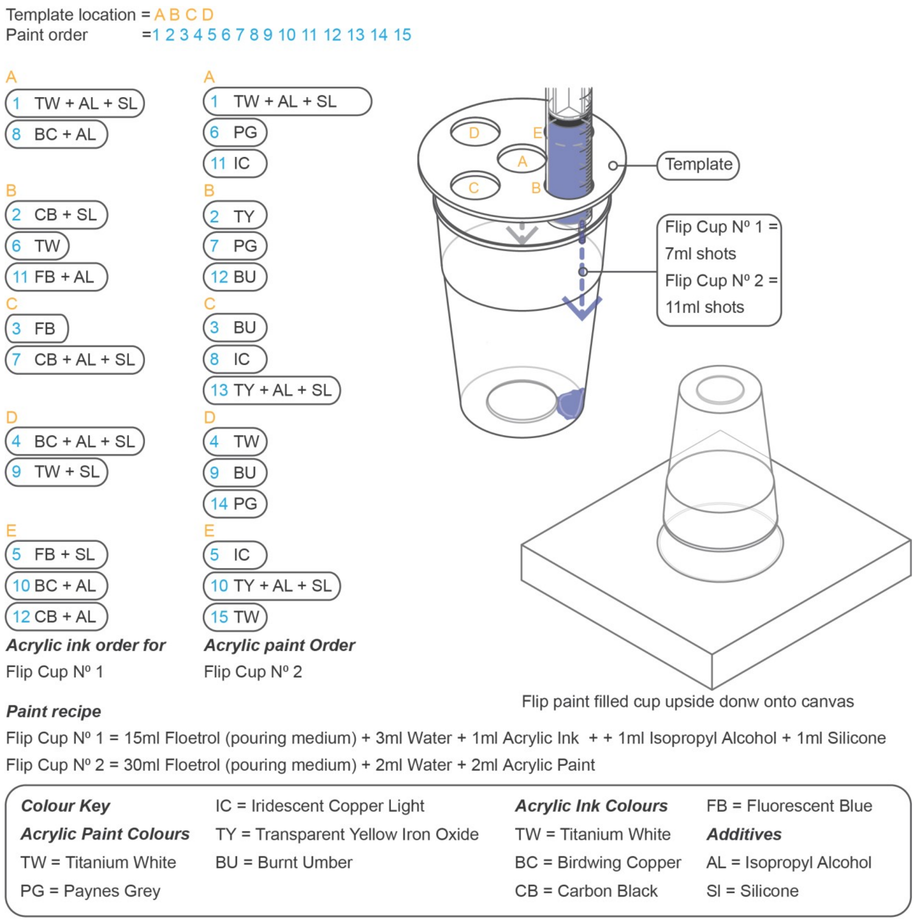


Figure 80: Experiment 8c flip cup. Again various paint mixtures are deposited via a syringe but by hand into a large plastic pint cup. 11ml of paint is deposited each time in certain orders and locations along with. 1ml additive is added at various locations and orders. The location the paints and additives are deposited into the cup is kept consistent through the use of a jig. The canvas is then placed on top of the cup and then flipped upside down. The cup is the lifted off of the canvas, after 1 minute, to allow the paint mixture to flow across the canvases surface. The experiment examines the impact of how the paint is deposited.

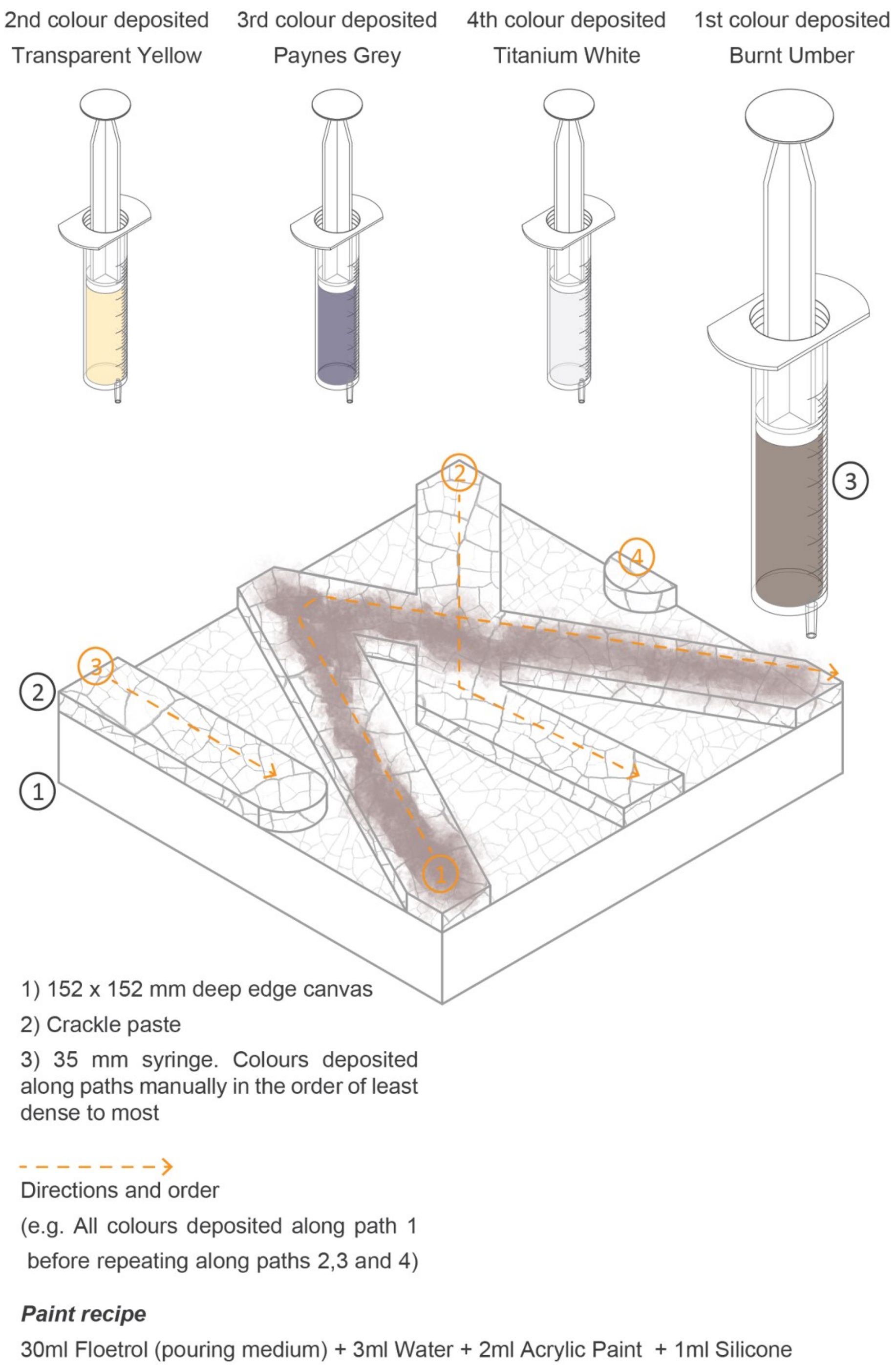


Figure 81: Experiment 8d surface texture. Similar to experiment 8a paint mixtures are deposited along a global path in order of least dense to most per path order. However, it is done manually. 2 variations of surface texture were created using crackle paste. First a thin layer is spread across the whole of the canvas using a palette knife, which results in lots of very fine cracks. A second 4ml thick layer was spread in the shape of the global pattern; this was done by using the template from experiment 8a. The thick layer generates fewer crack but they are much larger and more separated. The experiment examines of surface textures and physical interfaces can impact pattern generation.

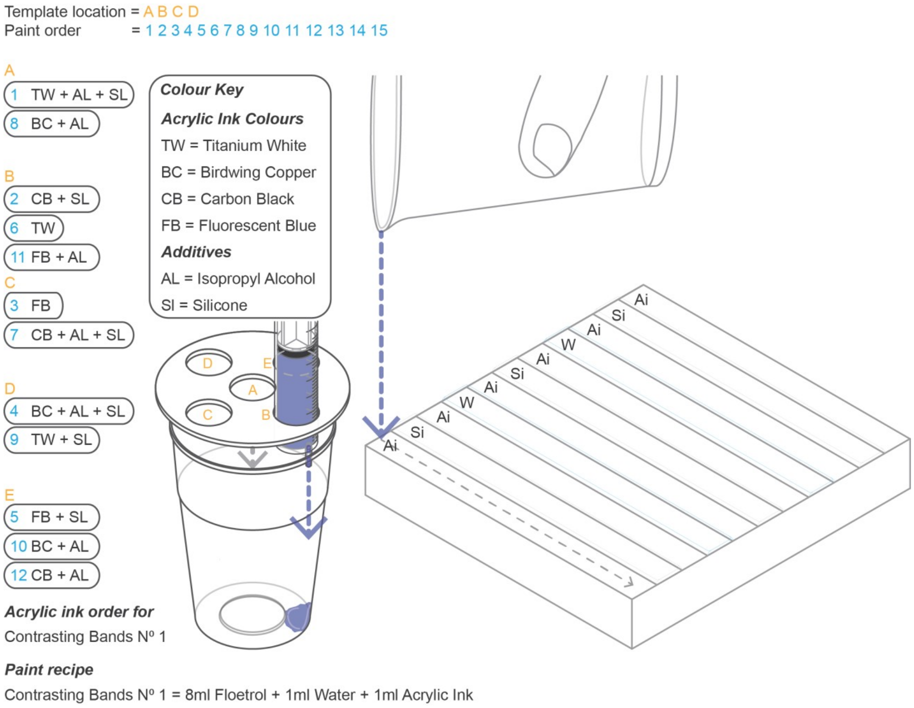


Figure 82: Experiment 8e contrasting bands. The canvases surface is separated into alternating bands where paint mixture, water, isopropyl alcohol and silicone will be place. Firstly, prior to depositing the paint from the cup 5ml of silicone is spread across its defined bands using a palette knife. This is because it repels the water based paint and needs to be placed first. Secondly, the paint mixture is then poured from a cup into the bands without silicone. Similar to experiment 8c paints are deposited into a cup. Thirdly, 5ml of water and then 5ml of isopropyl alcohol is then deposited in their defined bands. The experiment examines if defined pattern boundaries can be created and maintained using contrasting mediums prior to introducing paints and also the impacts on boundary patters by introducing disruptive materials (water and isopropyl alcohol).

8.4 Experiment 08: Results

The results are documented as a series of images, which reveal the effects and patterns generated in two dimensions (see figures 83 - 90). Table 13 describes the most significant effects across global and local scales. Videos of the 2D paintings further reveal the dynamic material interactions and pattern formations. A discussion for how the 2D patterns are generated is now given along with reflection on how they reveal new ways to guide self-assembly. These 2D experiments have informed experiments 09 and 10, which seek to create more elaborate 3D structures and volumetric patterns, which are then physically augmented via digital design tools.

Table 13: Description of 2D generative paint recipe results (Room temperature and pressure = R T&P)

Painting reference	Global effect	Local Effect	Stimulus
A	Global pattern lost	Defined boundaries	R T&P
B	Vague global pattern	Crazing	R T&P
C	Vague global pattern	Granulation + small voids	R T&P
D	Homogenous colour	Large + small voids	R T&P
E	Homogenous colour	Shallow indentations	R T&P
F	Homogenous colour	Surface folds	160°C for 60 seconds
G	Diverse streaks and cells	Granulation, bands + cells	R T&P
H	Diverse bands and streaks	Uniform cracking + granulation	R T&P
I	Random cracks + global pattern lost	Pools and streaks of colour	R T&P
J	Defined and undefined Bands	Defined boundaries next to Silicone	R T&P

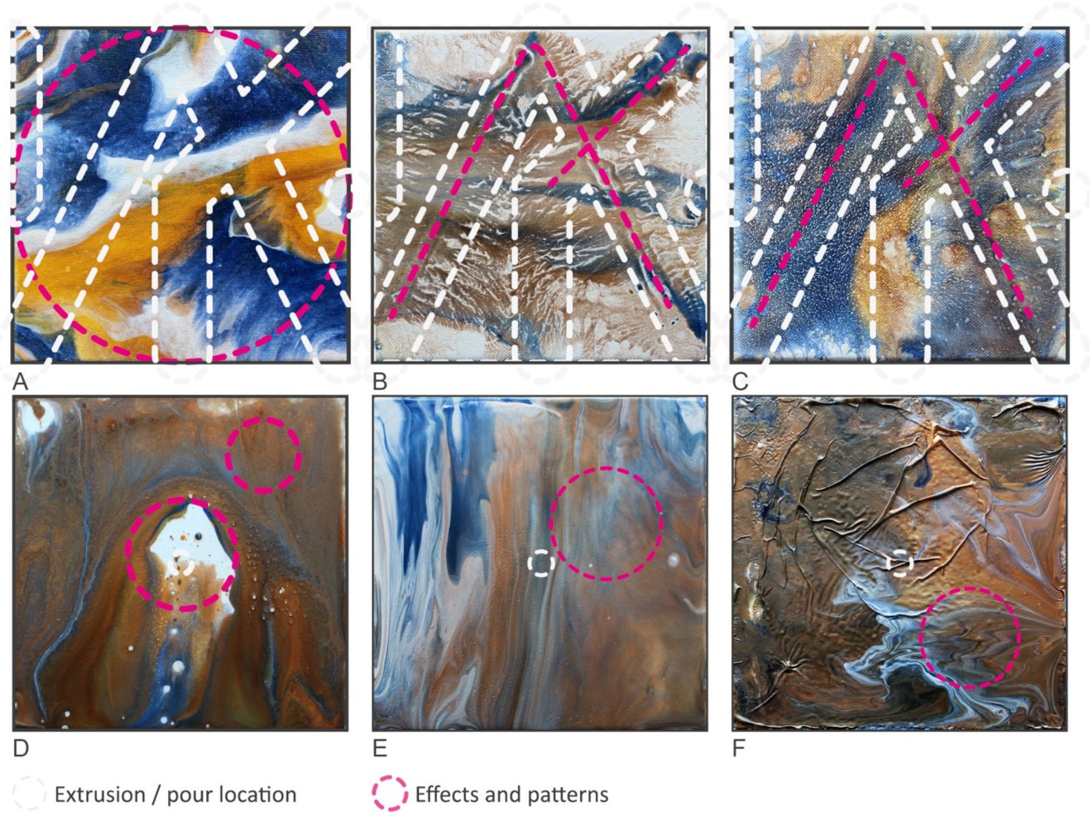


*Figure 83: 2D paint experiment photographs highlight the diverse range of effects achieved. **A - J**) reveal the global patterns.*

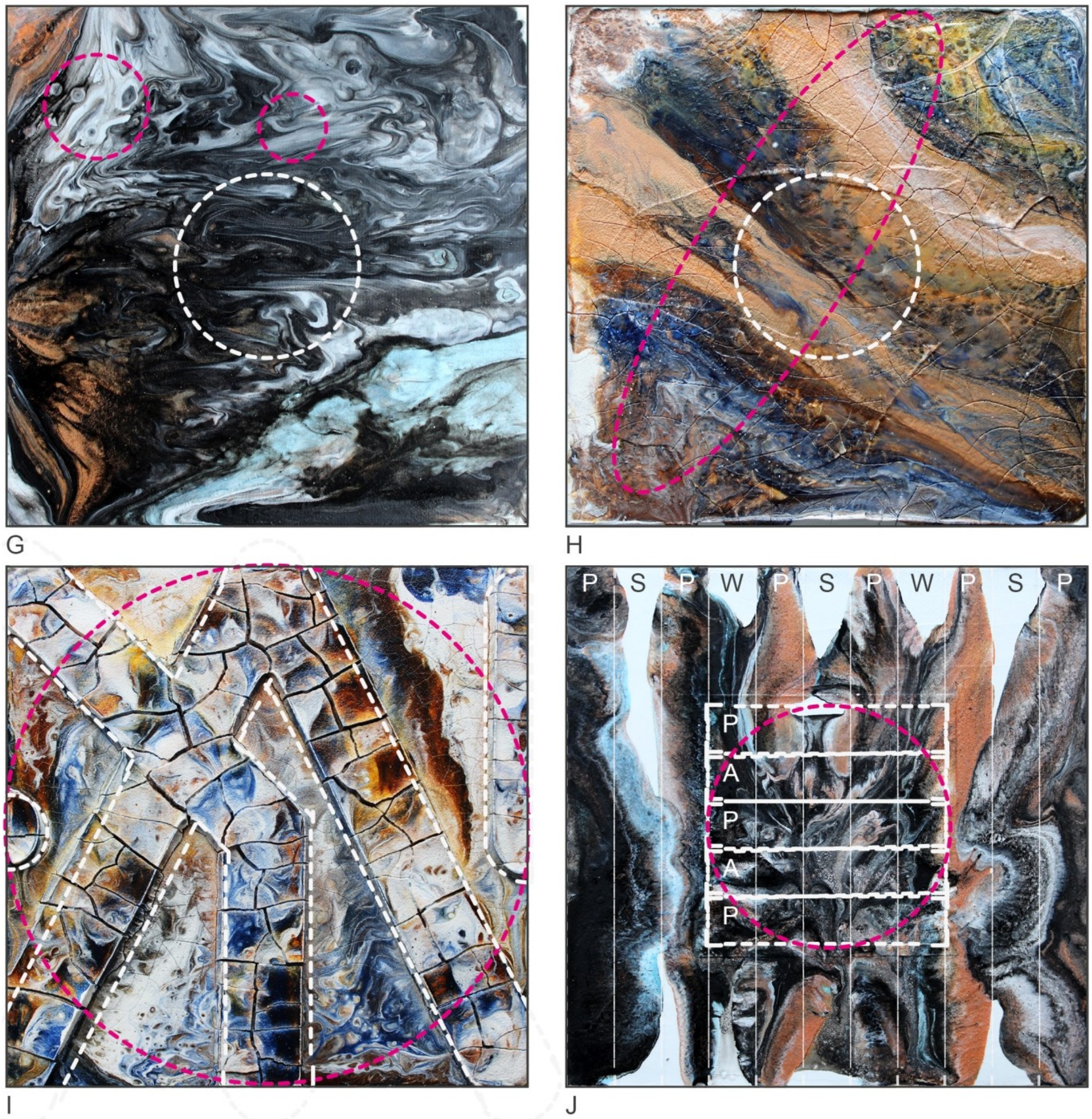


*Figure 84: 2D paint experiment photographs highlight the diverse range of effects achieved. **A** - **J**) reveal the global patterns.*

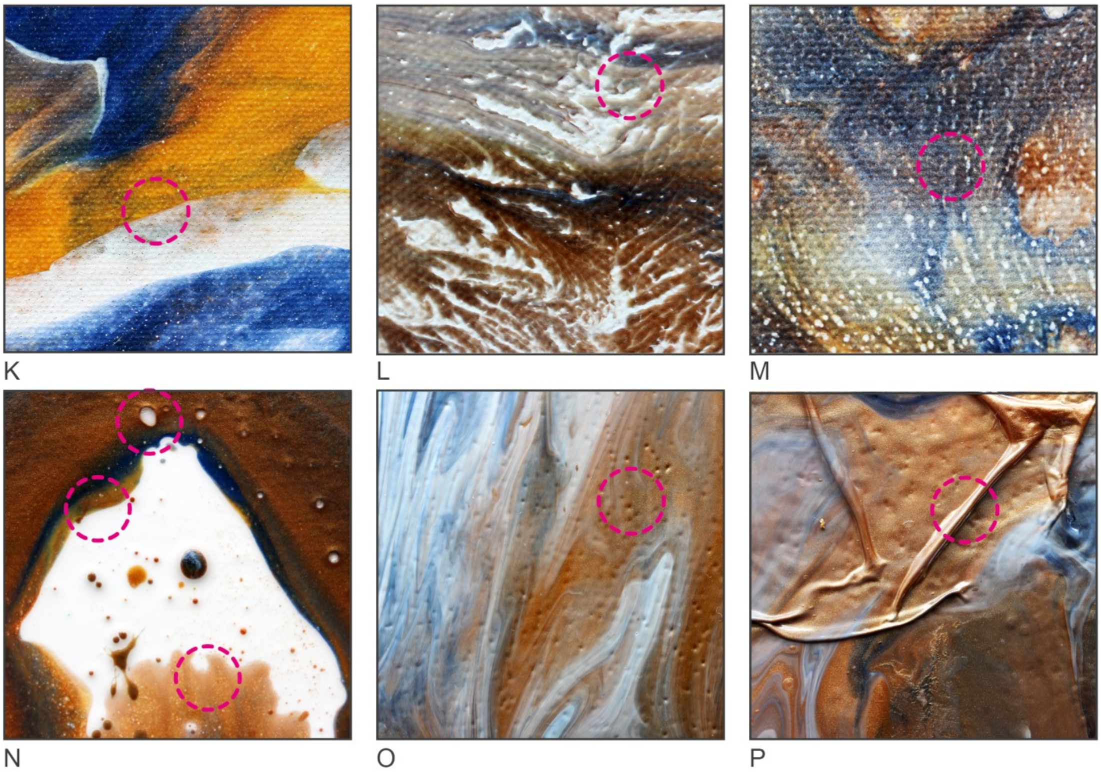


Figure 85: 2D paint experiment photographs highlight the diverse range of effects achieved. ***K - T****) highlight the local effects generated.*

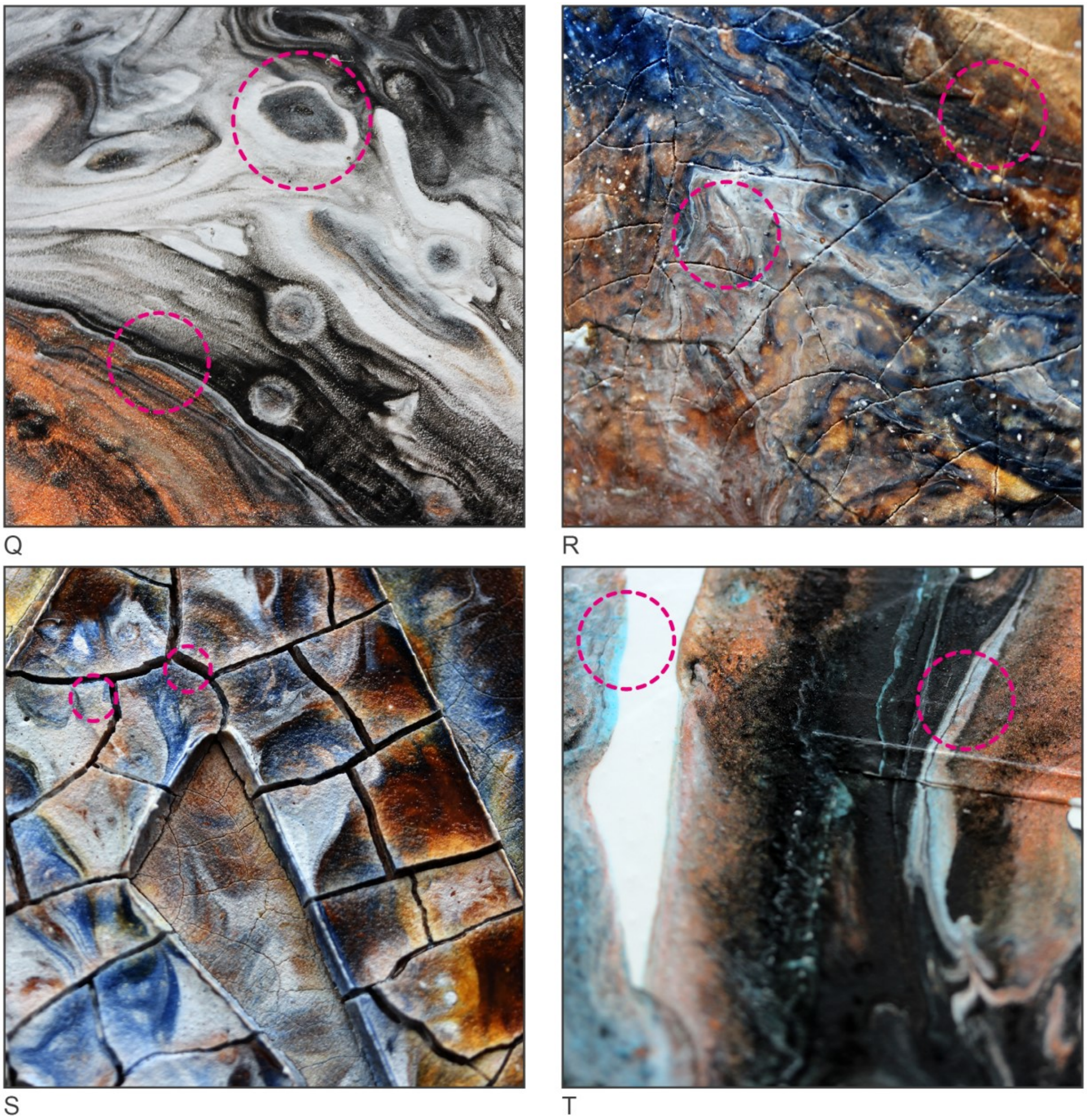


Figure 86: 2D paint experiment photographs highlight the diverse range of effects achieved. ***K - T****) highlight the local effects generated.*

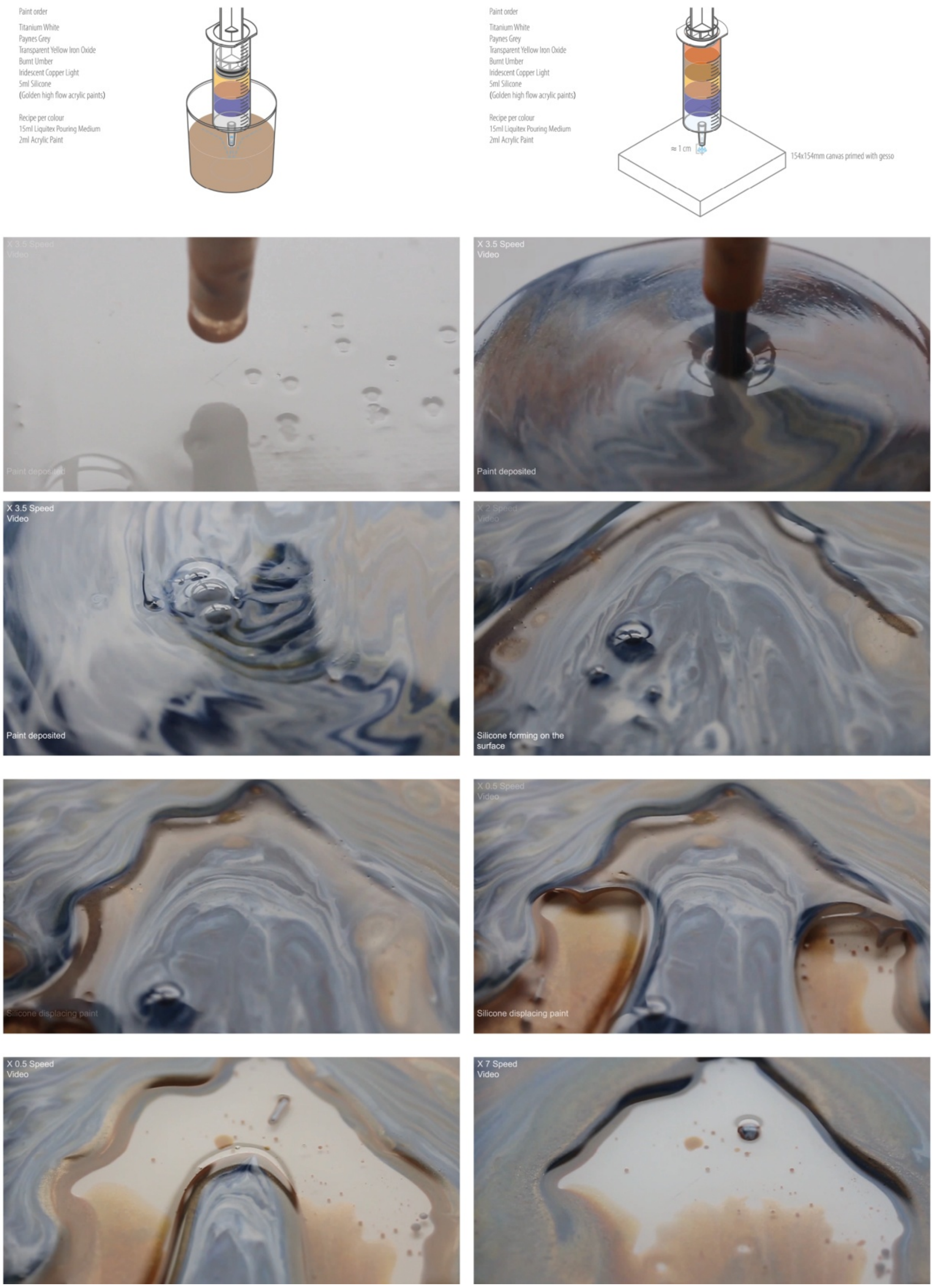


Figure 87: Silicone contrasts and displaces acrylic paint informing: voids spaces, boundaries, layers and streak formations, which highlights how contrasting materials can guide self-assembly. Video link for painting D: https://vimeo.com/270687667

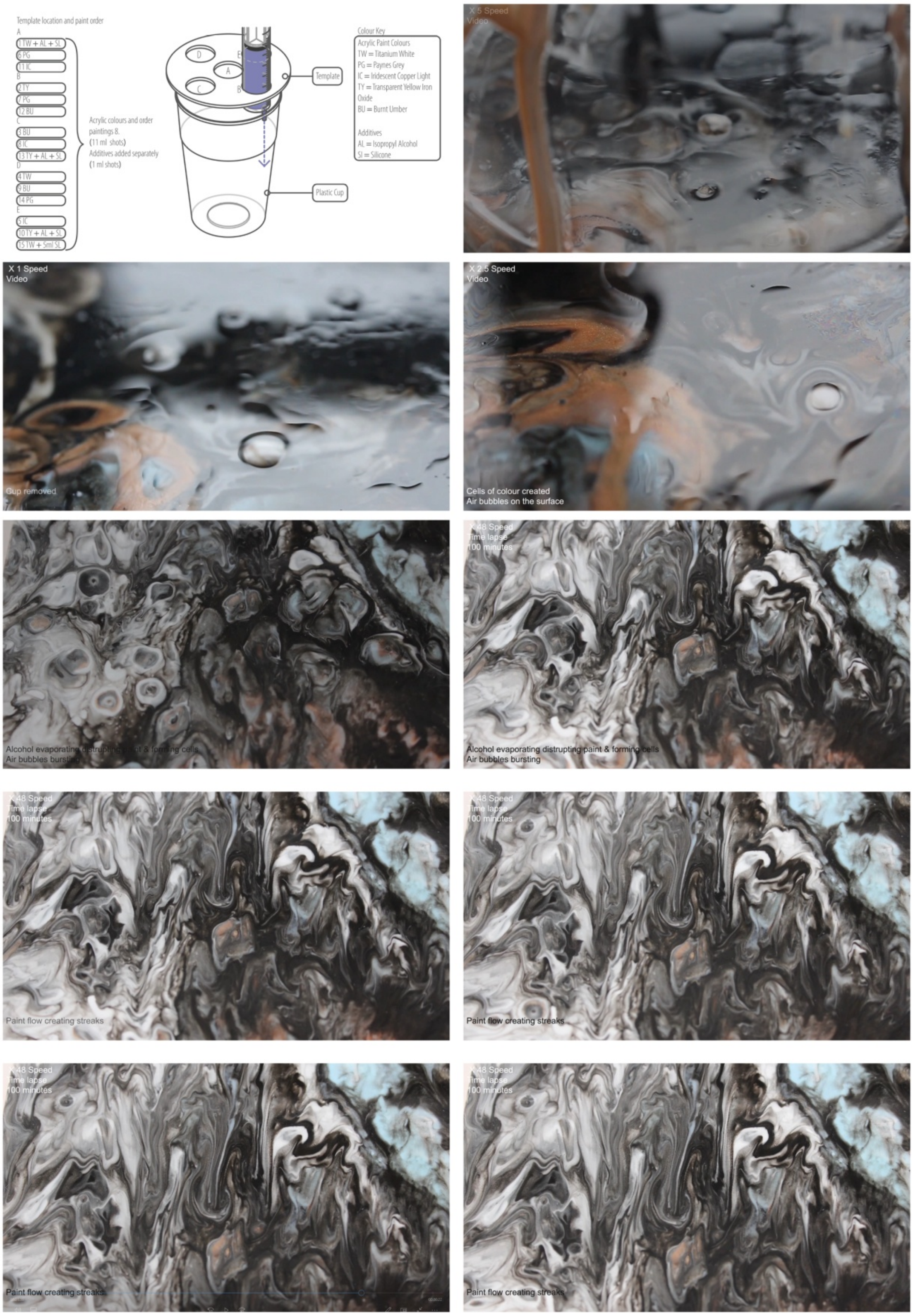


Figure 88: Images reveal interactions taking place in situ produces greater pattern diversity. Video link for painting G: https://vimeo.com/270696373

Figure 89: Series of images revealing how surface texture effects paint interactions and the patterns generated. Video link for painting I: https://vimeo.com/273500850

8.4.1 Viscosities, volumes and global patterns

The appearance of the global pattern diminished when layers of paint were deposited with higher viscosities (figure 83A). However, defined colour boundaries were created (figure 85K). Recipes with lower viscosities (figure 83B&C) maintained a very faint global pattern, with an increase in colour mixing. The change in base mediums also generated global to local material effects. Crazing occurred in figure 83B and 85L, compared to figure 83C and 85M, which highlights global granulation and small void spaces. In this case, imagine using tuneable environments to delicately control material viscosities by increasing a condition, for example, the temperature at a specific location so colour mixing amount, location granular properties (e.g. granulation, crazing) could be controlled locally. This could lead to self-assembled structures with gradient-based material properties (Oxman et al., 2011, Richards et al., 2017).

8.4.2 Pre-initiating Interactions

Figure 83D-F and 85N-P highlights the importance of where materials interactions are initiated if diverse effects are required material interactions must occur in-situ. For these paintings, all the paints were sucked up sequentially then deposited all at once via a large syringe, which resulted in more homogenous, blended colours. This highlights another strategy for transitioning between material boundaries when using self-assembling materials, creating structures with improved material integrity as there are no defined joint lines. Soldevila demonstrates how controlled material transition can be achieved using 3D printing technologies (Soldevila et al., 2015). However, the combination of silicone and paint (figures 83D, 85N and 87) revealed an exciting possibility to guide the shape of material self-assembly by using *contrasting materials*. *Contrasting materials* meaning materials that the combined materials do not mix with one another. These combinations are robust and don't need to be carried out in-situ to achieve the void effects and could be introduced and removed to manipulate and guide material adaptations. Meaning, contrasting materials could be used as a flexible scaffold to guide material scale self-assembly in comparison to the rigid scaffolds required in the mineral accretion process.

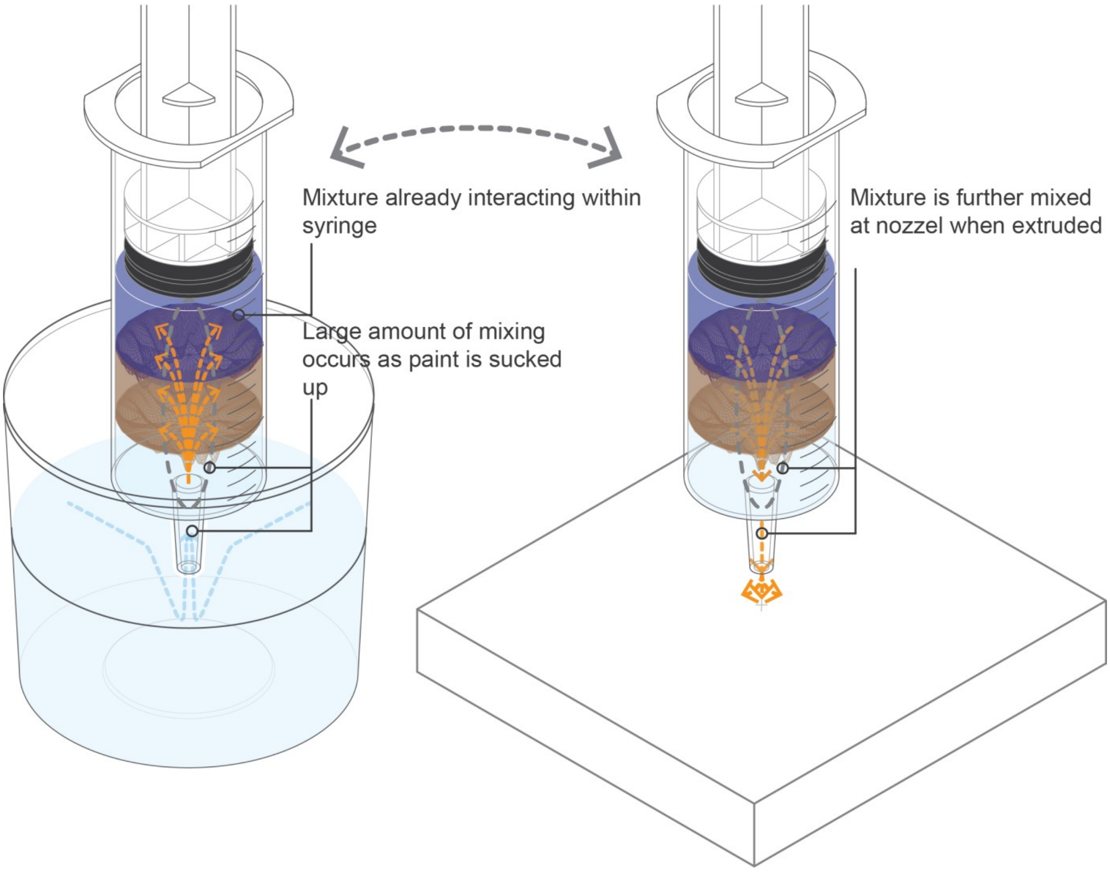


Figure 90: As the paint layers are sucked up within the syringe the paint flow and then gravity cause the colours to mix. Additionally, further mixing and colour homogenisation occurs as the collection of paints is then squeezed out through the syringes' nozzle and onto the canvas.

8.4.3 In-situ interactions

Figures 83G, H, 85 Q & R and 87 reveal the diverse patterns possible when the interactions are carried out insitu as they both have their mixtures deposited from a cup turned upside down. Once the paints are deposited the patterns generated are created predominantly by gravity and material flow. These studies inform how setting up reservoirs off un-mixed fluid materials can create infinitely diverse patterns.

8.4.4 Surface textures

Figures 83I and 85S demonstrated the effect varied surface textures have on paints deposited in individual layers compared to figures 82 A - C. Pools of colour are created on the higher levels, with streaks and highly blended colours produced at the lower level. This highlights how physical interacts or temporary scaffolds could be used to filter, funnel or prevent self-assembling interactions within a 3D volume.

8.4.5 Defining and disrupting boundaries

The use of silicone again demonstrates how global patterns can be maintained as the *contrasting materials* do not mix. However, in order to maintain material separation, there is a threshold volume of material required, in this case, materials heights must be equal. If the material / liquid volume heights are not equal the higher liquid can flow over the lower one, as seen in the middle of the left and right side of figure 83J. Water and alcohol acted as *disruptive materials* as they initiated material mixing and broke down material boundaries (figure 85T). *Disruptive materials* could be used to create fine films which can disperse light, or as a means to bridge materials and initiate mixing. Introducing both *disruptive and contrasting materials* at various times could create complex highly granular structures.

8.5 Experiment 08: Reflections

The results have revealed challenges of reproducing patterns and effects. These effects and their possible applications will be broken down;

- *Firstly,* the ability to reproduce homogeneous colour patterns (using these 'mixable' material types) can be achieved as the overriding factor is to initiate material mixing not in-situ. In terms of an architectural context, carrying out material interactions / material scale self-assembly *'off-site'* could lead to structures / structural components with greater structural integrity as the materials are highly mixed and do not have material interfaces / junction connections. The diffused material patterns have material gradient based qualities, which have recently been shown to be structurally and mechanically beneficial within architecture research (Soldevila and Oxman, 2015, Soldevila et al., 2015).
- *Secondly,* the results also highlight the potentials of employing *contrasting materials* to guide and achieve reproducible intricate and diverse patterns generated in-situ. This is because they still enable but also manipulate and induce self-assembly across scales and dimensions. Incorporating *contrasting materials* also enabled more robust interactions, meaning they do not mix but still effect the patterns generated. By combing these materials into an environment that could be delicately tuned in real-time (i.e. using stimuli such as temperature, pH, electrical current) with digital design tools would leverage greater control. Additionally, monitoring the resultant conditions would enable continual feedback between design, fabrication and material properties leading to an *adaptive fabrication system* without the need for constraining cathode structures. This is possible because environmental manipulations can be used to change the *state* of the self-assembling materials themselves. For example, the fluidity and density of a *disruptive material* could be altered by temperature, meaning material dispersion, diffusion or mixing could happen at various levels and amounts within a 3D volume. The ability to govern diffusion rates and enabling feedback could lead to new ways of repairing damaged objects / structures and could also open up new ways of embedding and visualising data within materials.

- *Thirdly*, the potential power of *contrasting materials* will likely be best suited to developments in 3D printing, where materials are deposited into a gel that supports the deposited materials but does not interact with them as they cure. This approach is effectively what enables *'Rapid Liquid Printing'* (Hajash et al., 2017). Additionally, then, it could be possible to make the supporting material itself a *tuneable environment*, where the support material could be agitated and/or its material properties could be altered by temperature (or some other stimuli), which in turn, would tune and adapt the deposited material properties.
- *Finally*, the results have revealed the possible benefits of incorporating contrasting with tuneable environments to achieve more controlled interactions across scales and dimensions.

8.6 Experiment 08: Conclusion and future work

The results demonstrate the variety of material effects made possible when using undefined self-assembling materials. Guiding these material scale interactions to generate desired and functional effects is a challenge but they also open up radically new material abilities, such as digital augmentations and adaptations being physically represented across scales. This could lead to completely new ways of designing and fabricating architectural structures all based on material computation abilities, which are guided by controlled stimulus. Imagine a building where surfaces in a room melt, move and rapidly grow objects to form 3D physical holographs, where an individual could sit directly within a movie or physically interact with computer games. The two main challenges that need to be addressed in order to advance these initial explorations are;

- *Firstly,* moving from patterns generated at 2D into 3D so physical adaptations can occur across scales and dimensions. Generating 3D patterns can be done by depositing ink into liquids or support mediums that enable diffusion, or perhaps inhibit and suspend diffusion.
- *Secondly,* being able to induce stimulus throughout a 3D volume of support material to create a tuneable environment, which can manipulate, and tune 3D patterns generated. Additionally, exploring various support material properties (viscosities and density) could be used to subtly control the impact of stimuli upon the material properties generate. For example, diffusion and dispersion rate reduced using more viscous support materials.

The next two experiments will explore these challenges. In doing so, the experiments re-imagine 3D printing processes, which are based on volumetric material diffusion and manipulations instead of the current typical layer-by-layer process.

A published conference paper for the paint experiments can be found within the paper: *Designing Parametric Matter*.

8.7 Experiment 09: Contrasting Interface

Experiment 9 is a small experiment, which is to initially understand how 2D generative patterns can become 3D and how varying support material properties (densities) in which inks are deposited into can be used to alter the inks 3D diffusion properties. The 3D patterns generated are the inks diffusion patterns, which are generated from gravity and concentration gradients.

8.7.1 Experiment 09: Properties

The colours of the acrylic inks used are carbon black and titanium white. The inks are deposited manually via a syringe through a hypodermic needle into a glass half-filled with water and half with clear oil. The volumes of inks deposited as well as the water and oil are not recorded, where the water and oil are the support materials in this experiment. The different properties of the support materials are the only focus of this experiment. There is no stimulus deliberately induced upon the materials once they are all combined / deposited. The significant stimuli which are acting upon the materials in this set-up are: 1) *gravity*, which causes the inks to sink and 2) *surface tension*, which is created between the oil and water interface. The video link also provides insight into how the experiment was carried out https://vimeo.com/274898577.

8.7.2 Experiment 09: Analysis

The experiment is recorded via videography to highlight the material properties and interactions that occur over time. To do this a camera was positioned directly in front of the glass until all of the inks were deposited. The camera was then moved above the glass to provide a plan view of the inks interactions.

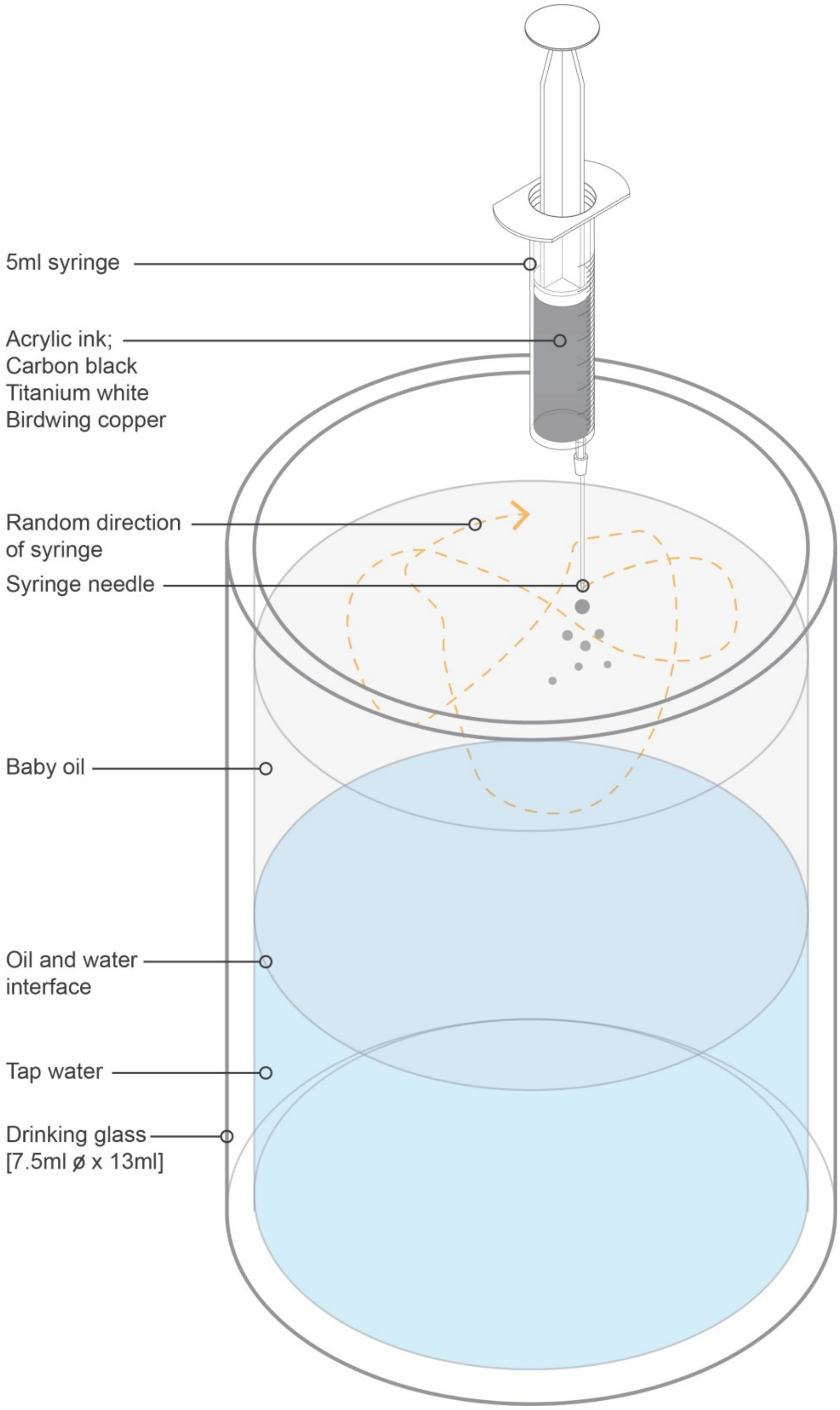


Figure 91: Experiment 09 contrasting interfaces. A glass was filled half with water then half with baby oil, which creates a contrasting boundary interface. Acrylic ink was then deposited into the mixture manually, using a syringe with an attached hypodermic needle. The experiment examines how various liquids impact 3D ink diffusion. Video link highlighting the process: https://vimeo.com/274898577

8.8 Experiment 09: Results

The results from depositing the inks are highlighted in figure 92, which is a sequence of images taken from a video. The several factors of interest witnessed (see attached link below figure 92) will be discussed sequential, these are;

- **A)** A physical boundary / interface is created between the volumes of oil and water.
- **B)** Spherical droplets of ink are created as they are deposited within the volume of oil. This is because the oil contrasts the water-based inks, inhibiting diffusion throughout the oil's volume.
- **C)** The ink droplets are stopped at the oil and water boundary. Due to the droplets weight, this causes the boundary to slightly dip, resulting in the droplets forming a cluster around the centre of the glass. Interestingly, the surface tension of each ink droplet temporarily prevents them from mixing with one another.
- **D)** Overtime, the ink droplets randomly burst at the oil and water interface, which then results in three material properties; *firstly,* the energy created from the droplets bursting can displace and eject other droplets from the cluster. Meaning contrasting materials can be used to instil energy into the materials to move units without directly inducing a stimulus from hardware devices. *Secondly,* 2D ink patters are generating at the boundary, a property that does not occur if the inks are injected directly into the water. These 2D patterns radiate from the burst droplets creating solid bands of colour that distort around the remaining droplets. *Thirdly,* the bands of colour eventually make contact with the volume of water and diffuse into 3D ink clouds. As the diffusion occurs the bands of colour break down into fibrous forms from their periphery inwards, highlight multi-material patterns and forms are generated across times.

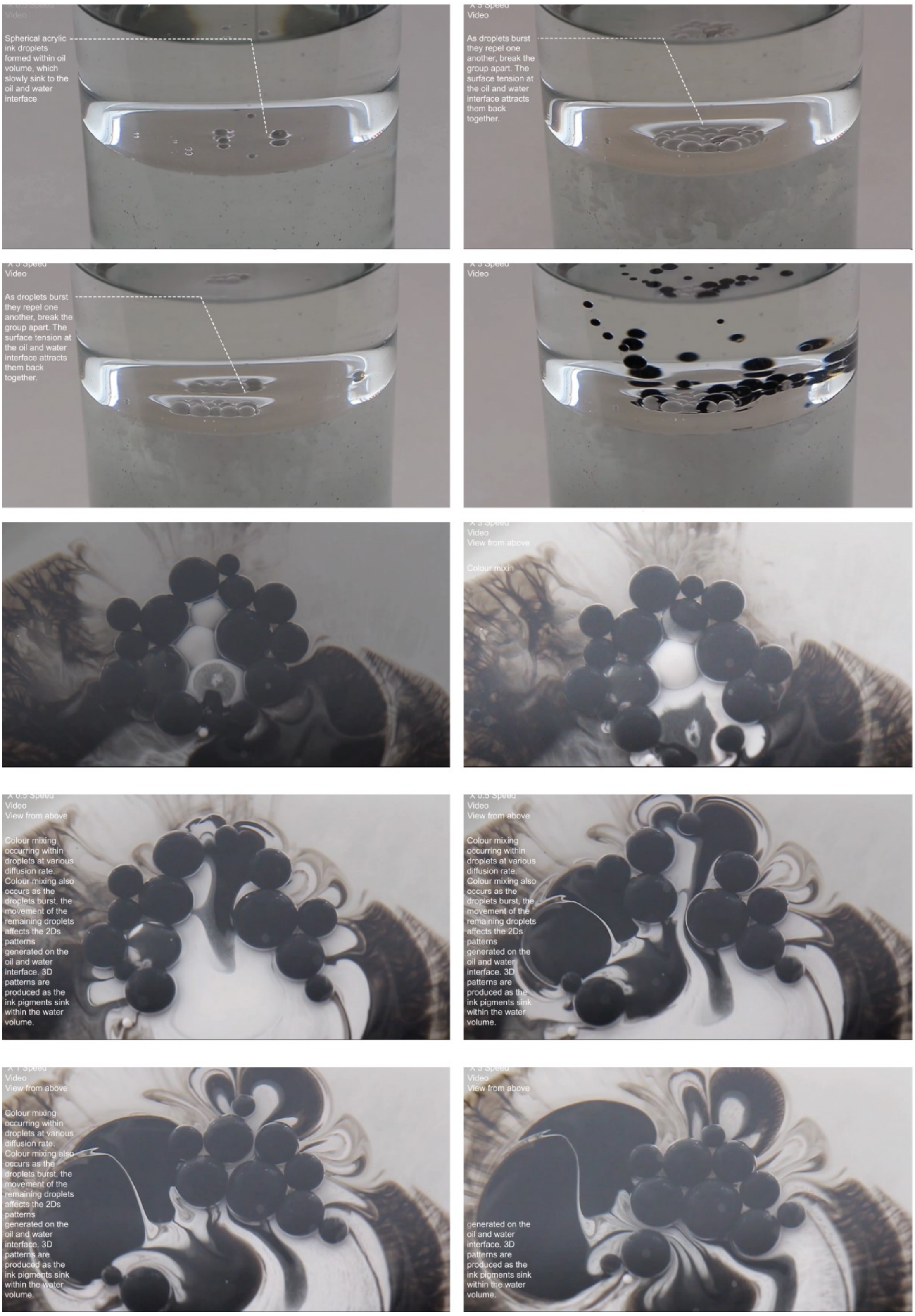


Figure 92: Contrasting interfaces. Reveals ink behaviour within contrasting support volumes; bursting at the oil and water boundary to form ink clouds. Video link for interface induced diffusion: https://vimeo.com/274898577

8.9 Experiment 09: Conclusions and Development

Interestingly, the very simple set-up is capable of producing complex temporal, multi-dimensional (from 2D to 3D) and multi-material properties. For example, 3D spherical forms co-existing with 2D solid planes of colour, 2D fibrous networks with variable gradients as well as complex 3D volumes of ink that diffuse and disperse through the volume of water. Additionally, even though no stimulus / energy had been induced upon the materials intentionally, the volume of oil, which contrasts with the volumes of ink, instils energy into the system by generating surface tension for each droplet of ink. These individual droplets then burst randomly resulting in clusters of droplets being dispersed across an area in random directions as well as material mixing in 2D planes and sometimes in 3D forms as neighbouring droplets unify. Importantly in this system, the release of energy is due to the interface between oil and water and highlights the potentials for guiding self-assembling material interactions using semi-rigid boundaries / interfaces. For example, imagine being able to vary the height of the boundary to rapidly generate solid planar 2D patterns throughout a volume.

Although the experiment is an initial study for moving from 2D into 3D pattern generation it has shown promise for exploring the material properties of support materials to enable a fabrication process based on material computation processes, one which is temporal and can generate multi-material properties. The temporal, multi-material properties could extend two areas of research;

- *Firstly,* new forms of 3D printing processes, which shift from fixed layer-by-layer form generation into rapid multi-dimensional form generation. Imagine suspending in time and space the complex multi-material properties generated from controlled fluid material diffusion, then inducing a stimulus, such as light to physically change the state of the deposited material i.e. from liquid to solid. These abilities could result in highly intricate fabrication abilities where the structures created achieve gradient-based material property transitions, for example, delicate fibrous material properties gradually transitioning into solid planar or globular forms in either two or three dimensions. Significantly, the gradient-based material property transitions would not be based changes to sequential layer build-up strategies found in 3D printing process, which can lead to mechanical failures occurring at abrupt material transition interfaces (Soldevila et al., 2014, Soldevila and Oxman, 2015, Soldevila et al., 2015, Bader et al., 2016a, Richards et al., 2017) because the system is based on diffusion.
- *Secondly,* the experiment could extend drug development strategies by controlling small volumes of material mixing under certain conditions, specific times and locations. However, controlled stimulus would need to be induced to guide these interactions. It has been demonstrated that electrowetting-on dielectric technology is a stimulus / system that can precisely control water droplet movements and location to govern material mixing on a defined grid matrix (Umapathi, 2017, Umapathi et al., 2018).

Significantly, the temporal, multi-dimensional and multi-material properties generated in the experiment are possible as the process is based on material computational processes, such as diffusion. The final experiment looks to manipulate these materials properties and processes (diffusion) by inducing controlled stimulus through various types of support materials.

8.10 Experiment 10: Diffusing Clouds

Experiment 10 is the final experiment carried out within this thesis. It builds on experiment 10 by exploring how temporal, multi-material properties of volumetric ink patterns can be manipulated and guided by inducing controlled stimulus and using different support materials.

8.10.1 Experiment 10: Overview

The ink diffusion experiments are investigated as a means of moving from the 2D paint experiments into 3D volumes. The ink diffusion experiments explore how volumetric ink diffusion properties can be manipulated by varying the viscosity and density of the material / liquid they are deposited into. The liquid is then agitated via two pumps to evaluate the impacts this stimulus and gravity has on the inks volumetric properties, such as diffusion rate, dispersion rate and the forms generated. The inks will be deposited into 3 different types of liquid, these are; 1) water. 2) A sugar syrup at a ratio of 1 parts sugar to 2 parts of water and 3) vegetable glycerine. Table 14 highlights the support materials properties at temperatures between 20 - 25 °C. Water is the least viscous with vegetable glycerine being the most viscous.

In order to evaluate these properties, the same volume of ink must be deposited across all of the experiments and at set time intervals. Additionally, the two pumps that agitate the liquids must also be done at set intervals, a set number and at set intensities. In order to deposit the same volumes of ink four peristaltic dosing pumps are used. The duration of time and time intervals between dosing pumps and pump agitation will be controlled by an Arduino microcontroller along with other components. The timing values can be altered manually controlled via a control interface created using processing. Additionally, real-time flow rate data is recorded from one of the agitation pumps to see how varying liquids viscosities impact on the amount of energy / stimulus supplied to the self-assembling ink clouds.

8.10.2 Properties

Figure 93 documents the set-up of the experiment. The volumetric patterns are recorded using videography at a standard and macro resolution. Set volumes of acrylic ink are deposited into 5 litres of support material, water, sugar syrup or vegetable glycerine. The sugar syrup was created by adding 2.5kg of plain caster sugar to 5 litres of tap water, which was then heated until the sugar is totally dissolved. Creating a solution ratio of 1 parts sugar to 2 parts water. The syrup is then removed from the heat as soon as all the sugar has been dissolved the left to cool to room temperature (≈23°C). Other sugar syrup ratios were produced and tested in preliminary experiments but this ratio proved to be the most effective. Table 14 documents the properties of the other support materials used.

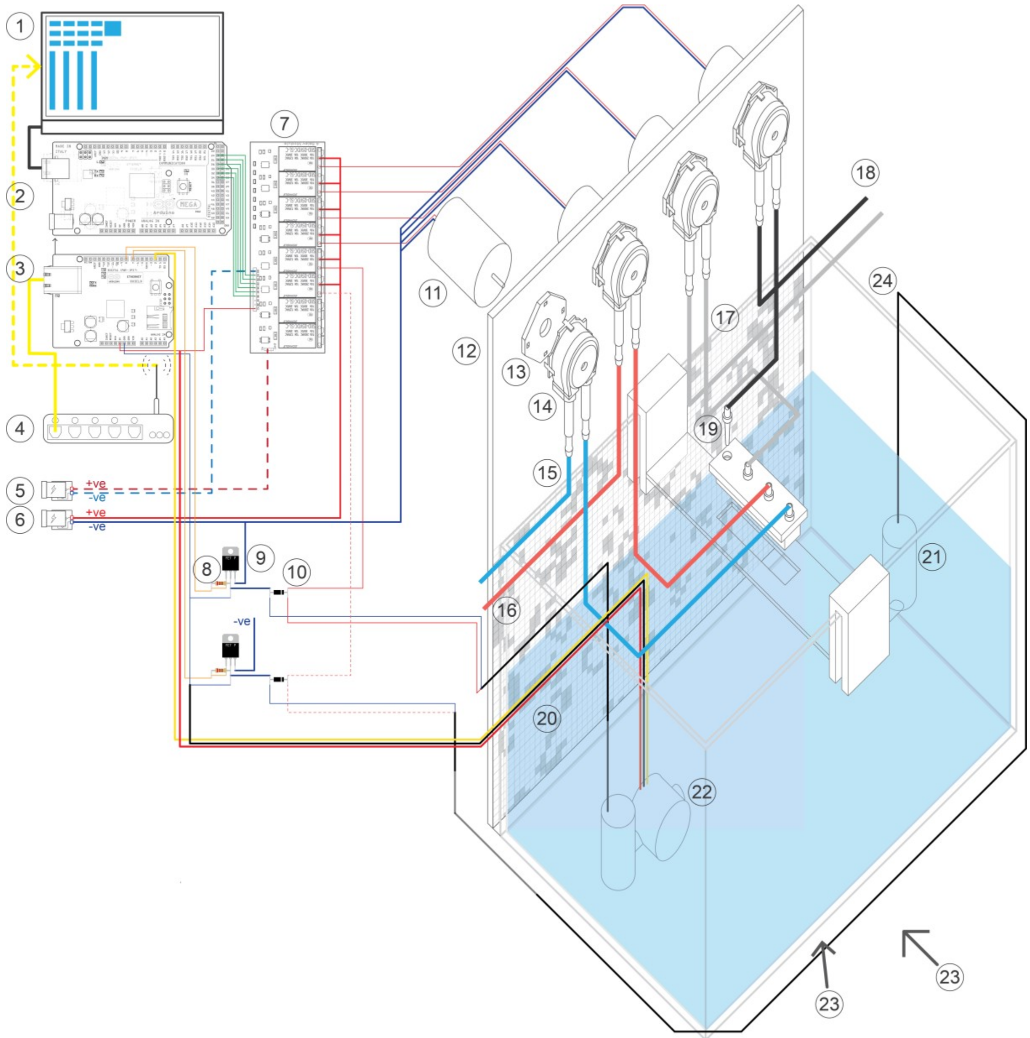
Table 14: Density and viscosity data of support materials

Support material	Density	Viscosity (centipoise)
Water	1 g/cm^3	1.5018 cp
Sugar syrup (1:2)	1.08609 g/cm^3	1.877 cp
Vegetable glycerine	1.261 g/cm^3	1412 cp

The acrylic ink colours and order of deposition are: 1) fluorescent blue, 2) birdwing copper, 3) titanium white and 4) carbon black. The acrylic inks are deposited via 4 separate peristaltic dosing pumps. The peristaltic dosing pumps enable consistent control over the volume of ink deposited based with a duration of 0.8 (fluorescent blue) and 0.3 seconds (all other colours). The intervals between ink depositions are 0.5 seconds. Fluorescent blue is deposited for a longer duration as it is a lighter more transparent colour so a greater volume is needed for visibility. The pumps used to manipulate the ink patterns via agitation also have a set sequence to allow comparison. The sequence dictates: 1) the number of cycles (5 each). 2) The duration of agitation (0.3 seconds). 3) The intervals between agitations (2.0 seconds) and 4) the magnitude / speed of the pumps (250 and 11). Two different speeds are used as a hall effect flow meter is attached to one of the pumps, which reduced the comparative impact of this pump so the other pumps speed was slowed in an attempt to make them similar. The timings of the peristaltic dosing pumps and agitation pumps are controlled using arduino (see figure 93 for connections). The time durations are defined using a simple user interface created using processing.

8.10.3 Experiment 10: Analysis

The experiments results are captured by recording material interactions via videography to highlight and compare the material properties generated over time. The videos created are edited and time-stamped to highlight the comparative material properties generated between water and sugar syrup. The sequence of images for figure 94 highlights the global effect with the sequence of images for figure 95 highlights the local properties. A 5mm grid is engraved on the back of the tank to help determine diffusion and dispersion rates. Vegetable glycerine is not compared via videography for reasons below. Additionally, a hall effect flow meter is attached to one of the agitation pumps to record the volume of fluid circulated from the pump during each cycle (see figure 96).



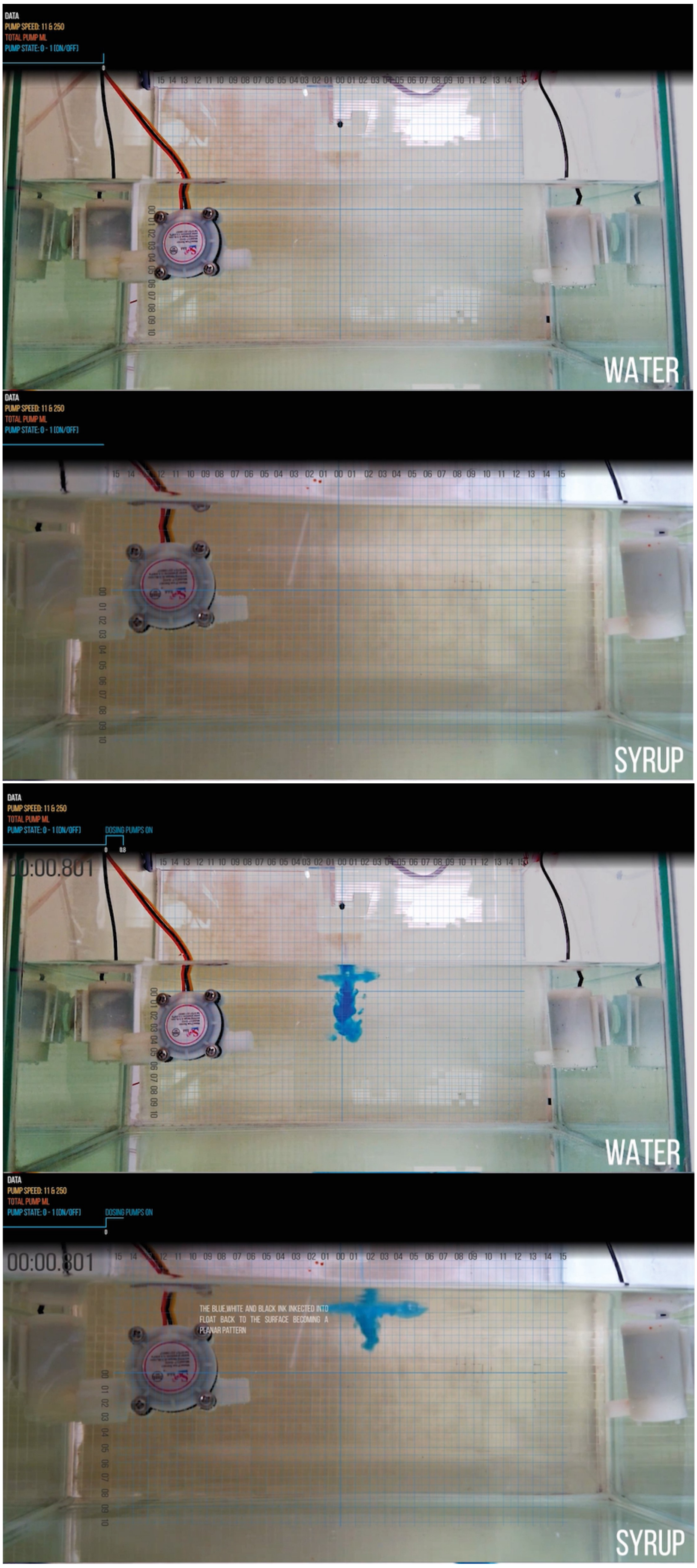
1) Design tool control the hardware developed in processing
2) Arduino Mega
3) Ethernet sheild stacked on top of Arduino Mega
4) Wifi router connected to ethernet sheidl via an ethernet cable
5) Bench Power supply for relays
6) Bench power supply for dosing pumps and pumps [10 volts supplied]
7) 8 channel solid state relay
8) 220 ohm resitor
9) FET transitor
10) Diode (components 8 - 10connected on prototyping bread board)
11) Peristaltic dosing pump motor
13) Mounting bracket for peristaltic dosing pump
14) Peristaltic dosing pump
15) Tubing for fluorescent blue acrylic ink
16) Tubing for birdwing copper acrylic ink
17) Tubing for titanium white acrylic ink
18) Tubing for carbon black acrylic ink
19) 3D printed nozzles help in 3D printed jig
20) 5 litre support solution, either: water, syrup of vegatble glycerin
21) Agitation pumps
22) Flow meter
23) Camera positions
24) Galss tank 198x 300x 200mm

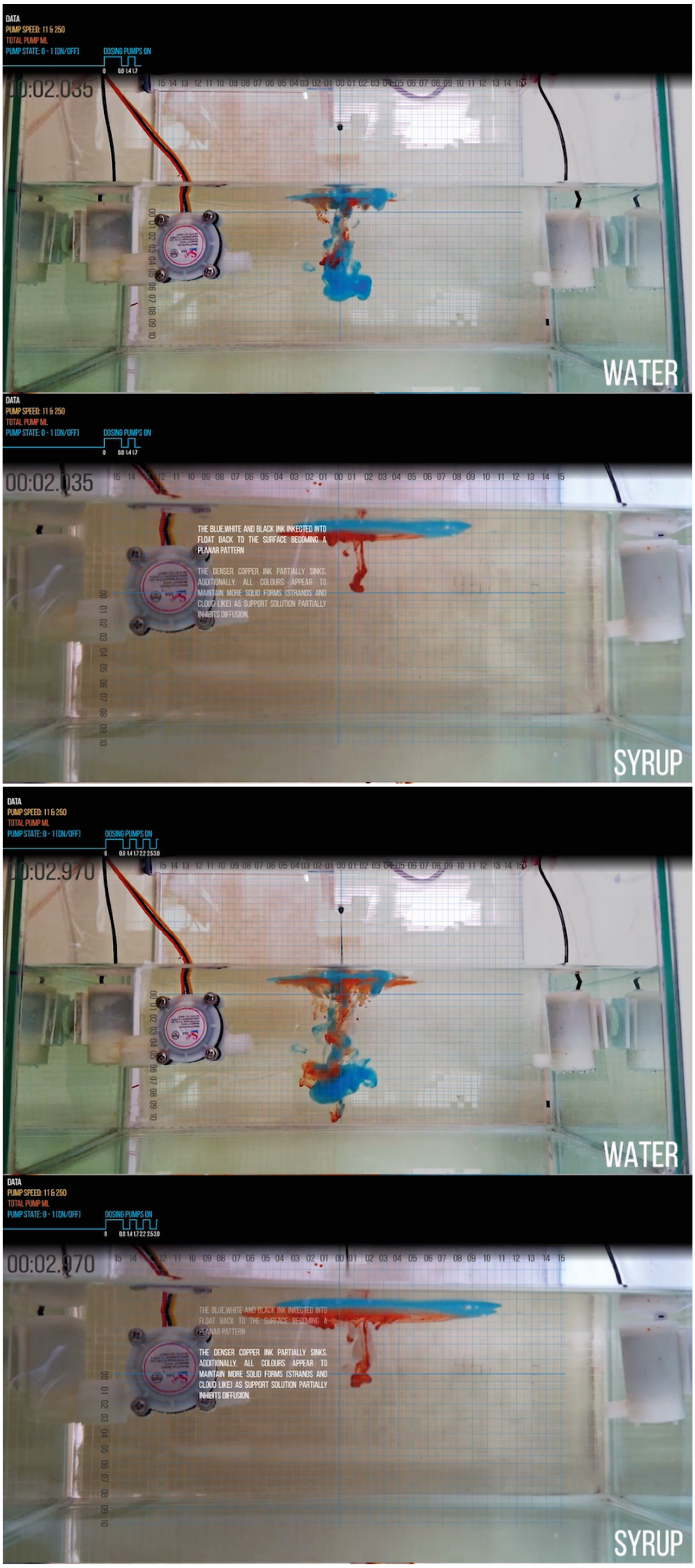
Figure 93: Experiment 10 - 3D ink diffusion. 4 colours of acrylic ink are deposited into 5 litres of liquid, water, sugar syrup or vegetable glycerine contained within a glass tank. 2ml of each ink colour are deposited via peristaltic dosing pumps with tubing connected to 3D printed nozzles. Once all the inks are deposited the solution is agitated via two pumps, which affects the volumetric diffusion and dispersion patterns generated. The sequence, time and intervals the inks deposited are kept constant. The pump agitation duration, intervals, speed and number of times the pumps agitate the solution are also kept constant. However, these values can be adjusted and manually controlled via a design tool, which controls the hardware used to automate the process. Maintaining consistent parameters allows comparison between studies.

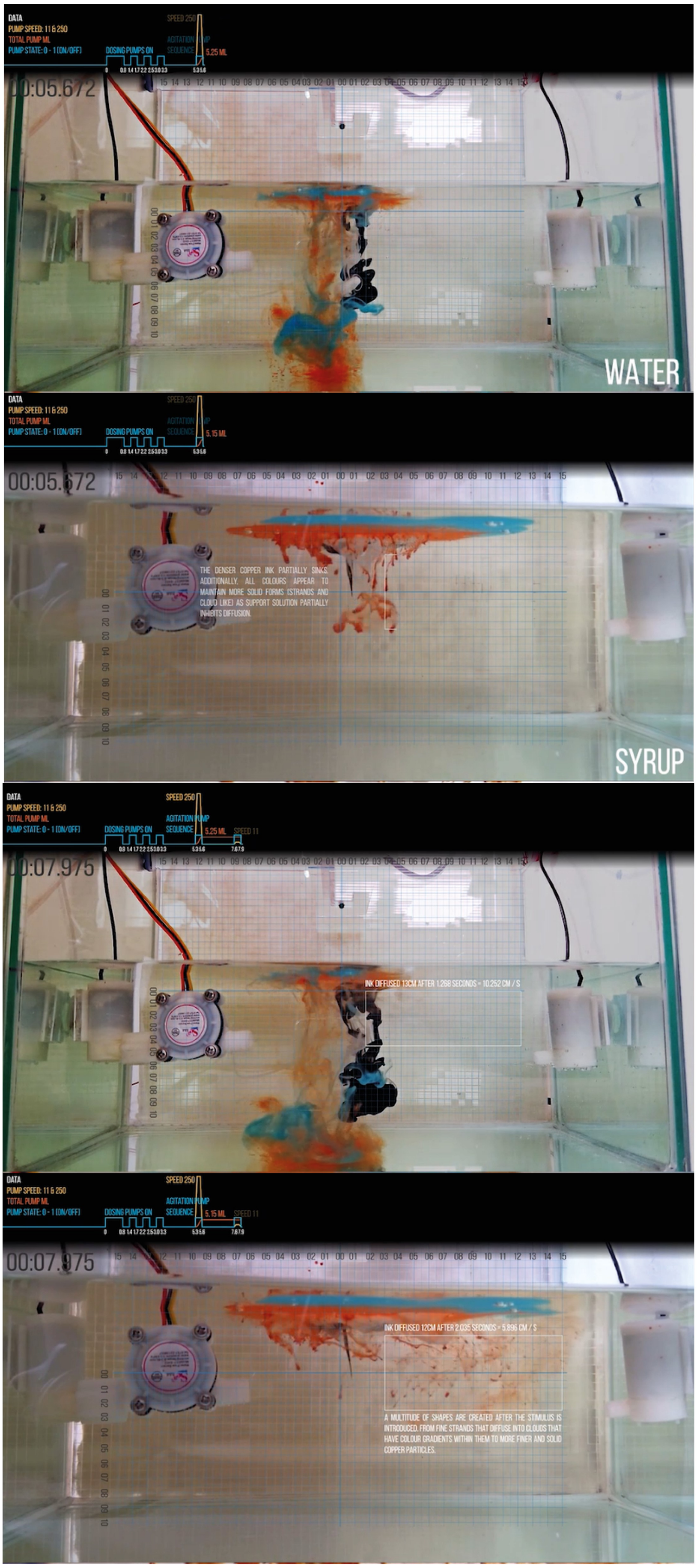
8.10.4 Experiment 10: Results

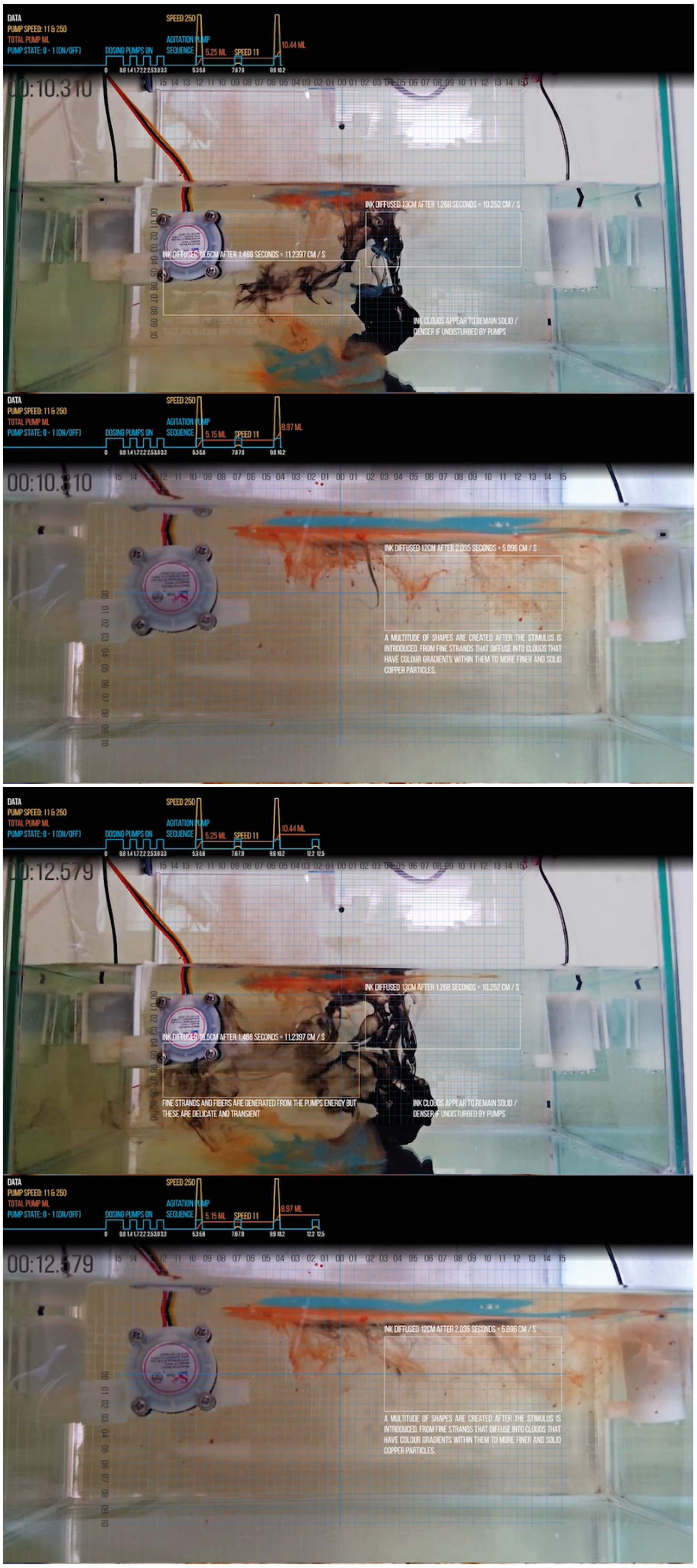
The comparative results between a support material of water and sugar syrup demonstrate several main interesting factors (see figures 94 - 95);

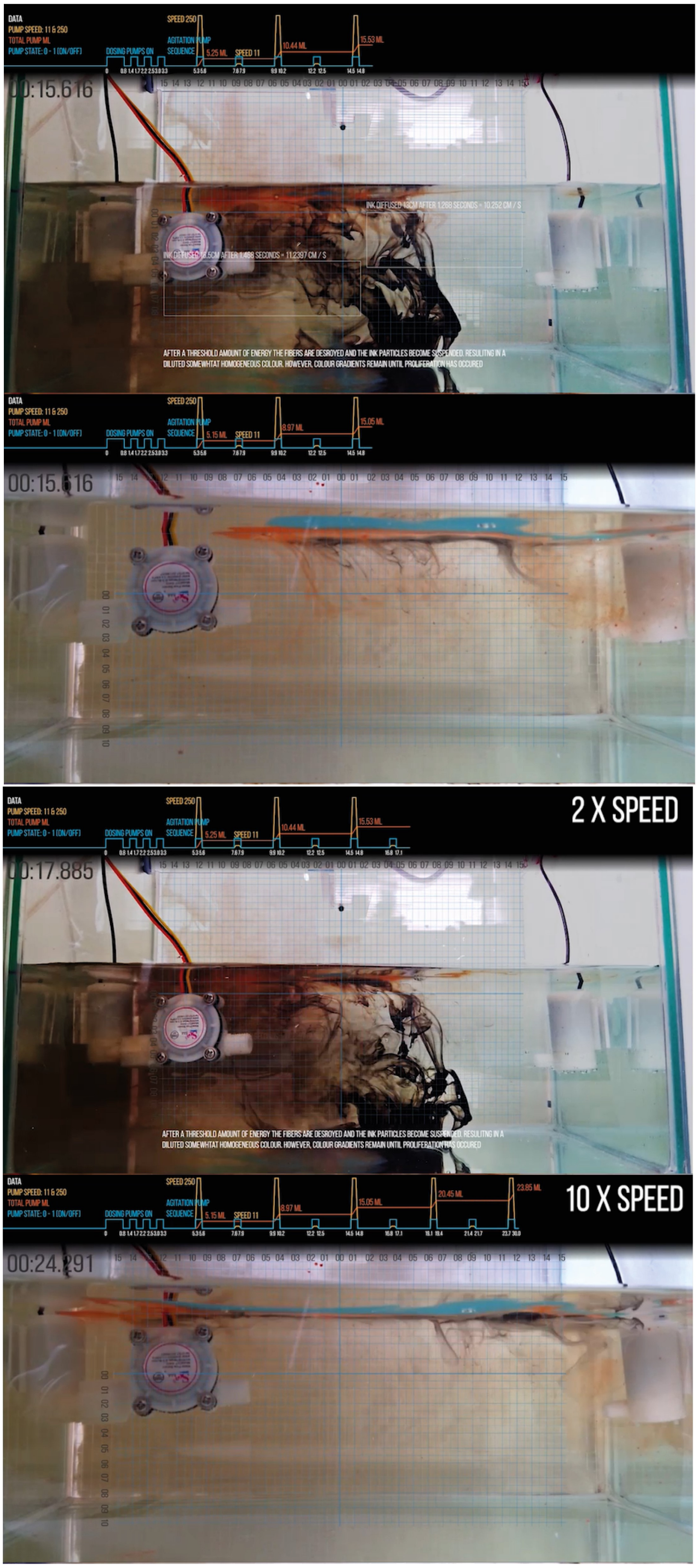
- ***Dispersion Rate***. The ink patterns generated within the water are rapidly manipulated and diffused when energy is supplied to them. For example, the inks were dispersed linearly 13cm in 1.268 seconds (10.252 cm/s) after the first pump agitation. Comparatively, the ink patterns are manipulated / linearly dispersed at approximately half the speed, 12cm in 2.035 seconds (5.896 cm/s) after the first pump agitation. Meaning interactions can be slowed down twice as much a slight change in support material density (0.086 g/cm^3) and viscosity (0.37 cp).
- ***Multi-Dimensional Patterns***. The patterns generated within the water are all 3D. However, 2D and 3D patterns are generated within the syrup. The initial 3D patterns are generated from the copper ink. Regarding the 2D patterns, these are generated by all of the other ink colours as they floated back to the surface as the support material is denser. The pumps and inks created 2D swirled patterns on the syrup's surface. This informs the third point.
- ***Homogeneous and Heterogeneous Patterns.*** Due to the comparatively rapid diffusion rate within the water, the ink patterns and colours quickly become homogenised. Within the syrup support material patterns and colours remain heterogeneous for longer, resulting in volumetrically intricate curtains, networks and strands of colour. These curtains of colour are generated because of the inks initially floating on the surface and then eventually sinking over time. The water solution becomes homogenous after 31 seconds, whereas the syrup solution maintains heterogeneous patterns well after 125 seconds (4x longer).
- ***Flow Rates.*** The final flow rate data for water and syrup is 25.93 ml and 23.85 ml respectively. Meaning the increased viscosity of the syrup reduces the energy supplied to the inks from each agitation (see figure 96).
- ***Threshold Support Material Density.*** The vegetable glycerine support material is not compared with water and syrup as it was witnessed that the inks did not sink to create volumetric patterns and the pumps did not agitate solution, which meant 2D surfaced patterns were not manipulated either. Highlighting a threshold density and viscosity for the support solution is required to enable pattern generation and manipulation. Because of this, inks were deposited into the vegetable glycerine and manipulated manually to generate patterns, see figure 97.


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
WATER
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
SYRUP
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
00:00.801
WATER
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
00:00.801
THE BLUE,WHITE AND BLACK INK INKECTED INTO FLOAT BACK TO THE SURFACE BECOMING A PLANAR PATTERN
SYRUP


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
0 0.8 1.4 1.7
00:02.035
WATER
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
0 0.8 1.4 1.7
00:02.035
THE BLUE,WHITE AND BLACK INK INKECTED INTO FLOAT BACK TO THE SURFACE BECOMING A PLANAR PATTERN
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
00:02.970
WATER
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
00:02.970
THE BLUE,WHITE AND BLACK INK INKECTED INTO FLOAT BACK TO THE SURFACE BECOMING A PLANAR PATTERN
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.25 ML
WATER
5.15 ML
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP
SPEED 11
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED. FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.25 ML
SPEED 11
10.44 ML
00:10.310
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
INK DIFFUSED 16.5CM AFTER 1.468 SECONDS = 11.2397 CM / S
INK CLOUDS APPEAR TO REMAIN SOLID / DENSER IF UNDISTURBED BY PUMPS
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.15 ML
SPEED 11
8.97 ML
00:10.310
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED. FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.25 ML
SPEED 11
10.44 ML
00:12.579
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
INK DIFFUSED 16.5CM AFTER 1.468 SECONDS = 11.2397 CM / S
FINE STRANDS AND FIBERS ARE GENERATED FROM THE PUMPS ENERGY BUT THESE ARE DELICATE AND TRANSIENT
INK CLOUDS APPEAR TO REMAIN SOLID / DENSER IF UNDISTURBED BY PUMPS
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.15 ML
SPEED 11
8.97 ML
00:12.579
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED. FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
AGITATION PUMP SEQUENCE
SPEED 250
SPEED 11
5.25 ML
10.44 ML
15.53 ML
00:15.616
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
INK DIFFUSED 16.5CM AFTER 1.468 SECONDS = 11.2397 CM / S
AFTER A THRESHOLD AMOUNT OF ENERGY THE FIBERS ARE DESROYED AND THE INK PARTICLES BECOME SUSPENDED. RESULITNG IN A DILUTED SOMEWHTAT HOMOGENEOUS COLOUR. HOWEVER, COLOUR GRADIENTS REMAIN UNTIL PROLIFERATION HAS OCCURED
5.15 ML
8.97 ML
15.05 ML
2 X SPEED
00:17.885
20.45 ML
23.85 ML
10 X SPEED
00:24.291

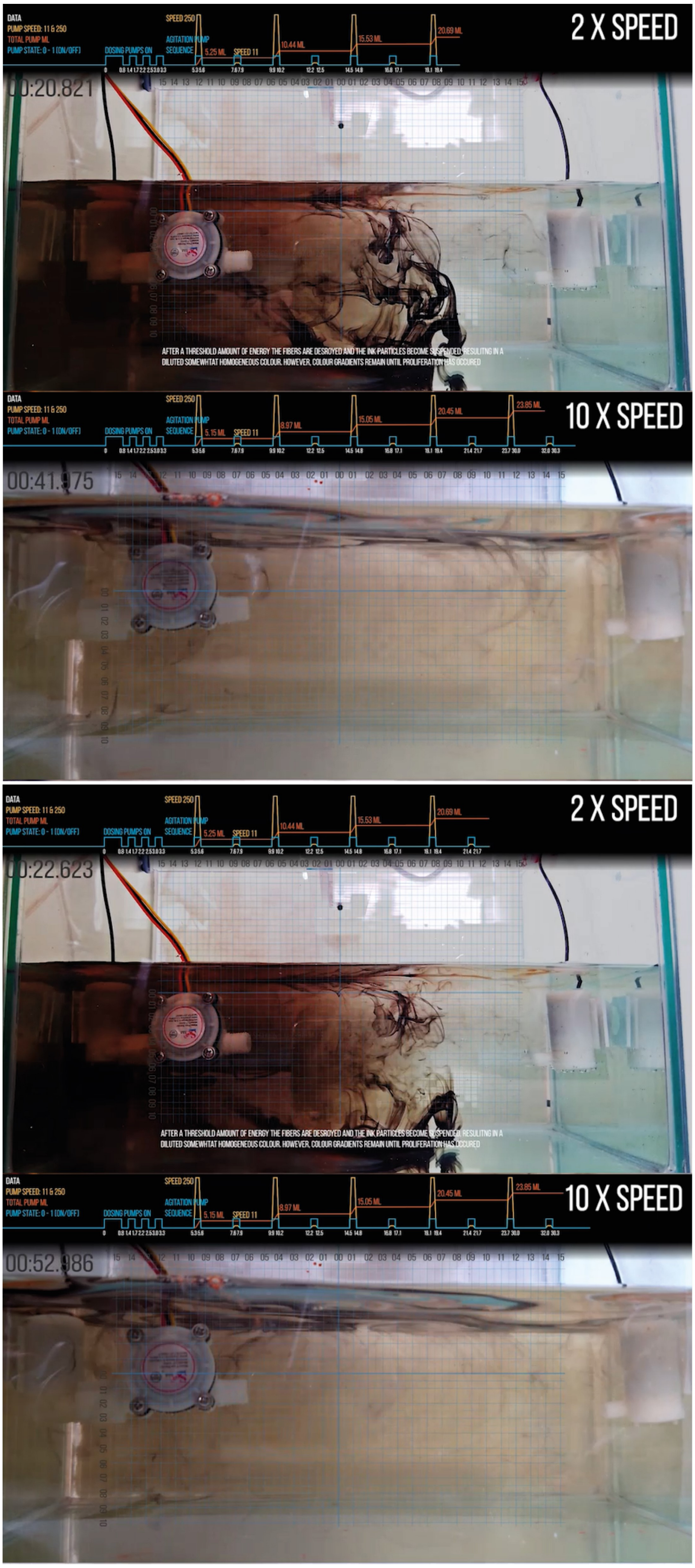
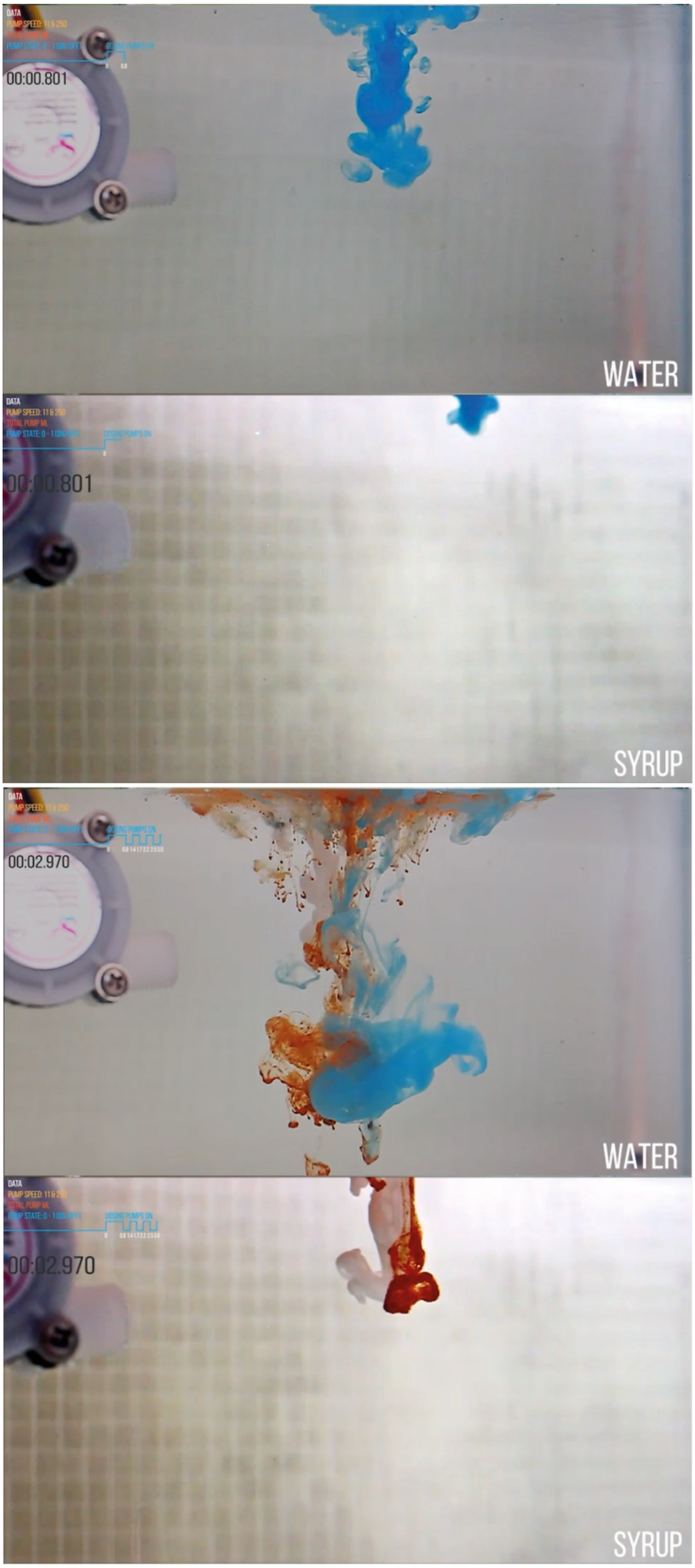
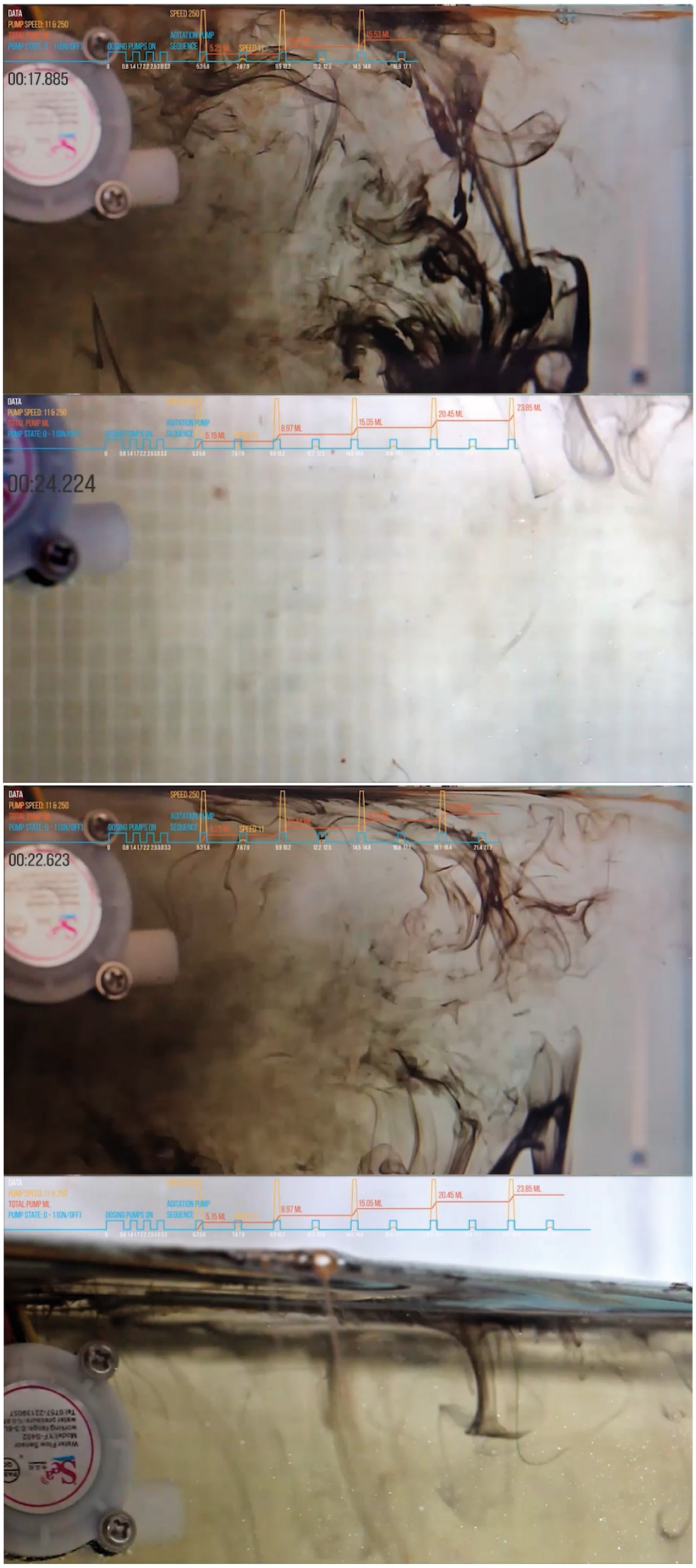

2 X SPEED
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
10 X SPEED
2 X SPEED
10 X SPEED

Figure 94: Sequence of images highlighting the impacts support material properties have on volumetric ink pattern. Water enables the inks to diffusion and disperses more rapidly resulting in a homogenised volumetric colour and pattern. The sugar syrup initially prevents colours from sinking and results in 2D patterns forming at the surface. Over longer periods of time the colours begin to sink and results in delicate multi-coloured, volumetric fibrous patterns begin generate, which are maintained for longer periods of time. Significantly, the syrup support material generates an increased range of material properties, which slowly alter over time compared to the volume of water. Video link: https://vimeo.com/367431096


00:00.801
WATER
SYRUP
00:02.970
WATER
SYRUP


DATA
00:07.975
DATA
00:07.975
DATA
00:10.310
DATA
00:10.310


DATA
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00:24.224
00:22.623

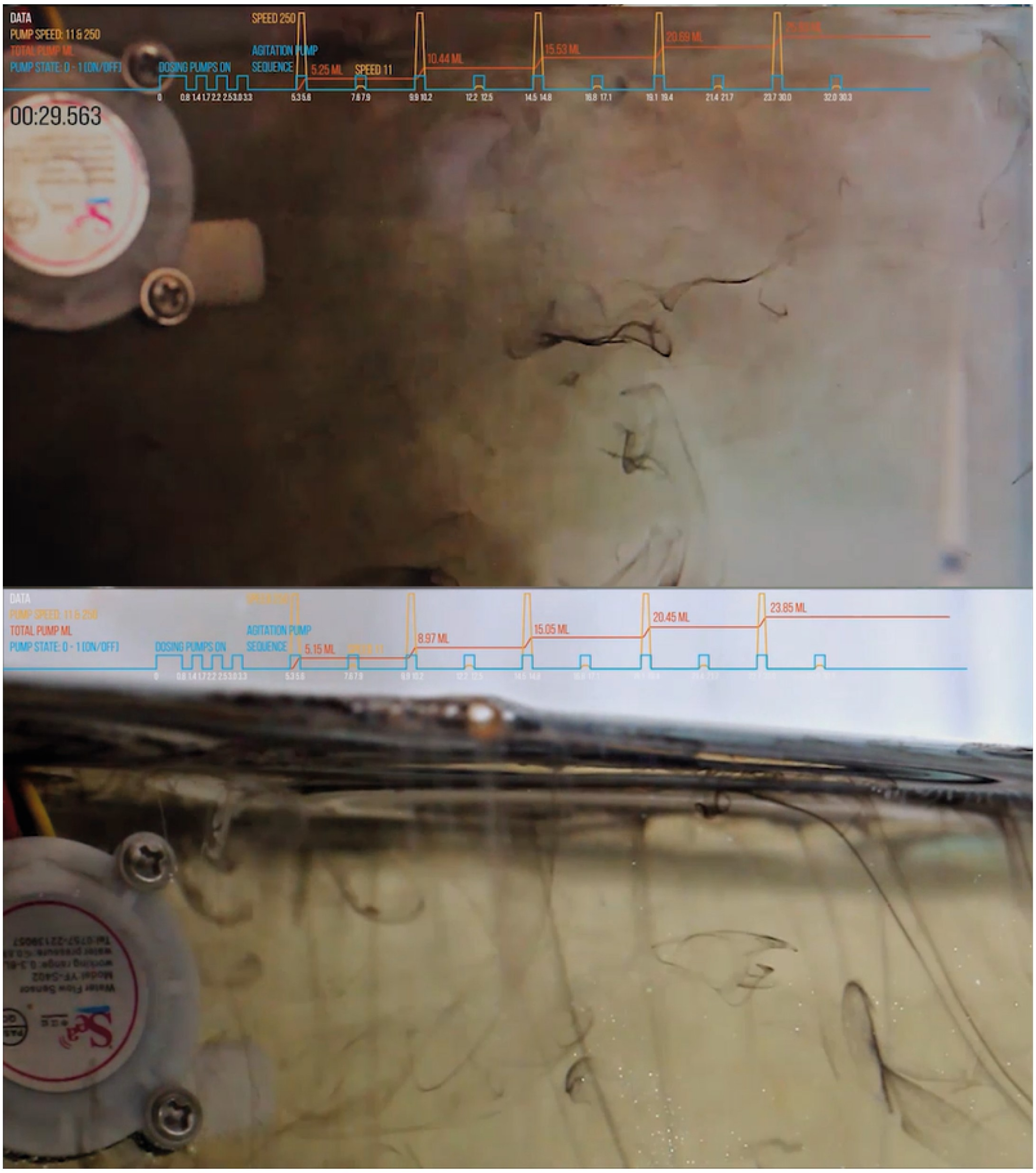

Figure 95: Sequence of images highlighting the localised material properties generated from the two different support materials. Video link: https://vimeo.com/367431096

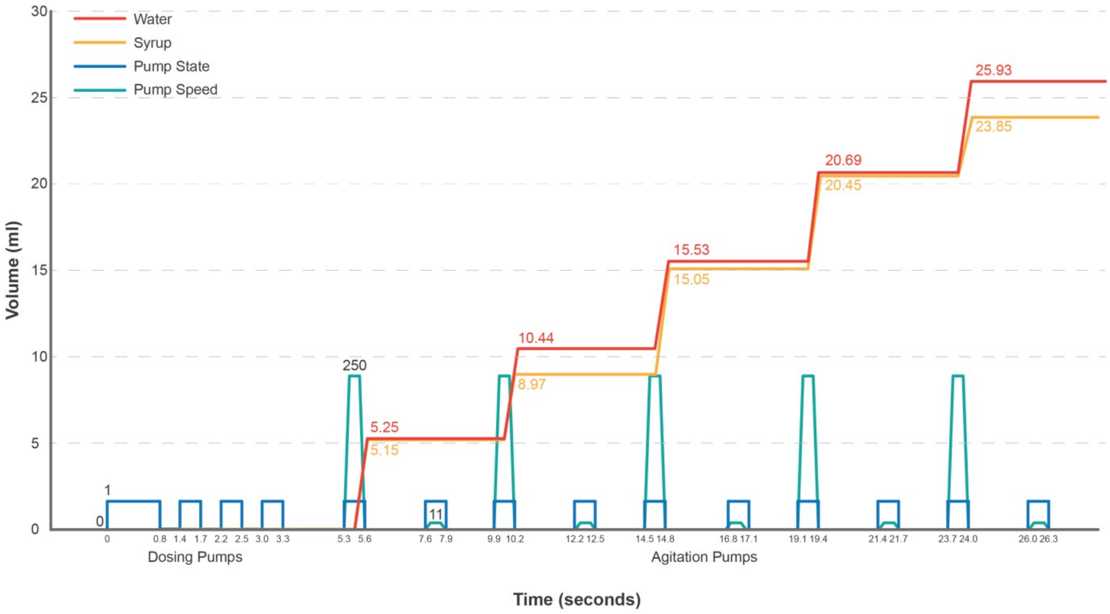

Figure 96: Flow meter sensor data highlighting less total volume record with the syrup support material. The reduced volume recorded, particularly during the 2nd and last cycle reveal the syrup support material reduces the energy supplied to the inks, which slow and could enable more delicate pattern adaption.

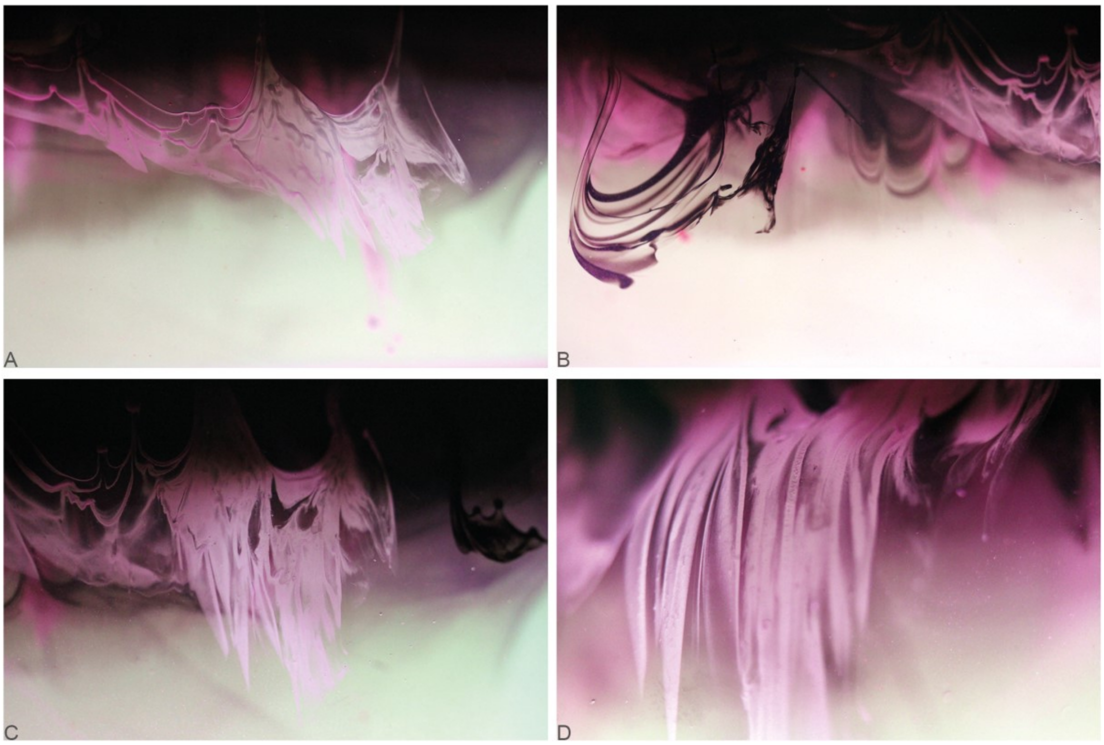

Figure 97: Inks were manually deposited into the vegetable glycerine and then manipulated manually moving a pipette around randomly. The viscous and dense support material suspends the diverse volumetric ink patterns in time. A multitude of properties are generated from web-like (A, C), curved-strand-like (B) to granular (D) as well as fine gradient dispersions.

8.11 Experiment 10: Conclusion

The conclusion is used to discuss; *firstly* the significant results of the experiment, *secondly,* how variable volumetric material properties have been produced and *finally,* possible future potentials of a volumetric fabrication process.

The results have demonstrated the possibility of utilising tuneable environments to rethink 3D printing processes, which can simultaneously and volumetrically generate multi-dimensional, multi-scale and multi-material properties (colours, textures, forms, patterns gradients). Additionally, extremely delicate, complex material properties can even be suspended in time as witnessed in the vegetable glycerine support material experiment.

These multiple material properties have been achieved by again developing a fabrication processes based on material computational processes but also by exploring the crucial role the support material properties can play in guiding these material computational processes, such as, slowing and even suspending: 1) diffusion rates and dispersion amounts, 2) generating-gradient based 2D and 3D patterns and properties that occur at global and local scales and 3) energy transference / inhibition, which could enable subtle material manipulations that create or maintain extremely delicate forms, such as the fibrous networks generated. Significantly, these self-assembling patterns could be tuned and adapted to become functional if feedback based on a contrasting effect could be detected or a mechanism that creates repeatable reliable patterns is used. In section 3.1.3 it has been proven that high-frequency vibrations can generate reproducible 2D patterns.

Figure 98 is used to speculate on the future possibilities of volumetric fabrication system enabled by tuneable environments. The idea combines the reproducible frequency patterns of *cymatics* with the possibility of variably altering the properties of the support material (viscosities and densities) via a controlled stimulus (e.g. temperature, light) in order to govern / guide the material interactions that generate the 3D patterns. The reproducible patterns generated by the high-frequency stimulus could potentially enable functional and controlled 3D forms to be created. Speculating on a volumetric fabrication system that utilises material computation could lead to several desirable factors;

- The fabrication system could still enable emergent highly desirable properties to arise as it is non-deterministic and leverages material computational abilities.
- New forms of rapid mass customisation could be achieved with reduced set-up and tooling costs as the process itself is flexible and adaptable. However, more research would have to be carried out into 1) the deposited material properties, 2) the support material properties and 3) control over the stimulus-induced, its parameters and interrelationships.
- As the structures are fabricated volumetrically, they could lead to enhanced mechanical performance for gradient based structures.

- Damaged objects or components could be placed back into the support material to repair them or update them at highly intricate resolutions, which would reduce material waste and result in a component, object of structure avoiding redundancy

.

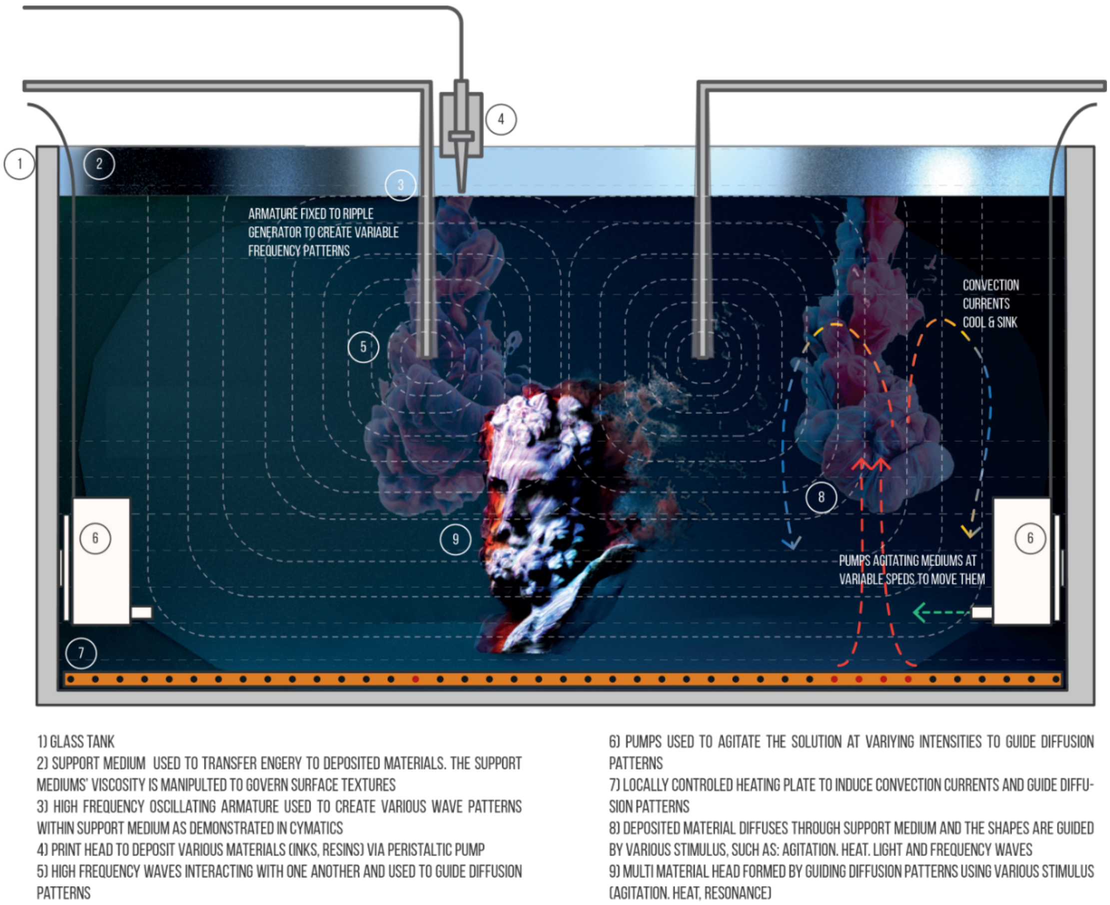

Figure 98: Speculative idea of a diffusion based fabrication system. Stimulus controlled via digital design tools is used to manipulate and inhibit diffusion rates of various liquids to create multiple textures, colours, patterns, compositions and shapes, which could potentially lead to novel 3D holographic displays.

8.12 Chapter Summaries

The main factors and key areas of interest produced from each experiment are briefly discussed with a focus on how they could lead to new fabrication possibilities based on tuneable environments, which guide material computational processes without the need for constraining scaffolds.

2D Generative Patterns

- **In-situ Interactions:** In order to achieve greater diversity of colour patterns, interactions must take place in-situ if the materials are capable of mixing with one another and homogenising.
- **Surface Texture:** Material interfaces and boundaries can be significantly affected by surface texture variation / boundary interfaces as they can manipulate liquid surface tensions.
- **Contrasting Materials:** The contrasting silicone and paint mixtures highlighted defined boundaries and void spaces can be created robustly even if the material interactions begin to occur within the deposition process. Contrasting materials could act as flexible scaffolds to guide more open self-assembly.

Contrasting Interfaces

- **Boundary Interfaces:** The volume of oil was able to instil energy into the contrasting deposited material as they formed droplets. The oil also imparted various timings of interactions between the materials and patterns generated.
- **Simultaneous Properties:** The contrasting oil and water interface enabled the deposited materials to generate gradient-based, multi-dimensional, multi-scale, multi-material properties simultaneously.

Volumetric Fabrication

- **Tuneable Environments:** The results demonstrate that tuneable environments can be extended beyond the mineral accretion process. However, no feedback is achieved.
- **Support Material Properties:** Exploring properties of support materials highlighted future possibilities for 3D printing process based on volumetric fabrication where gradient-based, multi-scale, multi-material properties are generated simultaneously.
- **Material Property Suspension:** The increased viscosity and density of the vegetable glycerine support material established that very delicate, complex, multi-material properties can be generated and suspended in time and potentially finely tuned as energy transmitted through the support material is significantly reduced or even inhibited.
- **Cymatics:** Reproducible patterns could be generated by incorporating high-frequency vibrations.
- **Feedback:** In order to achieve functional and intended patterns feedback and interrelationships between stimulus and material properties generated need to be established.

9 Conclusions & Key Discoveries

This chapter focuses on the overall key contributions and limitations of this research. The contributions and limitations are discussed in three main areas, which also form the order of this chapter. The three areas discussed are: 1) how the research methodologies have been employed throughout this research, which highlights the key factors of what they have enabled as well as what their limitations are. 2) The key principles the collection of experiments have raised and how they have extended existing knowledge in regards to design and fabrication processes that are based on material self-assembly as well as extending the knowledge of *persistent modelling* (Ayres, 2012b). 3) The limitations of the research with a main focus on the mineral accretion experiment findings, which also highlight existing problem areas within *persistent modelling* and self-assembly.

Detailed conclusions from each individual experiment are not discussed in this chapter as these have previously been discussed within the multiple conclusions sections in the previous chapters (chapter 7 and 8). For this reason the overall conclusions focus on the main principles highlight from the practice based methodology employed.

9.1 Contributions

This section briefly highlights the main contributions of this thesis before going into more detail on how they have been established based on the key findings generated from the experiments.

The aim of this research was to explore; *how can structures be grown and adapted throughout the fabrication processes using programmable self-assembly?* Exploring this aim was achieved by: 1) employing an RtD methodology combined with additional methodologies of sensing and actuation. 2) iterative and practice-based prototyping. 3) utilisng various material analysis techniques and technologies to quantify material properties and the system's parameters when stimuli are induced.

The methodologies, results and conclusions generated from this research have generated several contributions based on re-thinking design and fabrication processes, which could be applied to multiple areas, from architecture, fashion, medicine to manufacturing or novel physical displays.

Firstly, the research has contributed towards a framework or series of principles for how design research methodologies can be used to explore adaptive design and fabrication processes that utilise and govern parameters of stimuli that can guide material scale self-assembly.
Secondly, the research contributes to defining novels approaches for creating design and fabrication systems based on interrelationships, which critically, engage with and leverage material computational processes, enabling material properties to be tuned and adapted in relation to conditions induced and generated by the materials themselves.
Thirdly, the research contributes towards developing fabrication processes that are based on the notion of *'tuneable environments'* where various stimuli (e.g. electrical current, temperature, agitation) and their parameters (e.g. time, magnitude, location) can be used to guide material scale self-assembly / material computational processes, which can be associated to instructions from digital design representations / tools as highlighting in experiment 05 - 06.
Fourthly, the research highlights that feedback mechanisms within design and fabrication processes that are based material platforms that can self-assembly on the material scale that 1) do not have predefined properties (e.g. geometries) 2) cannot not self-sense and 3) have inherent interrelationships when subjected to stimulus require design tools and processes that are based on non-linear associations as the interrelationships become increasingly complex to enable direct associations to be made. *Tuneable environments* can guide these material interactions but significantly, must ensure *favourable conditions* are crated and maintained in order to initiate and sustain material growth. Maintaining favourable conditions though is dependent on engaging with the system interrelationships by enabling feedback between all of the systems components that induce stimulus that affect and are affected by the conditions generated in order to prevent proliferation within the system.
Fifthly, foundational / substrate materials used to support and initiate material scale self-assembly have a significant impact on material growth properties and the resultant conditions they generate that are used to determine associations. Furthermore, creating cathode scaffolds from variable material properties (insulating and conductive) can be used to enable greater control over material properties generated (highlighted in experiment 07).
Sixthly, exploring the impacts of support material properties within the ink and paint experiments that are contrasting and semi-permeable to the materials being deposited with

them enables a diverse range of material abilities across various time-scale, material-scales and dimensions. These contribute towards rethink 3D printing processes to enable new material abilities that can be rapidly fabricated, which can then be tuned and adapted by employing tuneable environments.

Finally, surveying the literature in combination with results generated from this research highlights a main challenge in regards to the limited resolution of persistent modelling when incorporating design tools that are based on boundary representation and associative modelling strategies e.g. parametric design processes based on linear cause and effect relationships.

These contributions and overall conclusions are sequentially discussed in further detail next in the order, they are mentioned above, so as to further unpack them and highlight how the contributions have been generated. Additionally, these sections highlight how the aim of this research has been achieved as well as further explored. Following these contributions, the limitations of the research are then discussed. The limitations highlight the challenges to be addressed and inform the future work section, which is the final section of the chapter. The cconclusions and contributions of the research methodologies are now discussed.

9.2 Research Methodologies Conclusions

An RtD methodology was mainly employed to explore this research via practice-based iterative prototyping, which also incorporated additional methodologies of actuation and sensing. Employing an RtD methodology as the means of carrying out this research has enabled contribution to other areas of design research methodologies based on the definitions described by Forlizzi et al (Forlizzi et al., 2009b). The contributions provide a framework for design and fabrication methodologies that can guide processes of material computation without predefining properties of the individual material units.

In regards to contributions for **Research on (or about) Design:** the series of experiments have highlighted a design process that centres around and engages with parameters of stimuli in order to understand *how* to guide processes of material computation. Within architectural research, design and fabrication processes utilise and advance CAD / CAM technologies, which typically treat materials as inert. However, current digital design tools have begun to engage with and based designs on multiple material properties, which has enabled the physical fabrication of increasingly sophisticated, multi-functional structures (Richards and Amos, 2015, Bader et al., 2016a, Richards and Amos, 2016, Richards et al., 2017, Bader et al., 2018a). However, the advancements in CAM / fabrication processes typically have enabled extremely accurate and multi-material properties to be achieved (Oxman, 2011b, Oxman et al., 2011, Soldevila et al., 2015, Bader et al., 2016a, Richards et al., 2017, Bader et al., 2018c) but still treat materials as inert and physical form is imposed upon them. Meaning, the CAM processes do not specifically leverage or engage with a materials ability to compute form, which ultimately limits the physical structures capacities e.g.

self-reconfiguration, self-assembly, self-adaption or self-healing. This research demonstrates that rethinking design processes to centre around engaging with material computational processes by inducing and manipulating stimuli parameters can generate highly desirable physical material properties and abilities such as self-reconfiguration, self-assembly, self-adaption or self-healing, that significantly, can be tuned and adapted across dimensions (2D – 3D), length scales and time scales.

In regards to contributions for **Research for Design:** the series of experiments have highlighted a design process that: 1) guide material interactions by inducing stimuli to create turbulence within the closed system so desirable material activity is carried out. 2) The requirement of non-linear design tools / process in order to maintain favourable environmental conditions so interrelationships can be determined and regulated so desirable material properties can be fabricated in relations to stimuli.

These strategies of inducing and maintain environmental conditions to generate a fabrication process based on turbulence can be applied to other material platforms, such as protocells or bacteria, where the activity for these materials platforms is based on threshold conditions in order to 1) guide the material interactions and processes (Dade-Robertson et al., 2015, Dade-Robertson et al., 2013) and 2) preventing the closed system reaching a state of equilibrium, which results in material activity stopping (Armstrong, 2014). However, utilisng these material platforms could address issues of associations as the material units themselves can self-sense and perform certain actions based on threshold environmental conditions (Armstrong, 2014, Cejkova et al., 2016, Dade-Robertson et al., 2016a, Dade-Robertson et al., 2017b, Dade-Robertson et al., 2018b, Čejková et al., 2018).

In regards to contributions for **Research through Design:** the research has contributed towards the rethinking of design and fabrication processes and their relationships, from a typically linear process to an iterative / inter-related process. Significantly, this research establishes a design and fabrication process that can leverage and guide material computational processes by creating *tuneable environments* and governing its parameters to create *favourable condition* by monitoring the stimuli's resultant effects. Feedback between digital design, fabrication, material properties and stimuli was not achieved within the system due to the complex interrelationships. However, this research establishes design principles for developing an adaptive design and fabrication system. These principles can extend the research of *Persistent modelling and Self-Assembly,* in architectural design and fabrication research, by effectively combing them, without the need for predefining properties of the material units (e.g. geometry, interface connections, composition, density). Limitations to employing an RtD methodology have arisen over the course of this research, which will be discussed next.

9.2.1 Methodology Limitations

An RtD methodology has been employed to carry out this research, which has enabled a re-thinking of future architectural design and fabrication processes. The two main benefits of utilising an RtD methodology are: 1) design and fabrication processes can be re-imagined without being constrained to incremental improvements of current processes. For example, incremental improvements to design and fabrication processes based on 3D printing accuracy, 3D printing multi-materiality, or material synthesis techniques for more exotic materials are not explored. 2) An RtD methodology does not set out to prove or falsify a specific / set process for exploring how programmable self-assembly can be tuned or adapted throughout the fabrication process. Because of these two benefits though, which have enabled explorations, an RtD methodology has become limited to the extent in which the prototypes have been developed as it does not help to improve the control over the more subtle material properties generated within both material platforms. For example, within the series of mineral accretion experiments, RtD has not enabled association to be made between multiple stimuli, conditions and material properties (variable material porosity, density or surface textures) and how they are generated over time.

In order to address these challenges, a shift towards traditional science and engineering methodologies could be employed to help understand these interrelationships within the prototypes so material properties can be finely tuned and adapted with more accuracy. However, utilising an RtD methodology that is practice-based and has created multiple artefacts / prototypes has enabled interdisciplinary collaborations throughout the course of this research, which highlights a combination of methods and further interdisciplinary collaborations can address issues of control.

9.3 Adaptive Design and Fabrication: Details of Contributions & the Overall Conclusions

This section expands on the main contributions and overall conclusions produced from this research based on the main properties of the prototyped and the material properties the systems enable and generate.

9.3.1 Interrelationships

Utilising material platforms that perform material computation (e.g. self-assemble) when a stimulus is supplied to them (e.g. electrical current or fluid agitation) has resulted in a novel approach for design and fabrication processes, which highlight the benefits of a non-deterministic fabrication process (Tibbits and Flavello, 2013). For example, highly desirable shapes / component organisations, material distributions / compositions or fabrication orders may arise within a non-deterministic fabrication process, which may not have been previously conceived during design stages. Significantly, these desirable properties and the ability to leverage material computational processes have been further enhanced through the interrelationships present within the material platforms used and then incorporating them into a system. This is evidenced in the extremely diverse range of emergent material properties generated within all of the prototype systems / experiments at various scales, dimensions and time scales. The design and fabrication process developed further extends these desirable abilities as the system directly seeks to engage with the material computational processes and interrelationships so as to tune and adapt material properties on the fly by altering stimuli's parameters (e.g. magnitude, location, duration). These interrelationships and how they have been understood and developed through a series of iterative prototypes has established that design and fabrication processes do not have to treat materials as inert and form does not have to be imposed upon the materials. Meaning, structures, objects or potentially wearable's (e.g. medical splints or fashion) created using these methodologies could have their properties tuned and adapted in relation to their local and global properties as well as fluctuating stimuli. Imagine an architectural structure that could tune and adapt is material properties volumetrically, across its' length scale (from local material scale to global scale) and across various time scales. Or self-reconfigure and self-heal based on aesthetic, climatic, performance demands or when damaged. Physical structures instilled with these interrelationships could also lead to reduced material waste and novel construction processes within the architecture industry, paving the way for decarbonising future cities by creating new forms of *'living architecture'*.

However, in order to understand the properties of the material platforms interrelationships and begin to solidify a discourse between digital design representations / tools, fabrication processes and material properties two other important principles / strategies are required, which arose from this research. These are: 1) developing a fabrication process based on *'tuneable environments'* in order to interact with and guide the material platforms interrelationships. 2) Determine feedback mechanisms present within the material platform when stimuli are induced based on the material properties generated. These two strategies and their conclusions are discussed next.

9.3.2 Tuneable Environments

This research defines *tuneable environments* as; a set of physical stimuli (e.g. temperature, pH) that are adjusted by digital design tools to alter the conditions of a volumetric space that contain self-assembling materials. The series of iterative prototypes helped to develop this notion and establish that it can be employed as the fabrication processes, where various stimuli (e.g. electrical current, temperature, agitation) and their parameters (e.g. time, magnitude, location) can be used to guide material scale computation processes (e.g. self-assembly). The development of a fabrication system based on tuneable environments further facilitates:

- Physical local (material properties) and global properties (shape, patterns, surface textures) of a structure or object to be altered, simply by subjecting them to stimuli that have a discourse with these properties and varying the stimuli's parameters to generate desired properties.

- Applications across multiple material platforms that enable or are based on material computation. This is as established as two material platforms are used in the series of experiments within this research. Experiments 01 - 07 use mineral accretion processes, where variable material volumes, textures, compositions and densities are grown upon cathode scaffolds. Experiments 08 - 10 use various paint, ink and additional materials (e.g. silicone and sugar syrup) to generate diverse 2D and 3D patterns and properties that can be multi-scalar, multi-dimensional and multi-material.
- Refining tuneable environments requires non-linear associations in order to create favourable environments and understand interrelationships.

Varying the stimuli's parameters that make up the tuneable environment can be done manually (highlighted in experiments 01 - 04) or via digital design representations / tools if hardware is incorporated into the system (e.g. micro-controllers and actuation devices) (highlighted in experiments 05 - 07 and 10). Significantly, incorporating digital design representations and hardware to control the parameters of tuneable environments enables a novel design and fabrication process, which extends and contributes to the research area of *persistent modelling* (Ayres, 2012b) as material scale self-assembly is incorporated. Additionally, design and fabrication process based on tuneable environments and interrelationships also extends self-assembly research within an architectural design and fabrication context (Tibbits, 2011, Tibbits, 2012a, Tibbits and Cheung, 2012, Tibbits and Flavello, 2013, Tibbits, 2014b, Tibbits, 2016, Papadopoulou et al., 2017). This is because the material results from the experiments establish that self-assembly occurs: 1) on the material scale. 2) Without the need for predefining material component properties (e.g. geometries and connection details), which extends to role energy plays within the system. 3) Without the need for directly embedding material units with sensors or having to design material interface connection details. However, in order to achieve feedback and self-error correction when using material scale self-assembly design processes or material platforms must be developed or used, which can determine or mediate the interrelationships generate when using stimuli as the fabrication mechanism.

A design and fabrication process that enables interrelationships and multiple material properties generated by inducing and varying multiple parameters of the stimuli result in high degrees of freedom / flexibility, which could have various benefits within a range of industries, from manufacturing to the medical or even the entertainment industries. Imagine a sophisticated type of *'wet fabrication process'*, where objects, components or structures are rapidly grown within tanks of liquid. This could revolutionise typical manufacturing processes that initially require expensive tooling and set-up costs. A wet fabrication process could additionally enable products, components or structures to updated by re-inserting them back into the tank of liquid and subjecting it to stimuli that could tune its properties based on sensor data recorded, forming a sort of digital twin (Grieves, 2016, Burnett et al., 2019), or through materials embedded with memory (Koch et al., 2019). For medical applications, a wet fabrication process could be used to directly grow highly customised medical splints or more comfortable prosthetics with greater material variability around the patients' limb when submerged directly into the tank of liquid, which would significantly reduce waiting times along with material waste generated from the additional stages currently required. Finally, rapid wet fabrication processes could lead to new types of physical holograms, where physical materials rapidly change properties to form 3D physical images.

However, the flexibility of these design and fabrication systems also raises two main challenges. *Firstly,* issues of control over material properties are raised, and *secondly,* the issue of feedback between stimuli induced and the material properties generated. Although these seem similar, they are discussed in the limitations section separately.

9.3.3 Associations and Feedback.

How feedback can be developed between material properties generated and the stimuli used to generate them is established only within the mineral accretion series of experiments. Additionally, the collection of experiments has helped highlight parameters for developing feedback and guiding multiple material properties across scales and dimensions.

Typically, material units capable of self-assembly and self-sensing that also enable a discourse with digital design tools usually directly embed the material units with sensors (Frazer et al., 1980, Frazer, 1995, Gilpin et al., 2010, Gilpin and Rus, 2010, Gilpin and Rus, 2012, Romanishin et al., 2013, Levi et al., 2014). This is an alternative strategy to this research, which enables high degrees of control as detailed information on neighbouring material interactions can be achieved. However, it results in two primary limitations to: 1) the scalability of the material resolution as the material units have pre-designed geometries. 2) The multi-materiality of the system, as the material units are homogenous and mechanical. However, it has been demonstrated that self-assembly accuracy can be improved by combining these self-sensing units with external stimuli to guide material interactions (White, 2005, Zykov and Lipson, 2007). Because of these two reasons along with the benefits of inducing stimuli as the predominant mechanism of fabrication was explored and addresses the objectives of this research. However, in order to tune and adapt as well as determine if desirable material properties have been grown when utilising stimuli as the fabrication mechanism feedback is essential.

The series of mineral accretion experiments establish that direct associations between feedback mechanism (stimuli and resultant conditions) and material properties cannot be determined due to the complex interrelationships highlighted in experiment 07. Instead, the collection of mineral accretion experiments establish a series of design principles that build towards enabling feedback within design and fabrication process based on material scale self-assembly and stimuli. These principles are discussed in the conclusion of experiment 07 but the terms defined and how they impact feedback are: 1) Foundational / substrate material properties. 2) Variable substrate materials. 3) Favourable conditions. 4). Maintaining favourable conditions. 5) Directly integrated sensors vs external sensors. 6) Non-linear associations. Exploring these principles further could ultimately lead to increased self-assembling material abilities, without the need for predefining the properties of material units. Enabling feedback would lead to improved abilities of self-reconfiguration, self-healing as well as tuning and adapting variable material properties at increased resolutions that can occur across scales and dimensions within a structure. Additionally, feedback would enable a more robust discourse between digital design tools and their parameter associations with stimuli, a more tuneable fabrication process and improved understandings of material properties and stimuli parameters / interrelationship.

These non linear associations appear to be a result of incorporating sensor externally to the materials, which was done so material scale self-assembly could be achieved but highlighted that the materials are effectively emitting signals. An alternative approach to addressing the issue of feedback though could be to directly embed material units with self-sensing abilities on the material scale so they can respond to threshold conditions (Dade-Robertson et al., 2013, Amos, 2014, Cejkova et al., 2014, Dade-Robertson et al., 2015, Cejkova et al., 2016, Čejková et al., 2018, Koch et al., 2019) However, these materials still have limited feedback with design representations but the notion of utilising material that can emit conditions or signals could extend these areas of research to create increasing sophisticated, reliable and robust material systems, which are guided by stimuli.

9.3.4 Contrasting Conditions.

Feedback is not achieved in experiments 08 - 10 as they explore how tuneable environments can be employed to guide material patterns without predefined scaffold structures. Instead, these experiments build on the idea of contrasting conditions in order to move away from the rigid scaffold structures used within the mineral accretion experiments. Significantly, within these material platforms contrasting conditions took the form of contrasting materials, which inhibited material interactions and acted as semi-rigid scaffolds. The effects of a semi-rigid scaffold are particularly evident in the 2D paint experiments that incorporated silicone and the 3D ink diffusion experiment that used vegetable glycerine as the support material. The combinations of these materials enabled several robust material properties. These are:

- 2D local void spaces and defined boundary edges are created but critically, a threshold volume of contrasting material is required to inhibit paint interactions.
- 3D volumetric diffusion patterns were inhibited and suspended in time and space as vegetable glycerine inhibited diffusion. Resulting in volumetric, delicate, multi-material patterns being generated.

- The 3D ink diffusion experiments also highlight that the contrasting materials do not have to be binary in nature, in the sense that they can only either inhibit or enable material interactions. This is demonstrated in the experiment that uses a sugar syrup support material and demonstrates that material interactions can be slowed as well as enabling multi-dimensional material properties to be generated that can then be manipulated by inducing stimulus through the support materials.

Engaging with material properties by combing contrasting materials highlights new possible 3D printing processes that could be: 1) rapid, 2) volumetric and 3) 3D adaptive by inducing stimuli.

9.4 Summary of Prototype Properties & Limitations

Before discussing the limitations of this research a brief list and description of the properties, key factors and limitations for each of the prototypes is given, which highlights how the main contributions emerged. The main properties, key factors and limitations for the prototypes developed using the mineral accretion process are now discussed and broken down into groups or individual experiments.

Experiments 01 - 03

- The overriding factor of gravity needs to be offset in order to grow materials volumetrically, which requires the system to induce turbulence via agitation.
- Proliferation can occur if threshold conditions are reached.
- XRD, XRF and SEM analysis establish that a multi-material system is possible when developing a design and fabrication system based on inducing stimuli.
- No localised control is achieved due to the cathodes typologies used, which are all physically connected.

Experiment 04

- Physically distributing cathode wires enables localised control over variable material properties.
- Interrelationships between stimuli, variable material properties and conditions can be created by altering the stimuli's parameters manually.
- Manually varying the stimuli's parameters leads to the notion of tuneable environments.
- Manual control over the stimuli's parameters and not monitoring the system's conditions limits the understanding of the interrelationships being created.

Experiment 05 - 06

- Material properties can be grown based on data, which creates physically transformable data-visualisation

- Incorporating hardware enables digital design representations and it's parameters to be associated with / mapped to the stimuli's parameters and material properties, which extends persistent modelling and self-assembly strategies.
- Predicting growth properties based on preliminary results do not generate accurate and reliable growth results as the fabrication process is non-linear and non-deterministic.
- Unreliable growth results highlight the requirement of feedback between interrelationships of the system's parameters that can be associated with one another in order to achieve more reliable growth results.

Experiment 07

- Defines a series of design principles for developing a design and fabrication system that utilises stimuli as the fabrication mechanism in order to guide material scale self-assembly and material properties generated. The design principles and issues they highlight are: 1) Foundational / substrate material properties. 2) Variable substrate materials. 3) Favourable conditions. 4). Maintaining favourable conditions. 5) Directly integrated sensors vs external sensors. 6) Non-linear associations
- Enraging with material computation process by re-thinking fabrication processes to engage with material computation through stimulus highlights that inert materials do not have to have from imposed upon them.
- Incorporating sensors external to the material units in the system and using stimuli to guide material interactions establishes that materials can emit signals. This results in complex interrelationships being generated, making design processes based on direct association redundant if feedback is to be established.

Experiment 08 - 10

- Tuneable environments can be applied across multiple material platforms that can perform material computation.
- Contrasting materials can be used as a means to move away from rigidly defined scaffold structures but require a threshold volume.
- Contrasting materials can also have variable / gradient properties, which can slow and suspend the material computational process and simultaneously create complex multi-dimensional, multi-scalar and multi-material patterns.
- Combining contrasting and variably contrasting materials with stimuli enable material computational processes to be guided and complex material properties to be reconfigured.

However, beyond these key principles, various limitations and future challenges have been highlighted. The main limitations of this research are discussed next.

9.5 Limitations

The limitations of this research will focus on two main points, which appear to be converging issues for other research areas that are exploring design and fabrication processes based on stimuli and material computation, which result in limited control over generating desirable material properties based on limited feedback and an understanding of the interrelationships within these design and fabrication systems. The two main areas are: 1) the discrepancies between digital representations and physical representations. 2) Problems of design tools based on direction associations between design parameters, material properties and stimuli. The limitations of the research methodologies have been discussed in the previous section **9.2.1**.

9.5.1 Digital Resolution Limitations

A significant limitation within this research is the inability of the digital design representation based on associated properties to account for physical materiality and complex interrelationships generated in all of the experiments. This inability of the design tool to account for variable material properties is also highlighted within *persistent modelling* (Ayres, 2012a). The inabilities of the design tools used within this research and in persistent modelling are due to the design representations being based on *boundary representations (B-reps)* along with the linear cause and effect relationships that are predefined and cannot adapt based on material data. Significantly, B-reps treat the internal make-up / materiality of a represented geometry as homogenous (Richards and Amos, 2016). The problem is that physical materials are not homogenous especially if they are made up of many granular elements (e.g. crystalline structures, fibres). Ayres appears to address this challenge by utilising materials that behave more homogenously (Ayres et al., 2014). The strategy of utilising materials that behave homogeneously can also be applied to an extent within material self-assembly processes that are based on a set of distributed parts, where that material units have been pre-designed and are effectively identical and homogenous (Tibbits, 2011, Tibbits, 2012a, Tibbits and Flavello, 2013, Tibbits, 2014b, Papadopoulou et al., 2017, Tibbits, 2017b, Gilpin et al., 2010, Gilpin and Rus, 2010, Gilpin and Rus, 2012, Romanishin et al., 2013). However, this strategy becomes limited even within these distributed material systems that are made up of uniform material units as the internal organisation could not be accounted for within B-rep digital design tools. Additionally, these discrepancies become more apparent as evidenced by this research when using a material platform that: 1) is extremely granular. 2) Is not composed of pre-designed material units as there is no predefined control over the materials geometries that can result in recursive patterns (Tibbits, 2014b). 3) Has inherent interrelationships within it when subjected to stimuli as there are high degrees of freedom within the non-deterministic fabrication process.

Gilpin highlights that converging the digital design representations with and basing it on the material units resolution enables localised material relationships or interactions to be represented accurately (Gilpin et al., 2010, Gilpin and Rus, 2012). The problem is though, the design tool itself has a low resolution, is based on predestined material units and direct associations. However, it has been established that material-based design computation strategies are capable of generating multi-material structures with variable volumetric properties as they are composed of a programme the digital 3D structures material units (typically voxels) (Doubrovski et al., 2015, Richards and Amos, 2015, Bader et al., 2016a, Richards and Amos, 2016, Richards et al., 2017). Incorporating these sophisticated forms of digital design tools could enable the diverse variable properties generated within the experiments of this research to be accounted for. Additionally, these forms of digital design tools do not also enable indirect (non-linear) parameter associations between material properties and design demands (Richards and Amos, 2015), which could become extremely valuable within this research based on the high degrees of freedom within the fabrication process due to the multiple interrelationships and could also enhance the feedback resolution within the system. These indirect associations will be discussed further next.

9.5.2 Limitations of Direct Associations

Dierichs and Menges have demonstrated that material interactions can be accurately digitally simulated when using designed granular materials within a non-deterministic fabrication process (Dierichs and Menges, 2016, Dierichs and Menges, 2017a). However, these simulations, physical material units and fabrication process used are not based on interrelationships between stimuli and variable material properties. Meaning, the interrelationships within this research cannot be further understood when using design tools based on direct associations. In order to engage with and uncover subtle interrelationships within the design and fabrication system developed by this research design tools are needed that are based on non-linear associations and can also generate associations between design parameters, stimuli and material properties. The generative design strategy developed by Richards and Amos, which uses the CPPN-NEAT algorithms, enables the non-linear associations (Richards and Amos, 2015, Richards and Amos, 2016). Utilising these sophisticated design tools to uncover complex interrelationships within the system could enable greater degrees of control, which could be further enhanced by incorporating hardware that enables machine learning so sensor values data can be further understood.

Attaining greater control over these interrelationships could pave the way for a totally new design and fabrication processes where complex multi-material structures can be volumetrically grown. These structures can then have their material properties tuned and adapted across time scales and across length scales. These forms of design and fabrication processes could create structures that have highly desirable abilities present biological structures (e.g. scalability, self-healing, self-adapting and self-organising) and lead to urban cities that behave like material eco-system, which could share material resources highlight new possibilities of addressing current global crises like global warming, diminishing resources, excessive waste and increasing pollution levels.

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