Designing Parametric Matter:

Exploring adaptive 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 Prof. Nick Dunn and Dr Jason Alexander.

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Abstract

3D digital models 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 structure's/object's colour, size, geometry and topology by adjusting values associated with those attributes. However, when these digital models are fabricated using traditional, highly deterministic fabrication processes, where form is imposed upon materials, the physical structure typically loses all of these adaptive abilities. These reduced physical abilities are primarily a result of how design representations are fabricated and if they can maintain relationships with the physical counterpart/materials post-fabrication. If relationships between design representations and physical materials are removed it can lead to redundancy and significant material waste as the material make-up of a physical structure can't accommodate fluctuating design demands (e.g. aesthetics, structural, programmatic). This raises the question: *how can structures be grown and adapted throughout fabrication processes using programmable self-assembly?*

This research explores and documents the development of an adaptive design and fabrication system through a series of '*material probes'*, which begin to address this aim. The series of material probes have been carried out using *research through design* as an approach, which enables an exploration and highlights challenges, developments and reflections of the design process as well as, the potentials of rethinking design and fabrication processes and their relationships with materials. Importantly, the material probes engage with material computation (e.g. self-assembly/autonomous-assembly) and demonstrate that various patterns, shapes and structures can have various material properties (e.g. volume, composition, texture, shape) tuned and adapted throughout the fabrication process by inducing stimuli (e.g. temperature, magnetism, electrical current) and altering parameters of stimuli (e.g. duration, magnitude, location). As a result, the structures created can tune and adapt their material properties across length scales and time

scales. These adaptive capacities are enabled by creating what is termed ‘*tuneable environments*. Significantly, tuneable environments fundamentally rethink design and fabrication processes and their relationships with materials, since inducing stimuli and controlling their parameters can be used as an approach to creating programmable self-assembly. Consequently, the material platforms’ units of matter do not have to have pre-design properties (e.g. geometries, interfaces)

This research points towards future potentials of structures that can physically evolve and lead to the decarbonising of urban contexts where they could behave like ‘living material eco-systems’, and resources are shared to meet fluctuating demands through passive means.

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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, p16)

Physical adaptation and change are 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), from global to local. Global properties could include shape and porosity; and local material properties may include composition, location, volume, and 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. As a result, each of them acts as an active design agent / driver (Oxman, 2010a) and establishes relationships between them. This results in, shape/form and material properties being interlinked with the forces (stimuli) that act upon them (Vogel, 2003), which enables external forces to inform adaption of the microstructure's properties over time (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 in regards to form and material properties being tuned and adapted, and across time scales and the designs' length scales, from material unit scale, such as molecules, to the global shapes they make up. However, 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 (Schumacher, 2009a; Burry, 2011; Bhooshan, 2017), which typically manipulates the geometric components of a design based on numerical values being altered that are associated with the designs' parameters. Recently, these digital shape-changing abilities have been able to mimic bottom-up biological processes and have resulted in the term *material-based design computation* (Oxman and Rosenberg, 2007; Oxman, 2010a). Importantly, local material properties affect global properties and vice versa, but performance of both can be orientated to fluctuating demands, such as live loading informing which informs: material location, rigidity, volume and global shape (Oxman, 2010b). Significantly, the 3D digital design models generated from these processes mean they 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?* To address this challenge this thesis explores and investigates design and fabrication processes to re-imagine them and establishes an approach for building towards physical designs (patterns, shapes, structures) that can adapt their properties. To explore this area, it is broken down into the several predominant components that can make up the proposed adaptive design and fabrication process. 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, processes and mechanisms must be identified.

Design

As mentioned previously, advancements in Computer Aided-Design (CAD) software and methods have produced digital models that can tune (Jabi, 2013), adapt (Richards and Amos, 2016) and evolve (Richards and Amos, 2014; Doursat and Sánchez, 2014) their properties. This 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 discussed are: 1) associative modelling/parametric design (Burry, 2003; Woodbury, 2010), which can be seen as being able to tune their properties within set/predefined parameters; 2) *material-based design computation* (Oxman and Rosenberg, 2007; 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 that can change their attributes (size, texture, colour and density, among many others) in real-time, by generally altering: numerical values, data sets or criteria constraints; b) they enable adaptation across dimensions and scales, which means that the 3D global shape can adapt based on its local material properties as demands fluctuate; and c) generating solutions based on relationships between multiple design demands, a model's attributes and material properties creates integrated (meets 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 artificial materials and structures is due to traditional design and fabrication processes, where inert materials are used (Spiller and Armstrong, 2011a) and 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 homogenous and can compute forms when subjected to varying conditions, e.g., loading or tension, enables their dynamic and shape-changing capacities to be leveraged. With these notions of materiality and the precedent of biological processes in mind design and fabrication processes are re-imagined, in regards to how materials can be interacted with by engaging with material processes, to: 1) instil material computation within a structures material make-up to enable physical adaptation, and 2) achieve a discourse between digital design tools and materials.

Materials

A suitable material platform or process must be identified in order to begin to engage with, manipulate and guide material processes/material computation to achieve physically tuneable and adaptive structures. Material self-assembly is chosen because: a) it is scalable and can be witnessed from molecular scale to a planetary weather system (Whitesides and Grzybowski, 2002); b) the global properties of a structure are based on its local material interactions, which give rise to emergent properties (De Wolf and Holvoet, 2004) that could be highly desirable; and c) it occurs within multiple material platforms, which will be explored through what the thesis terms *'material probes'*. How and why this term is used will be discussed later.

Re-imagining design and fabrication processes by incorporating material platforms that enable material computational processes raises the question; *how can material computational processes (e.g. self-assembly) be guided via digital design tools to create physically adaptive structures, so a discourse and relationships are maintained between design, fabrication and material properties?* The rethinking of design and fabrication processes aligns with an emerging area of research, Active Matter (Tibbis, 2017). Active Matter focuses on creating physical materials at various scales (from nano to meso to macro), which; *"self-assemble, 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"* (Tibbis, 2017). Current research in the area of design and self-assembly has established material types and multiple methods and the required ingredients to achieve objects and structures that can self-assemble. The defined ingredients within a design context 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 i.e. the material units are programmed; 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 these strategies address challenges of creating a robust fabrication process by self-error correcting when subjected to noise i.e. energy, by predefining the material components properties, such as geometries and interfaces of the material units or material location, orientation and composition of a structure. They are robust because these processes have multiple assembly possibilities but fabricate pre-determined objects as the units of matter have predefined properties. Thus, the end result is deterministic but they have been assembled through a non-deterministic fabrication process. The non-deterministic fabrication process affords a degree of flexibility, enabling various shapes, forms and fabrication sequences to be explored that may not have been conceived during design phases, which could be highly desirable (Tibbits and Flavello, 2013).

Energy in these systems is used as a way to alter environmental conditions, which enables varying conditions to initiate self-assembly. However, the parameters (e.g. magnitude, location, duration) of the various energy types used (e.g. agitation, temperature) is typically not governed throughout the fabrication process, both in a design research context and when using material units with designed properties (Tibbits, 2014b; Papadopoulou et al., 2017). Essentially, energy is random. As it is a defined ingredient within these material systems (Tibbits, 2016; Tibbits, 2012a) it has a significant impact on self-assembly processes and it has been demonstrated that interactions can be guided, and the speed of self-assembly of a structure can be increased when the parameters of energy are tuned (Zykov and Lipson, 2007; Tolley and Lipson, 2010). Because of the role energy/varying environmental conditions play within these self-assembly processes, the material probes within this research explore how varying properties of energy within material platforms that do not use pre-designed units of matter can be achieved so it becomes an informed material stimulus that guides material interactions. The two primary reasons for exploring how varying energy/environmental conditions so they can act as a stimulus are: 1) its potential abilities to guide the units of matter of a material platform that have not been pre-designed, which could lead to increased scalability, material resolution and variable material properties being generated; and 2) the ability to induce energy to act as a stimuli, which provides a means of linking digital design tools with fabrication and materials in an iterative system, as established by Ayres (Ayres, 2011). The first point can be witnessed in several examples that range from art, meteorology and micro-crystal growth. Artist, Perry Hall, asks how a painting can 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 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 alterations/augmentations to digital design tools/representations. The second point is established by Ayers '*persistent modelling'* strategy (Ayres, 2012b), where predefined metal components are physically deformed as water pressure is increased. The water pressure is governed by a digital design representation (i.e. digital parametric model) that controls and monitors the internal pressure the sheets are subjected to.

By employing energy (e.g. temperature, agitation) to act as the physical stimulus and explore how parameters of self-assembly can be guided, the thesis demonstrates that it is possible to utilise material platforms that do not require their units of matter to have pre-designed properties to grow various shapes and patterns. Furthermore, varying parameters of stimuli can be used to tune and adapt material properties of the shapes grown, which also enables a discourse and interrelationships between design, fabrication and material properties throughout the fabrication process. Tuning and adapting parameters of stimuli during/throughout the fabrication process has resulted in the approach of '*tuneable environments'* being developed. The thesis investigates and develops the strategy of tuneable environments through a series of material probes. These are iteratively developed and used to explore novel approaches for rethinking current design and fabrication processes, which are typically linear, to create design and fabrication processes that are adaptive, iterative and interrelated with material properties. The material probes and process of developing tuneable environments evidence that it is possible to grow 2D or 3D shapes and patterns from self-assembling materials, which, significantly, can have various material properties tuned and adapted at increased resolutions and degrees of freedom when properties of the material units are not pre-designed. The thesis defines tuneable environments as '*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, textures, volumes, densities, compositions, which can be tuned and adapted'*. The use and role of stimuli within the material probes facilitate engagement with material units that do not have pre-designed properties; however, this raises new challenges for design and fabrication processes based on tuneable environments, such as accuracy, feedback and functionality, which need to be further explored and understood to determine associations between design demands (e.g. aesthetics, structural performance), material properties (e.g. composition, location, density), stimuli parameters (e.g. location, duration, magnitude) and resultant conditions generated (e.g. an increase in temperature or pH).

Tuneable environments have been explored using a series of material probes that utilise two material platforms. Principally, the mineral accretion process

(Hilbertz, 1979), which is the electrolysis of seawater. Here material aggregation is used to grow materials with variable properties on 2D and 3D cathode scaffolds. Secondly, acrylic paints, inks and support materials are used to explore 2D and 3D liquid diffusion patterns to understand how self-assembly can be guided without being globally constrained to 2D and 3D scaffolds, where the scaffolds can be seen as the infrastructure behind the self-assembly processes.

The thesis contributes towards rethinking design and fabrication processes where form is not imposed upon materials, which points towards the future possibility of being able to create physical designs (e.g. architectural structures, medial splints, fashion items) that have materially adaptive abilities. The approach of tuneable environments could lay the foundations for a range of applications, such as medical procedures where splints or prosthetics can be directly grown onto a patient's limb, which also grow and adapt with the patient to increase comfort, healing rates and movement; and, potentially, new forms of architectural structures and infrastructures that act as *'living material ecosystems'*. Imagine the materials, components and structures of an urban or rural context being able to physically adapt as a collective across the context's length scales (from material unit to urban scale) in response to fluctuating design demands (e.g. climatic/seasonal, congestion, air pollution, programme change, resource demands), where adaption could be achieved through materials and other associated resources being shared. This could lead to a circular material system, where architectural structures can self-heal, self-reconfigure and self-adapt various material properties at extremely granular resolutions.

1.1 Aims & Objectives

Currently, there is a separation between the discourse and 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 post-fabrication. The loss of discourse and feedback results in the inability of physical objects to update their properties (shape, colour, texture, composition), which 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, this illustrates 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 make up the corresponding physical shapes and patterns, so any digital augmentations can be fabricated simultaneously. To achieve this, a design and fabrication strategy must be established that enables discourse and potential feedback between digital design tools and processes of material self-assembly, so objects or structures can be physically grown and have their properties manipulated. As a result, design and fabrication processes would be tightly linked, which enables physical objects to tune and adapt their properties across length scales, time scales and dimensions (2D or 3D). Developing approaches to rethink design and fabrication processes will aid further 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.

To begin exploring this overall aim, a series of sub-objectives are defined that will help to contextualise literature surveyed, as well as carrying out a series of *‘material probes’*. The literature reviewed will help to identify design and fabrication strategies, mechanisms and material processes on which to base and develop initial material probes. The material probes are explorative and iterative in nature, and are also 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 self-assembly that do not have properties imposed upon the individual material units. 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 self-assembly of material units that do not have pre-designed properties (e.g. geometries, interface connections, hardware).*

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

3) *To establish a design and fabrication process that creates interrelationships between properties of design, fabrication and self-assembly of material units that do not have pre-designed properties.*

At this stage, no overarching research question is defined because the nature of the research is seen as an explorative approach, which aims to a develop a design and fabrication strategy based on unknown parameters currently in relation to what material platform will be used; how stimuli will be used to interact with the materials; and how properties and associations will be determined between material processes, stimuli and design parameters. This means that developmental questions and reflections will be raised after each material probe or selection of material probes, which will help to develop a design and fabrication strategy that is: 1) not restricted based on predefined assumptions; 2) remains open and flexible enough to explore aspects of interest as well as major challenges or benefits that may emerge from the results; and 3) does not look to define a set method for a design and fabrication process, which could help to develop a strategy that has broader applications.

1.2 Thesis Overview

The thesis contributes towards establishing a novel approach for guiding material self-assembly that does not need to have properties of the individual material units pre-designed. The thesis relates to and extends research carried out in architectural self-assembly (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 models developed by Frei Otto (Otto, 2017). 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 via the mechanism of manipulating environmental stimulus. The literature review forms a sound theoretical basis for developing and carrying out informed prototypes that are seen as '*material probes'*, which explore potentials highlighted within the literature. The material probes are used to establish an approach for creating an adaptive design and fabrication system when using material platforms that do not define properties of the material units. The predominant material platform used to explore this research is the mineral accretion process, which reveals multiple abilities and future challenges. 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.

Chapter 2: Foundations for Adaptation

The chapter examines analogue design 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 (Otto and Rasch, 1995). These analogue models can respond and reconfigure based on a stimulus, which helps to form an understanding of how material computational abilities and relationships can be guided, which 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 representations (boundary representation) compared to the later strategies, which can programme the material make-up/material units of the design. Significantly, the abstraction of the digital processes means the digital representation becomes separated from the physical representation and materials. Consequently, any changes that occur to the digital representation post-production are not physically reflected. This chapter highlights how the 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 simultaneously. This shows that, digital design changes can be accommodated and physically reproduced in real time. However, the materials are typically still treated as inert within CAM processes and do not leverage or engage with material computational abilities. The materials cannot self-assembly or self-reconfigure when conditions are imposed upon them and this results in the inability of the structure to self-heal when damaged or self-adapt as demands change, which generates waste (e.g. energy, financial, material). For this reason, various CAM processes 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 demonstrates how the *'Persistent Modelling'* strategy can maintain relationships between digital representations and physical representations, where digital design models can be used to deform the physical model/structure (Ayres, 2011). This strategy establishes that inducing stimuli (e.g. water pressure) can link digital design tools with physical components. For example, the stimulus is controlled, monitored and represented by the design tool, which manipulates physical components' properties. However, design tools based on boundary representations cannot account for the granular nature of physical materials because the design model treats materials as homogenous. Additional digital tools and strategies are reviewed to understand how they can engage with and guide physical material interactions since the design tools are based on digital material units (typically voxels) or processes present within biology.

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 a restricted resolution in the material system, recursive patterns and predefined responses. To address these issues, alternative material platforms that 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 processes when subjected to stimuli without having properties of the material units predefined. For these reasons, these material platforms are used within the material probes that explore the development of adaptive design and fabrication approaches.

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 process. RtD is employed through iterative practice-based prototyping, which are termed as *material probes*. Terming the practice-based approach as material probes is intended to facilitate an explorative approach, and can be seen to align with the prototypes commonly witnessed within the field of architectural research. The development and reflections from each material probe are also presented as a flow diagram and annotated portfolio. A personal perspective on annotated portfolios is also discussed and how they are felt to be intuitive to capturing the RtD approach, although annotated portfolios were adopted after a significant number of the material probes had been carried out. 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 material probes acting as artefacts/boundary objects. Also discussed are methods of material analysis and why they have been chosen.

Chapter 7: Material Probes, Results & Conclusions: Buildings Towards an Adaptive Design and Fabrication System Using The Mineral Accretion Process.

The iterative development, results and key findings from the series of mineral accretion material probes are presented and discussed within this chapter. Critically, this chapter documents the reflections that informed the areas and parameters explored in developing an adaptive design and fabrication process. Significantly, the material probes explore the process by building from simply inducing a stimulus (electrical current/voltage), which results in a design and fabrication process based on interrelationships, due to the material platform. The material probes develop by inducing creates resultant conditions, which are monitored to find associations between design parameters and material mechanisms.

Examining the parameters and interrelationships of the material probes 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 whether 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 material probes are presented and discussed. Significantly, the results establish that tuneable environments can manipulate generative 2D and 3D patterns. However, it is also established that contrasting material is needed as they can act as a semi-rigid scaffold, which highlights how reproducible patterns and properties can be generated. Additionally, within the 3D ink diffusion material probes the material properties (e.g. density and viscosity) of the contrasting materials not only facilitate more subtle material manipulations but also simultaneously generate gradient-based, multi-dimension, multi-scale, and multi-material properties. These material abilities reimagine 3D printing processes, which are no longer based on layer-by-layer form generation, but on a rapid volumetric fabrication process.

Chapter 9: Conclusions and Key Discoveries

Chapter 9 first discusses the main contribution of *tuneable environments,* which is based on the reflections on the series of material probes as a whole, and presented as an annotated portfolio. Specific conclusions and reflections are discussed following each material probe. The chapter discusses the key findings and main parameters across the material probes and how these can be employed within other relevant research areas. Finally, how RtD and the use of material probs enabled an explorative research approach is discussed, highlighting new approaches and benefits of design and fabrication processes based on interrelationships, which are achieved through *tuneable environments*.

1.4 Clarifying Terms

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

- **Material computation;** the physical material's ability to process information and spontaneously generate patterns, shapes/forms or structures (e.g. self-assembly), which can be transformed/adapted, when stimuli (e.g. temperature, agitation) are induced on to the material units based on individual or collective material properties (Menges, 2012; Menges, 2016).
- **Self-assembly;** *"Self-assembly can be defined as the process by which disordered parts build an ordered structure without humans or machines"* (Papadopoulou et al., 2017, p30). **Autonomous-Assembly**: "*flexible and adaptive construction processes where design and assembly coalesce as a means of production*" (Tibbits, 2017, p9).
- **Unit of Matter;** is the smallest or base unit of the structure in which the material system is based upon and interacted with through stimuli. However, a structure or pattern can contain units of matter that can have their dimensions/sizes manipulated by inducing stimuli. Significantly, the structures unit of matter inform the degrees of freedom within the

fabrication process and result in diverse material properties being generated across the structures length scale. For example, the unit of matter for the material probes that employ the mineral accretion process is molecules of calcium carbonate or magnesium hydroxide. This is because the stimuli in the system produce a chemical reaction that generates two different molecule types, which form two crystal types composed from a vast number of molecules that self-assemble. The unit of matter informs the fabrication process and the structure's degrees of freedom, which can be witnessed across varying length scales of the structure depending on the resolution/dimensions of the unit of matter used, from crystal size, location, orientation (nano) to crystal formation numbers, compositions, density (micro), to material surface textures, volumes, porosities, translucency (meso) and finally to the structure's overall shape, collective composition, collective surface area (macro).

- **Material probes;** the various prototypes/design experiments within this research are termed as material probes, which are used as a personal approach to carry out design research centred around the act of 'making'. Terming the making process and explorations as material probes is based on the idea/term of *probes* developed by Gaver et al. (Gaver et al., 1999) as they are an open approach and facilitate the exploration of unknown opportunities, principles and challenges (Gaver et al., 2004). Material probes are explorative and used to rethink design and fabrication processes that engage with and enable material computational processes (e.g. self-assembly). At this stage, they are based on an individual perspective and reflections as each material probe is developed.
- **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, textures, volumes, densities, compositions, all of which can be tuned and adapted.

- **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 electrodeposition 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, p1). Significantly, the material growth self-assembles on the resolution of molecules 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 whether 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, e.g., 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 (e.g. 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 the process variables. This means that the physical stimuli induced are not monitored or regulated to determine if a desired property has been physically fabricated or grown in relation to one another.
- **Closed loop control system (CLCS);** physical stimuli (control actions) do have feedback with the material properties (process variables) grown. The intention is to determine feedback based on monitoring resultant environmental effects to determine associations between stimuli and material properties (volume, location, shape / pattern). 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 to be 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 material probes carried out within this thesis.

- **Interrelationships;** in the context of the mineral accretion material probes 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

Being able to fabricate artificial structures that can physically adapt their properties across their length scales, from the designs' smallest units of matter (e.g. brick, crystal or cell) to local neighbourhoods of matter to the structure's global properties, could lead to totally novel material abilities and future potentials across a range of scales. Imagine highly customised prosthetics that grow and adapt their material properties (e.g. rigidity, stiffness, smoothness, porosity) with the patient, to improve comfort and physical movement. Or architectural structures and urban contexts that behave like *'living material eco-systems'*, where the buildings can share material resources so they can self-adapt, self-heal and self-reconfigure over time to mediate and address demands to enhance passive strategies. Fabricating artificial structures with these abilities is yet to be fully realised and requires typical design and fabrication relationships, processes and methodologies to be fundamentally reimagined. Imagine, volumetrically growing structures or re-fabricating them within a tank of liquid, where digital updates can be pushed directly into the materials at a granular level so the structures can meet new design demands (e.g. aesthetics, structural, programme).

Surveying architectural design and fabrication research provides a sound starting point to begin to build towards fabrication processes and structures with these adaptive abilities. This is because architectural design and fabrication research offers 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, from associative based digital models (parametric design) (Bhooshan, 2017) to non-associative digital design processes, which enable structures to have their material properties programmed at extremely granular levels (Oxman, 2010a; Bader et al., 2016a; Richards and Amos, 2016). Architectural research also explores the incorporation and development of new fabrication technologies that provide a wide range of processes (Dunn, 2012; Iwamoto, 2013; Gramazio et al., 2014), which enables increasingly complex digital models to be fabricated with incredible accuracy, from multi-material 3D printing (Bader et al., 2018a; Richards et al., 2017) to swarms of robotic units acting as construction agents (Levi et al., 2014) as well as self-sensing (Frazer et al., 1980; Gilpin et al., 2010) and self-propelled material units (Romanishin et al., 2013).

The role and abilities of materials that make up the structure have also been explored more recently, with interdisciplinary research creating new material palettes. For example, it has been demonstrated that installation scale structures are fabricated from a gradient of bio-composite and bio-degradable materials (Soldevila et al., 2014; Soldevila and Oxman, 2015; Soldevila et al., 2015). Wearable scale products that can be bio-augmented (Bader et al., 2016b; Smith et al., 2019a) and the possibility of using bacteria as fabrication agents (Dade-Robertson et al., 2015). It has also been demonstrated that traditionally inert/unresponsive materials can be 'programmed' to respond (e.g. bend and flex) to environmental changes by either, creating composites of thin layers of wood with varied fibre orientations (Reichert et al., 2015; Wood et al., 2018; Wood et al., 2016) or by 3D printing wood (Menges and Reichert, 2015; Correa et al., 2015) and plastics (Tibbits, 2014a; Tibbits et al., 2014) to discreetly control material orientation, type, composition and locations. Furthermore, the typically passive role materials play within the fabrication process has been questioned, which has given rise to two avenues. First the possibility of material units being programmed to act as constructions agents (Armstrong and Spiller, 2010; Hanczyc and Ikegami, 2009), which has been mostly demonstrated via protocells, which are chemical units that can be programmed to: a) self-move to desired locations (Hanczyc, 2011) and solve maze patterns (Cejkova et al., 2014); b) self-sort amongst other chemical units (Čejková et al., 2017); c) deposit materials (Cronin, 2011a); and d) transform their shape and properties under certain conditions (Čejková et al., 2018, Cejkova et al., 2016). Second, material units that can self-assemble and perform computation (e.g. self-error correcting) without the need for incorporating hardware directly into the units themselves as the structure's material units have been '*programmed',* by designing the unit's geometries and interface mechanisms, to instil construction logics within them (Tibbits, 2011; Tibbits, 2012a; Tibbits, 2014b).

However, it can be argued that the challenge of fabricating structures that can adapt multiple properties across their length scale (base material unit to global properties) has yet to be fully realised. A possibility for this is typically due to design and fabrication processes being separated. Current design processes, fabrication methods and the materials used do not enable iterative interrelationships to be established between them. Imagine, physically growing a structure from material units with various properties that self-assemble, where the structures self-assembly process is guided by digital design tools. Hence, any updates to the digital design representation can be pushed directly into the physical materials / structure. To understand and create designs' that can physically adapt based on digital augmentations, literature was surveyed across a wide range of areas, including digital design, digital fabrication, computer science, 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, pattern or structure), that have not been pre-determined in response to changing environmental conditions or stimulus (temperature, humidity, light, loading)'.* Meaning, the intention is not to create or explore a process where the global transformation of a shape or pattern is predefined to an extent with pre-designed material units (Tibbits, 2012b; Papadopoulou et al., 2017), has recursive formations (Tibbits, 2014b) or is set between states when subject to a force or stimulus (Tibbits et al., 2014; Menges and Reichert, 2015; Correa et al., 2015), as these aspects have already been achieved.

Within biology, structures can tune and adapt their properties with greater sensitive across their length scales. 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 adaptions). The organism's adapted forms enable them to become more efficient or desirable in 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 in material properties adapting (composition, shape, density) to demands. An example of biology's ability to tune and adapt material properties 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 for examining related work, which highlights: a) a diverging lineage that maps the focus of form generation of current research compared to this research, 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 (Figure 1); and 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 (Figure 2). Reviewing Otto's experiments helps inform an approach for developing an adaptive design and fabrication system, based on three consistent parameters within his experiments: 1) forces or stimulus; 2) conditions or frameworks; and 3) materials and their properties. Significantly, these parameters are interrelated and brought to light through further examination and not focusing on their form-generating abilities. These parameters provide a scope and a common ground for linking back to and extending current research within digital design and fabrication.

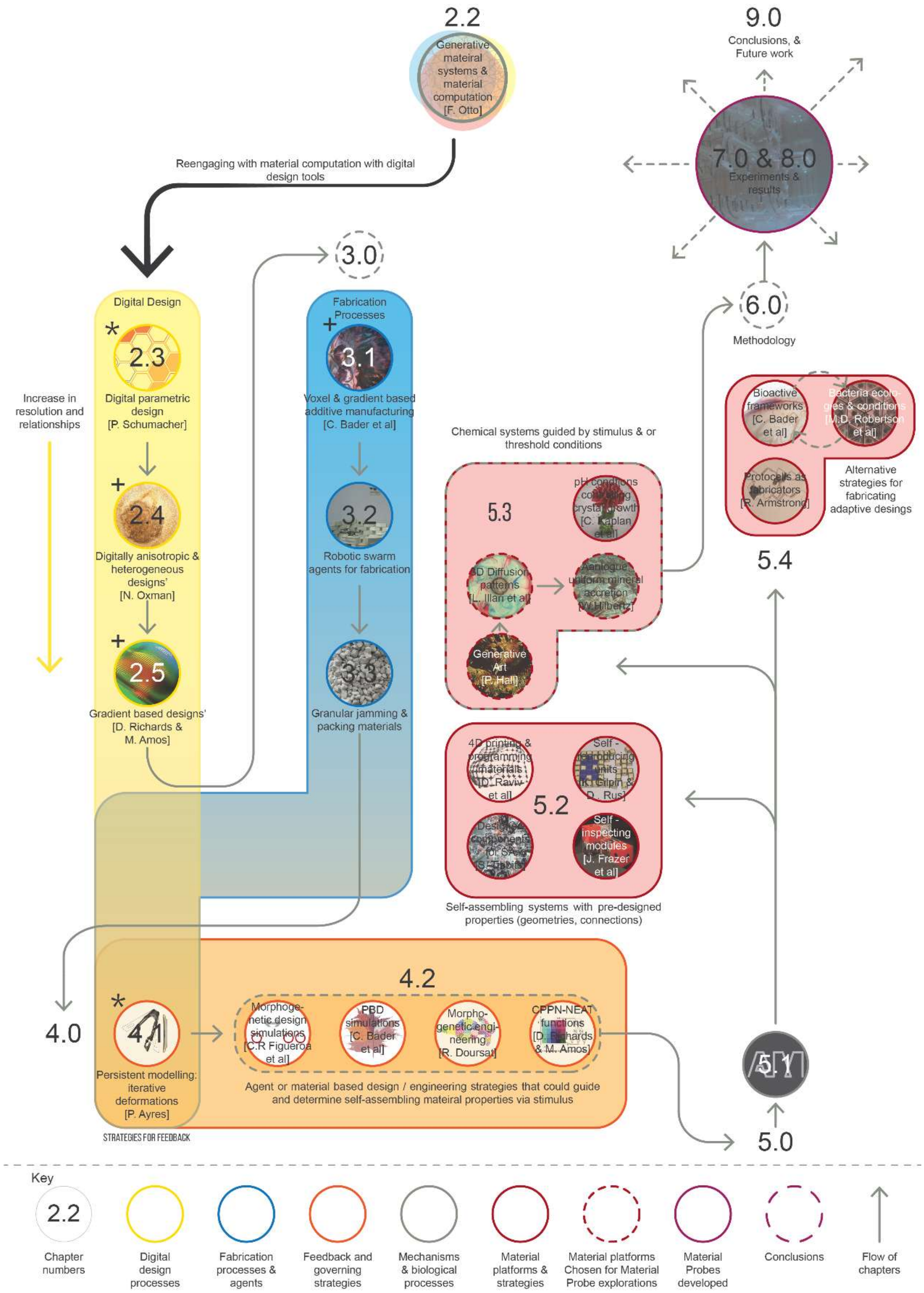
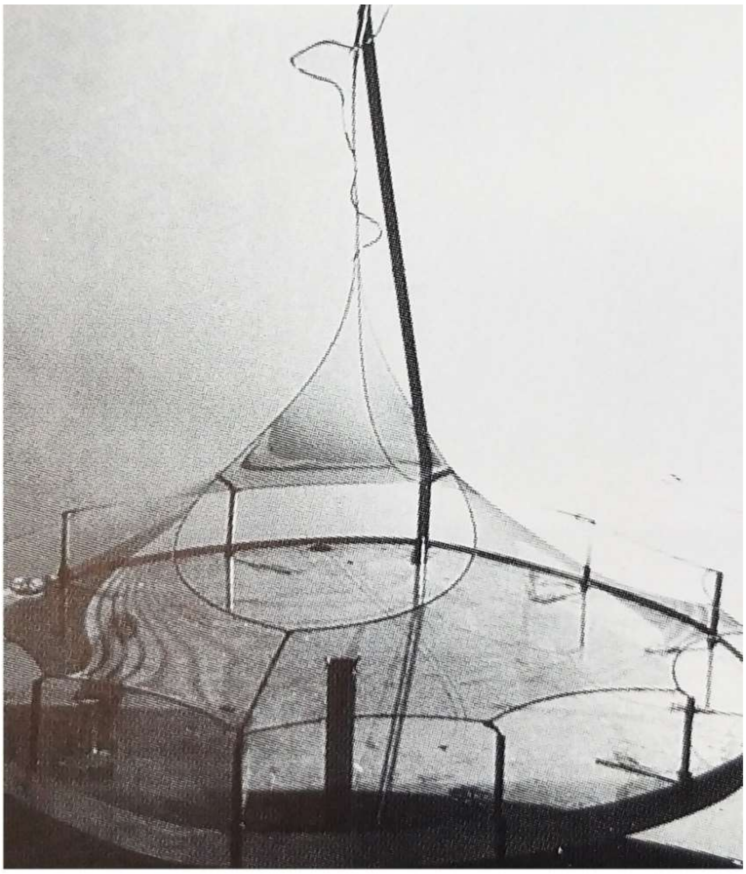


Figure 1: Literature examined and mapped based on a starting point of Frei Otto's form-finding experiments due to their material computational abilities. Diverse research areas are also mapped, which are surveyed to determine how they can be connected into a design and fabrication system by employing fabrication parameters based on multiple stimuli and create a tuneable environment within a volume to guide self-assembling materials interactions and properties.

2.1 Analogue Parametric Models & Material Computation



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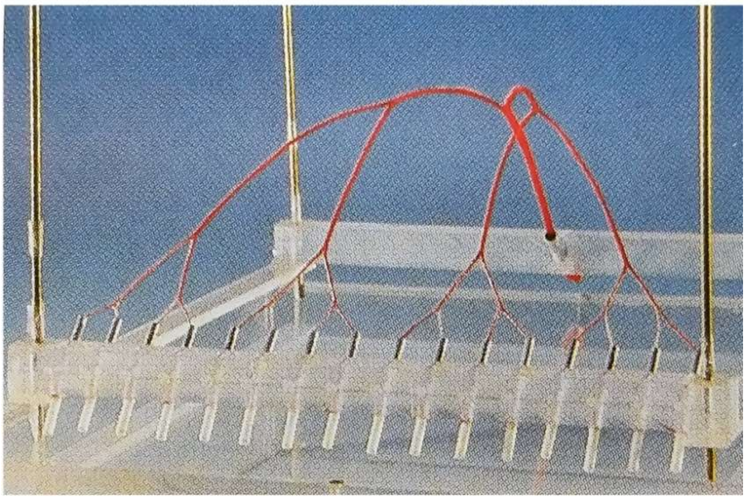

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Figure 2: Various Form-finding models by Frei Otto. The models represent a variety of material computation processes based on different material types which generated 2D and 3D forms. A) Soap films within frameworks create 3D minimal surfaces. Source: 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.

Otto's analogue parametric models 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 Figures 2 - 5). The resultant forms embody the interlinked relationships between materials and forces. The experiments allow conditions to be set up within a physical framework, enabling the material units to generate shapes that have a degree of flexibility based on imposed and resultant forces, such as; attraction of polystyrene chips to magnetic needles, with magnetic needles repelling and or displacing 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 reveal multiple material abilities, which enable 2D and 3D form-finding. The models and certain material types can 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 patterns 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 next, and 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: 1) what constitutes a framework or approach for guiding material interactions; 2) how forces can be utilised as the mechanism for guiding and monitoring material self-assembly; 3) how material properties (e.g. shape, location, volume) generated from self-assembly can be manipulated.; and 4) 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 materials and in the case of this research, guiding the units of matter that can self-assemble and form the basis of the material platforms used within the material probes of this research, which have yet to be determined.

2.1.1 A Framework from 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, p18)

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" (Schumacher, 2009b, p19)*. The threads are confined within a fixed circular wooden framework and can move with greater degrees of freedom the further away they are from the framework. Thus, illustrating that, 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 the slack provided to them, allowing the threads to move, with the materials becoming agents within the design process. The threads interact with other local neighbouring threads and converge, but do so based on local and global 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. In this way, the strings can 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 material units themselves, in this case, wool and their properties (slack, diameter, smoothness), and the properties of the mediums or liquid mixtures (liquid surface tension, viscosities) in which the material units are submerged. 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 enables 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 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 generated in the woollen thread model worth mentioning is how the void spaces are created during these material processes of convergence and bifurcation. The positive spaces are created by the threads, which contrast with the negative void spaces created between them as a result of material units converging (see Figure 3C). The pathways and spaces created reveal multiple forces at play in the experiment, which contrasts one with another and is 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 the woollen threads together. The displacement is aided by the water as it provides bounce, allowing the threads to move more freely. Conversely, more viscous mediums, such as a glue and syrup mixture (Spuybroek, 2004), would inhibit or reduce the amount of displacement caused by the initial shaking as the 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 setup 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 pattern’s generation.

The woollen thread model raises two points of interest: *first*, 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 entangled) 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). *Second*, 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 i.e. the wooden ring acts as an infrastructure within the model and plays a role in dictating the overall adaptability of the material units. The possibility of a liquid framework is demonstrated as the various liquid mixtures support the threads when they are submerged within them. Altering the 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 self-assembly; *How or what material process can be exploited by altering a support liquid’s properties to create a less rigid framework and environment for the materials to self-assemble and adapt their properties?*

Next, two instances of Otto's occupation and distribution experiment are examined because it uses more granular materials and engages with fields of force (magnetism). They will serve as another precedent 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.

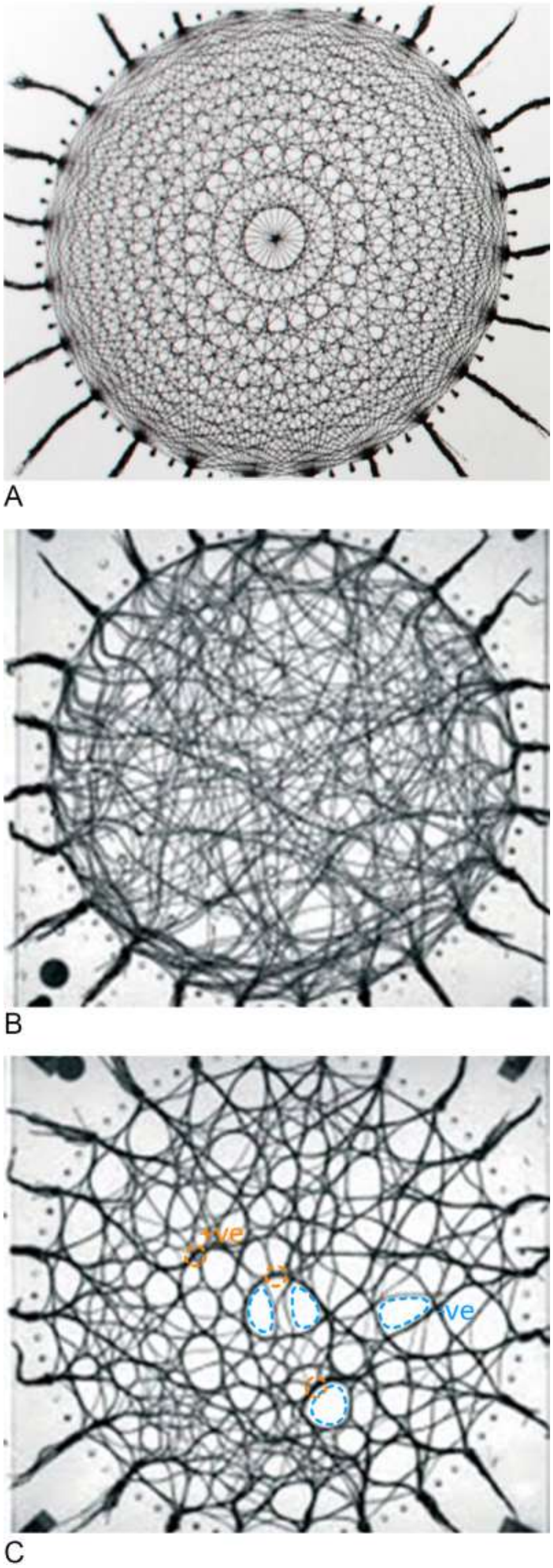


Figure 3: Three stages of Otto's woollen-thread model. C) Highlights the positive and negative spaces created from the conditions and resultant forces within the material system. Source: Otto, F., & Rasch. B., Year: 1995. Annotations: Author.

2.1.2 Granular materials and framework of forces

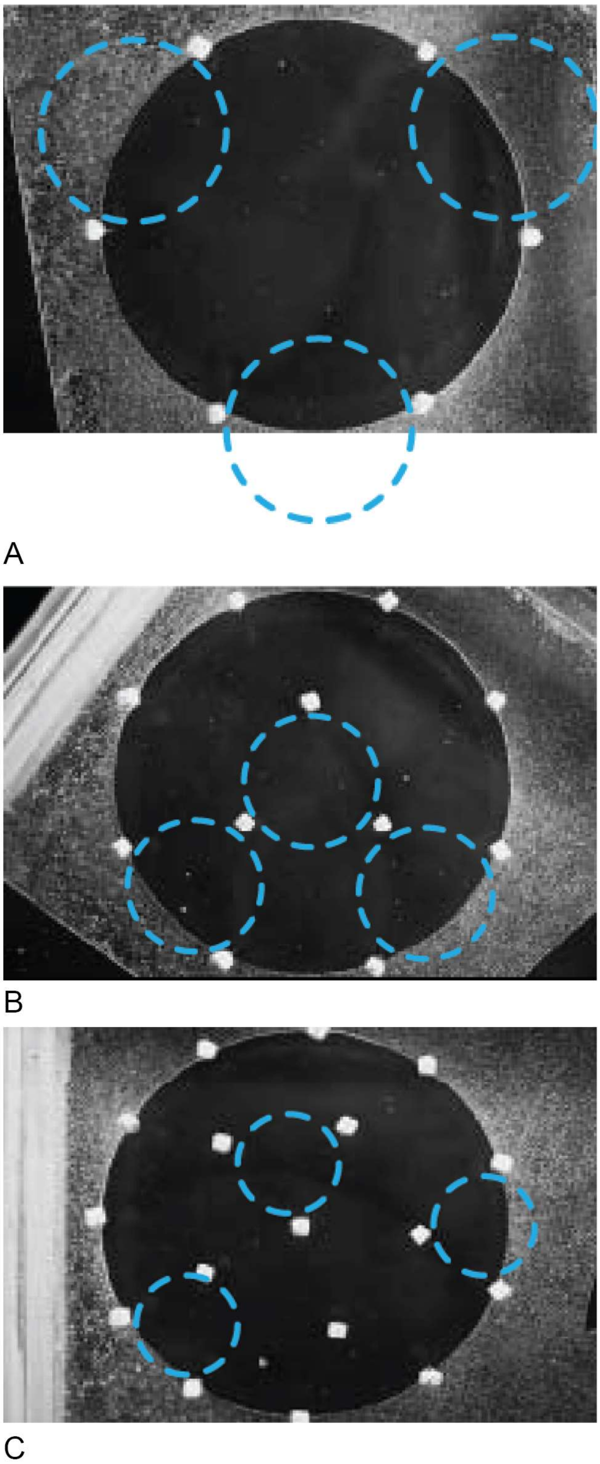


Figure 4: Otto's Occupation with distancing models. A - C) a sequence of images that depict varying organisational patterns as more needles are added. The patterns are created from neighbouring magnetic repulsion and have almost uniform distancing, highlighted by the dashed circles. Source: Otto, F. Year: 2003. Annotations: Author.

The first instance of Otto's *Occupation and Distribution* models use only magnetised needles. In this iteration, a series of needles are placed on the surface of the water within a defined boundary shape. The needles float as they have within cork floats, and the ability to float allows the needles to move. As needles are added within the defined boundary 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 Figures 5A - 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 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, p16).

The aspect of interest is the magnetic forces and how they can be manipulated to initiate fabrication and pattern transformation, which self-distribute. 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 material distributions are not mechanically fixed; b) the benefits of contrasting forces (magnetic attraction and repulsion) are again revealed – in this case as a way of creating and organising patterns with approximately equal distancing; c) the patterns created are a scalable process, which is also adaptable because they self-organise and change shape when needles are added or removed. The scalability in this system is due to the local neighbouring interactions of the material units, 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, p18); and 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.* W*hen carrying out the* *experiments, changes in field strength are very easily achieved by placing two or more needles on a buoy"* (Otto, 2003, p18).

The use of gradients in this system would allow for more sophisticated material computation, as 'weightings' can be assigned to individual needles. A hierarchy of order of logic could thus be assigned to individual nodes, due to localised variation in magnetic strength. The use and role of weightings are strategies employed in *Random Boolean Networks* (Weaver et al., 1999) (hereafter 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 that 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 due to the analogue nature of the models i.e. the materials units are not object orientated. For this reason, digital design tools are incorporated as a means of monitoring conditions and relationships.

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

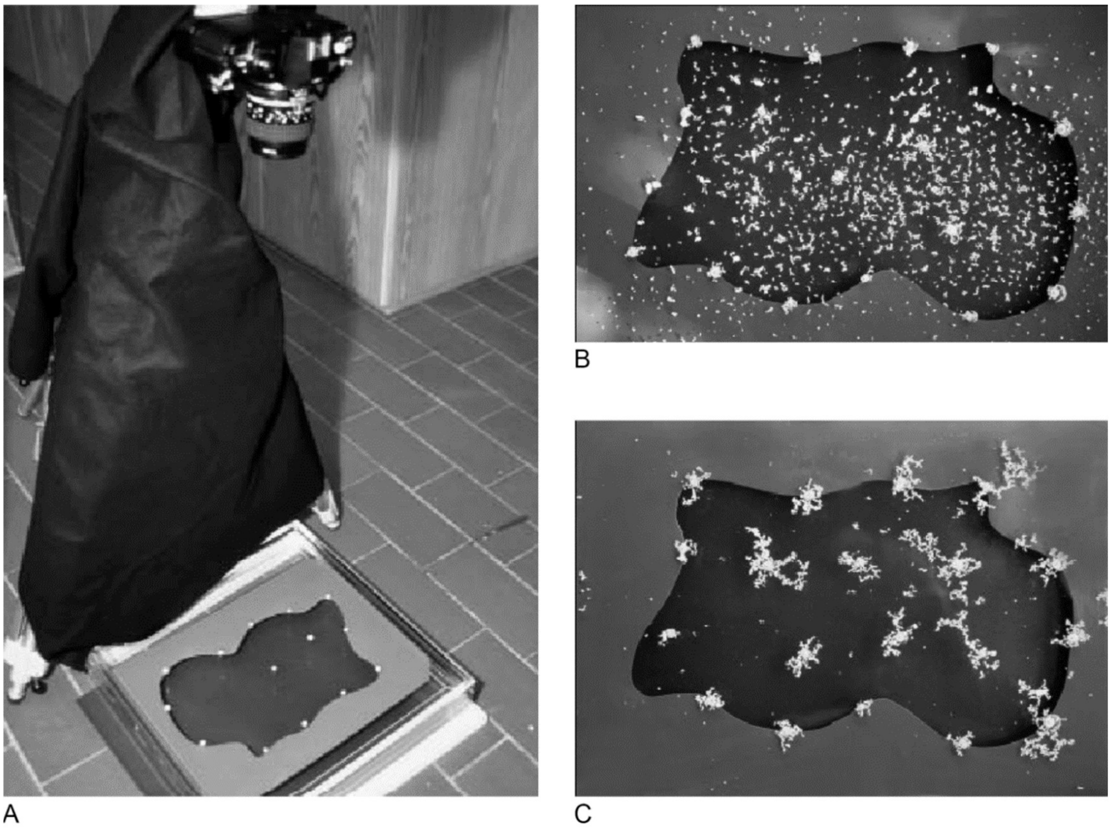


Figure 5: Otto's Occupation with simultaneous distancing and attractive forces model. A) Experiment setup with a framework of needles self-distributed within an irregular area. Source: Otto, F., Year: 1992. B) A framework of magnetic needles and unorganised polystyrene chips. Source: Otto, F., Year: 1992. C) Needles acting as nodes, which attract polystyrene chips to form clusters. Source: Otto, F., Year: 1992.

The second instance of the Occupation experiment introduces polystyrene chips (see Figure 5). 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; and 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 experiment, it is possible to alter the needles' pattern by varying their properties (amount, magnitude, location), which means that these material units create a type of flexible framework/infrastructure. This illustrates, it is possible to influence certain properties (amount, location) of the polystyrene chips more easily than others (cluster patterns). This demonstrates how analogue control over forces can be used to alter and guide properties of the 2D patterns created from self-assembling materials.

These experiments are used as a vehicle to speculate on the potentials of being able to develop programmable self-assemby strategies without defining the geometries or interfaces of the material components/units of the material platform. Instead, imagine continuously being able to manipulate the conditions in which the materials are placed, 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 needles, which in turn alters the configurations of the granular material units (polystyrene chips). 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 during the fabrication process (Tibbits and Flavello, 2013). Conversely, current computer-aided fabrication processes are typically deterministic, where the physical outcome is known prior to the fabrication process. 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.

First, 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).

Second, 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, that have varying affinities and sensitivities. 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's 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. Gradient-based material properties have been achieved within a host of 3D printing strategies typically through voxel-based digital models (Oxman, 2010b; Richards et al., 2017; Bader et al., 2018a), or by varying ratios of various liquid materials and extruding them through a single nozzle (Soldevila et al., 2014; Soldevila et al., 2015). However, the final gradients of these structures become fixed post-fabrication in these strategies i.e. they cannot reconfigure post-fabrication, unlike biological structures.

Third, the transformative potentials 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. However, the analogue nature of Otto's models and using forces as a means of fabrication raises two main challenges and questions: 1) *how can physical forces produced by each node be controlled and monitored based on augmentations to a design representation*? 2) *How can it be determined if the desired material properties they effect have been achieved, in this case, the clusters (amount, size location, global or local patterns)?* These two challenges open up an array of possible material platforms that can monitor or respond to varying conditions, which will be discussed in Chapter 5. 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 design and fabrication process, which separates digital design, fabrication and materials. However, current research is now beginning to integrate them, and this will be examined across the literature surveyed. Understanding the advances in *Computer-Aided Design* (hereafter CAD) and *Computer-Aided Manufacturing* (hereafter CAM) enable us to establish how these recent developments can be utilised and guide processes of material self-assembly.

2.1.3 Shifting focus

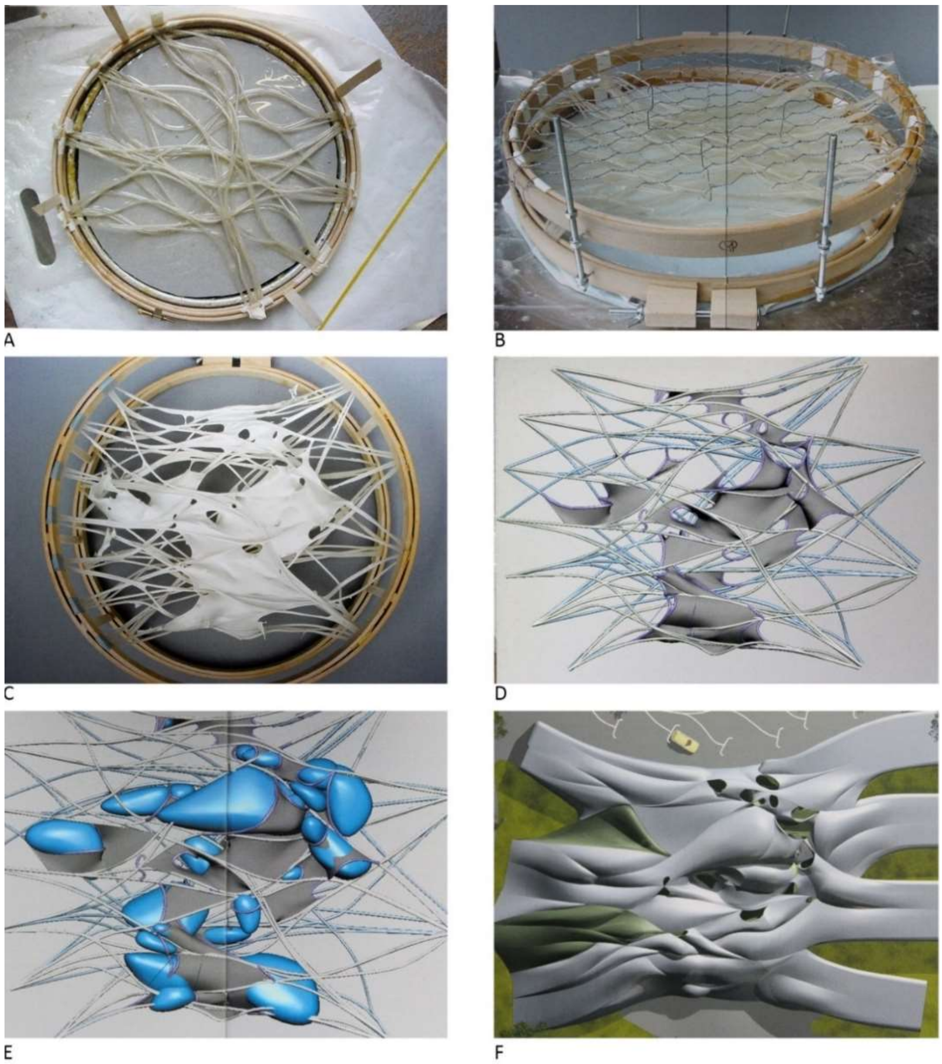


Figure 6: NOX Soft Office. A - C) Analogue experiment setup which creates 3D spaces from silicone tubes and lacquer within a wooden framework. As the lacquer cures, changing state, the frameworks are separated within the 3D space, creating forms and surface connections. D - F) the forms created within 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 a form-finding model similar to Otto's woollen thread model. Here, silicone tubes and lacquer are used and suspended in 3D space from two circular wooden frameworks (Figures 6 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 in which they are placed. Significantly, the model's 3D forms are digitised and then refined to create architectural spaces (Figures 6 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 physically reproduced. The method of digitising the physical shapes is not mentioned, but this could provide an alternative methodology for 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 material computational processes within the system; 2) the digital and physical models are separated as the digital shapes are not created based on the material relationships or conditions. Consequently, 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 traditionally 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, pxi).
'Computation', on the other hand, allows designers to extend their abilities to deal with highly complex situations" (Peters, 2013, p10). Ahlquist and Menges also provide a definition of computation which resonates with how it could manipulate material interactions: *"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, p13).

As witnessed in Otto's form-finding models, 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-assembly. The marriage of both digital and physical simulations has been utilised in evolutionary robotics, where the physical robot is directly engaging with real-world parameters, which more accurately informs the corresponding digital simulation (Lipson and Pollack, 2000; Zykov et al., 2004; Cheney et al., 2013). In doing so, digital models can be used to output instructions to guide self-assembly processes or interactions and link the two. The next three sections review three methods of digital computational design. They can all dynamically change properties of a digital design (shape, colour, texture, composition). Significantly, each section also increases in the resolution sequentially, which reveals how these digital design strategies can potentially engage with more intricate physical material properties and provide 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 on. 2) The strategies will be used to determine if a physical adaption has been produced during the fabrication process e.g. the desired volume of material growth has occurred at a defined location within 3D space. 3) This provides an understanding of the possible resolution on which a digital design can be generated; from global geometries to local material composition. This raises tensions between increases in digital resolution and if this enables control over less defined material properties of a self-assembling material platform, such as surface texture and porosity, that are not directly linked to a specific stimulus but potentially to the overall conditions. 4) Their potential use for governing and revealing relationships of a system as the relationships become increasingly complex or interrelated.

Three types of design strategies are surveyed. *P*arametric design; material-based design computation; and gradient-based designs. They are examined because of the digital shape-changing abilities they afford, which become increasingly extensive in regard to what properties they can adapt, from geometric boundary representations to global adoptions based on local material compositions. To bridge the gap between digital model and physical materials, parameters of the digital model need to be mapped to material properties or processes to create relevant relationships and discourses with a chosen self-assembling material platform. 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 coordinates of the digital model would be related to temperature and agitation. The main intention of this thesis is to explore how parameters and relationships are mapped between the digital model and physical materials, through a practice-based/research through design approach. These explorations could highlight challenges of translating relationships when adopting certain digital design processes in relation to the behaviours of the material platform used i.e. are the material behaviours linear, non-linear and or interrelated, such as parameters of a digital model based on associative modelling approaches (i.e. parametric design) compared to digital models generated from non-linear relationships?

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, 2004, p10)

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 that 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 are 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 a visual documentation of the relationships between geometric components and ratios that determined certain column typologies (Gibbs, 1753).

With the advent of computers and development of various CAD software packages, it is possible to generate these associated design relationships digitally, this process is termed associative modelling and results in digital parametric models. The advantages of combining a computer's processing abilities with parametric design processes (procedural logics and geometric interrelationships) allows the following: 1) 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 with the geometries and can limit the 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 enhanced scalability to this design process (see Figures 7D & E); 4) description of increasingly complex geometric structures which can be structurally efficient and ornate (Block, 2016).; and 5) digital fabrication instructions/processes that can be produced directly from the model's 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. To do so, digital parametric models are thought of in relation to 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.

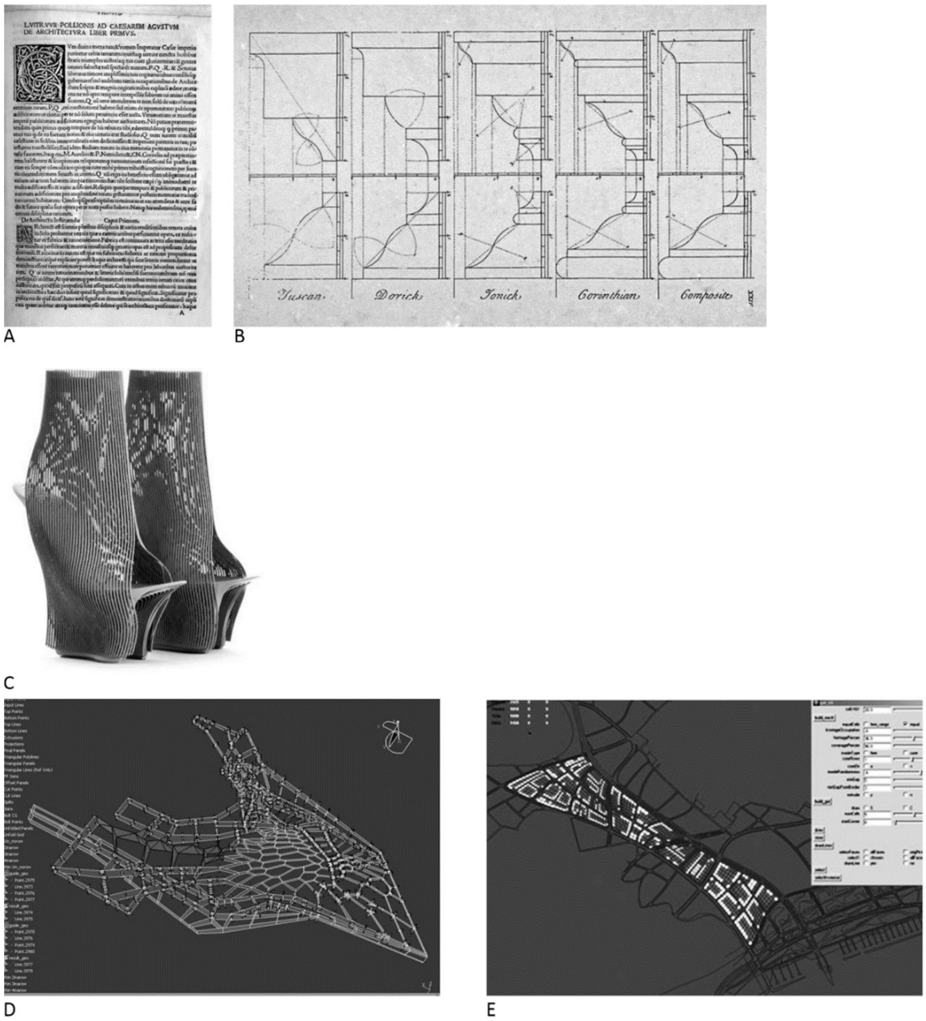


Figure 7: Parametric design process, both analogue and digital. A) Vitruvius describes procedural rules and formal relationships for creating architecture. Source: Vitruvius. Year: 25BC. B) A sequence of images that depict how to produce mouldings to make up the geometric components and relationships 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 the product (Image C: Lovegrove, R., Ilabo, 2015) to D) 1:1 structural canopy installation (Image D: Wiscombe, T., & EMERGENT, Dragonfly, 2007). D) The organisation and formal logics of urban-scale planning for Kartal-Penkik Masterplan, Istanbul, Turkey (Image F: Zaha Hadid Architects, Kartal-Penkik Masterplan, 2006).

The ability to set up conditions to generate design models via material computation was witnessed and discussed in Otto's form-finding experiments. The conditions become somewhat fixed during these experiments as the stimuli (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 8). Digitisation in this context is the process of converting physical properties into digital. Significantly, the digital versions enable an increase in speed regarding ease of set-up along with the ability to explore multiple properties of the structure with greater ease, because conditions (gravity, node distances, wool sur-length) can be manipulated in near real-time, allowing for greater degrees of flexibility in the system.

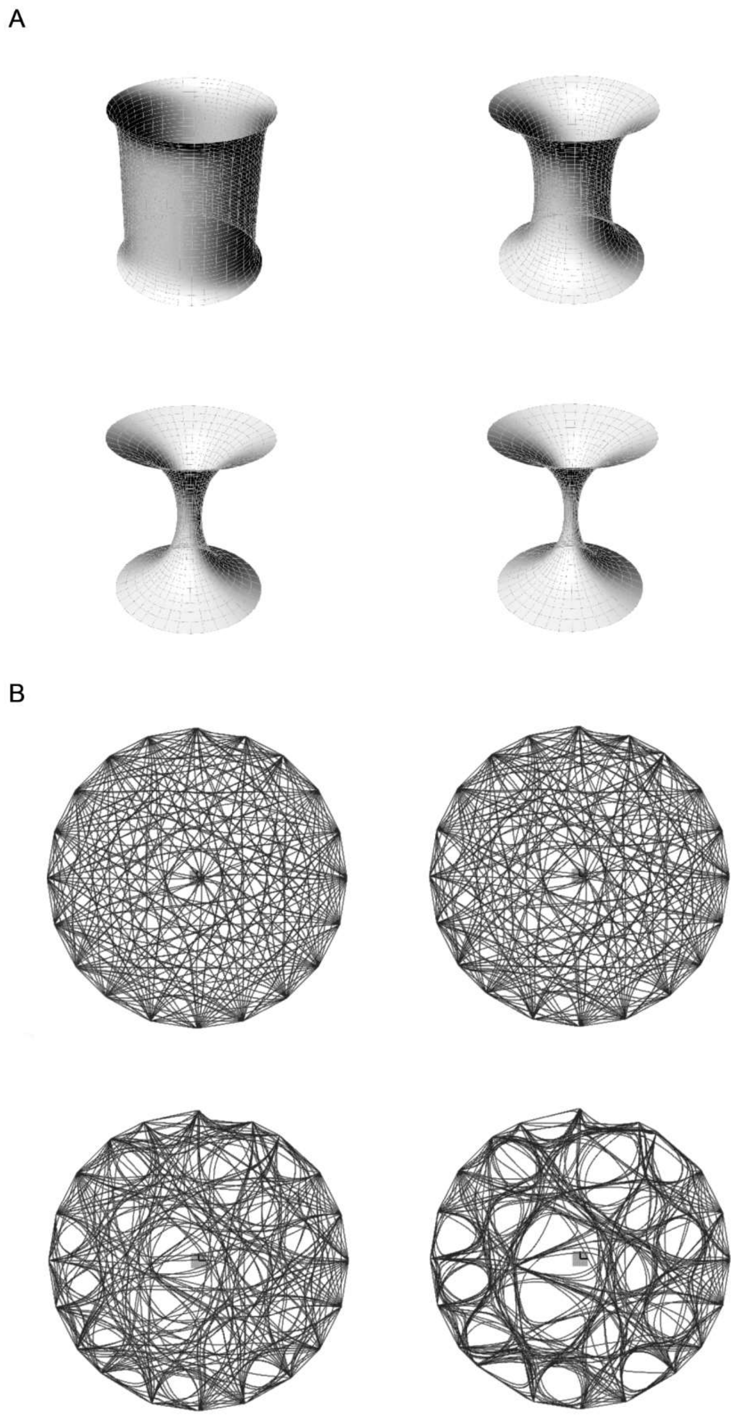


Figure 8: Digital simulations of Otto's experiments shown as a sequence of screenshots to highlight dynamic geometric behaviours when subjected to simulated forces. A) Minimal surface model (Image A: Leung, N., surface tension simulation, 2018). B) Optimal detour path network model (Image B: Hristov, 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 can result in the abstraction of actual physical processes; hence, the digital version has comparatively reduced processing power compared to the physical system (Kwinter, 2011). The digitisation process combined with how CAD tools typically represent materials reveals challenges when reconnecting the digital with physical materials.

First, due to digitisation, it will be necessary to map digital design parameters to a relevant stimulus that can affect corresponding self-assembling material processes to create a discourse between the two. For example, simply altering a digital circle's 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.

Second, typical CAD software represents the components and objects of design as *boundary representations* (B-reps), because of this, they would treat the material of a structure as homogenous (Richards and Amos, 2016). This means they are not capable of representing or manipulating internal material architectures and 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 homogenous. As a result, any digital manipulations are geometrically driven and not based on how material properties could compute form when subjected to demands or conditions.

Third, The result of combing the first two points means all of the nuances present in the physical system, such as material variations, are not represented digitally (Ahlquist and Menges, 2012). A significant result of this is that the typical linear behaviours exhibited by deformations to digital models are not represented within physical materials, especially when threshold conditions are surpassed and cause the material to produce non-linear behaviours (DeLanda, 2015). These discrepancies between behaviours may become more prevalent when attempting to guide self-assembling materials as they are granular in nature and can have high degrees of freedom within the fabrication process.

Fourth, accurately uncovering, determining and further understanding nuanced interrelationships within the proposed adaptive fabrication system between digital augmentations, induced stimulus, resultant material properties and environmental conditions could become limited if based on strict cause and effect relationships (i.e. linear). A consequence of this would potentially limit how reliable the fabrication of the physical design is compared to the digital model. A strict cause and effect strategy could also inhibit the discovery of novel and robust fabrication logics and processes, which could arise from combining multiple stimuli. These fabrication abilities have been demonstrated within existing strategies of self-assembly, where the geometries and connections of the material components are predefined (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 design strategies based on material units and how they could more accurately relate to the material units of the self-assembly process. The digital design strategies examined are a) material-based design computations (hereafter MBDC) (Oxman, 2010a) and b) gradient-based designs (Richards and Amos, 2015). Both of these computational design strategies can generate digital structures based on their material units, typically a voxel. 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, since digital materials are not represented as homogenous and more accurately represent real-world materials.

Oxman established MBDC, which takes inspiration from biological form generation and generates designs that are not geometrically driven (Oxman, 2010b). By contrast, 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 3D space in relation to multiple environmental conditions (structural, environmental, corporeal, sound), making the material of the structure, the internal architecture of the 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), and material heterogeneity with variable properties (Oxman, 2011b), which can also have functional gradients (Oxman et al., 2011; Richards and Amos, 2015; Richards and Amos, 2016). This ability to digitally inform a digital structure's material properties based on design demands enables its matter to be physically 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 their properties across their length scales (Oxman, 2011a). The thesis intends to explore how these highly desirable properties and digital abilities, such as variable compositions and remodelling, could be achieved physically by altering conditions to guide material self-assembly.

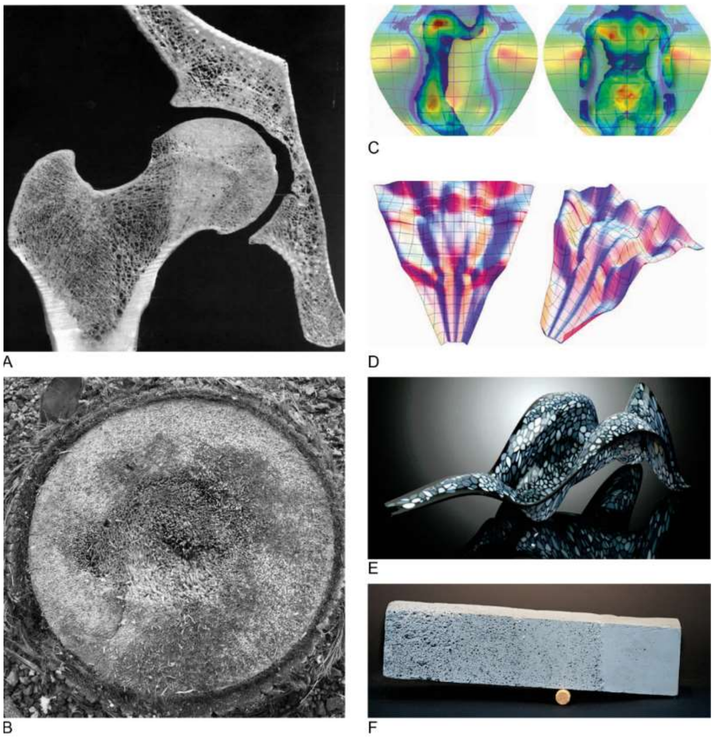


Figure 9: Biological and artificial gradient structures. A) Femur head cross-section highlights biological structures achieve varied internal spatial organisations by locating materials and varying their properties in relation to demands they are exposed to, for example, the vaulted structures of trabecular 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 reveals variable densities in relation to bending stiffness along its height, enabling material's 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) A 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.

Generating digital models based on gradients of material units (voxels is a current research topic that extends MBDC and will be briefly discussed because of: 1) the possible digital material resolution afforded; 2) the scalability of processing information based on highly granular digital models; and 3) the ability to utilise a gradient-based design methodology to determine relationships.

2.5 Gradient-based Models

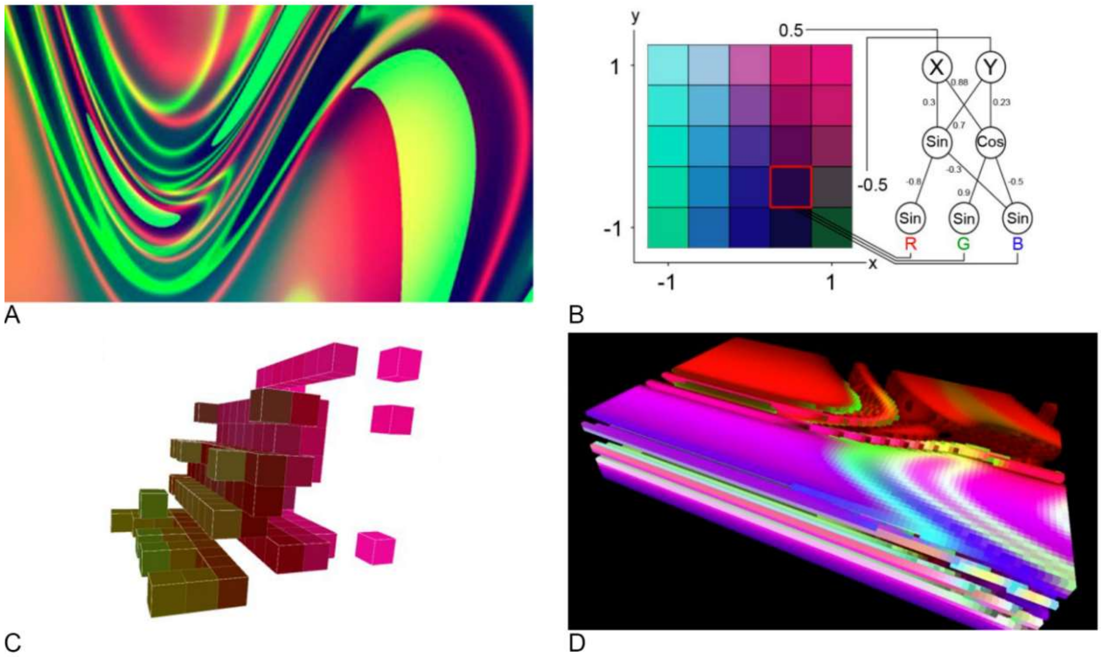


Figure 10: CPPN-NEAT patterns and relationships. A) Infinite voxel pattern resolution is possible as the CPPNs regenerate new colours when zooming into patterns. Source: Richards, D., and Amos, M. Year: 2015. B) RGB colour generated by feeding the coordinates of the nodes into the CPPN and using various 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. As a result, volumetric material compositions can be achieved throughout a digital model's 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 voxels, combining this with the ability to programme the voxels' properties in relation to multiple design demands (structural, acoustics, aesthetics, transparency), enabling 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, functionality relates to material properties informed by design demands, with gradients being the gradual transition from one material type to another, for example, from hard to soft and from transparent to coloured, which can occur throughout the model's volume. Now imagine being able to harness the ability to tune and adapt all of the digital model's local material properties in conjunction with its complex global geometry and being able to do this physically simultaneously. This could lead to totally new artificial material possibilities, such as body armour that repairs itself when damaged or splints and prosthetics that grow and change composition with the patient to aid healing and improve comfort. In order to develop these ideas and material aspirations further a methodology called *Composition Pattern Producing Networks - Neuroevolution of Augmented Topologies (CPPN-NEAT)* is examined.

The CPPN-NEAT methodology employed and developed by Richards and Amos generates highly granular material gradients that are also functional, evolvable and based on non-linear relationships between parameters. 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 are 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, which can be used to guide material self-assembly without predefining relationships between parameters of the digital model and physical processes, properties and conditions throughout the fabrication process. Figure 10 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 are possible (Richards and Amos, 2017), i.e. imagine patterns within patterns. The benefit of this highly granular digital resolution begins to resemble physical materials at smaller resolutions and can accommodate or generate digital models that are not materially homogenous. Thus, potentially 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 material 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 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 model's 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.

C) The significance of real-time manipulations and analysis of weightings between CPPN's relationships to generate the patterns further strengthens the discourse with material computational processes as the time lag or discrepancies are reduced. As previously mentioned, the strengths of linking physical and digital computation are exploited within evolutionary robotics. The time and resolution similarities could 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 scales (Hiller and Lipson, 2009), with semi-permanence enabling programmable reconfiguration (White, 2005; Zykov et al., 2007; Levi et al., 2014).

D) They are robust as the CPPNs are not based on predetermined associations between parameters, i.e. they are non-linear. Again, this could further align with material behaviours that are non-linear, 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 fabrication stimuli or environmental conditions can be used to suppress or promote more discrete material properties (surface texture, porosity, density) being generated for fabrication based on self-assembling materials that can tune and adapt their properties.

E) 3D digital designs generated from volumetric voxel patterns using CPPNs produce challenges in regards to physical buildability, as voxels can sometimes be located in space without connection to surrounding voxel networks that connect to a ground plane (Richards and Amos, 2015). This 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.

In relation to the gradients, there are two points of interest highlighted: 1) models based on global and local features can be programmed and reprogrammed across the model's length scales as demands change, which not only begins to mimic biological processes where materials can be tuned but could go beyond them as materials could completely change their properties if demands radically change but require a physical material that can also have its materials re-programmed. 2*)* They provide a transition between various material types (stiff to soft) that do not have an abrupt boundary or interface. An 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 model is fabricated and the mechanism that enables material transitions. Understanding how this is achieved could lead to physical gradient patterns that can be iteratively reprogrammed over time. A mechanism that achieves this will be highlighted in the following chapter, which examines fabrication processes.

2.6 Chapter Summary

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 throughout time, nor are interrelationships discovered due to the analogue nature of the models.
- Digital parametric design platforms can create shape-changing models as well as aspects of Otto's experiments that can be easily augmented in near real-time. The manipulations are made by altering values of parameters associated with the model's geometries. However, the process results in linear geometric behaviours and relationships that require all associations between parameters to be predefined, resulting in scalability issues. Additionally, typical CAD software produces models that are based on B-reps, which treat materials as homogenous and result in abstractions/separation from real-world materials.
- Both MBC and CPPN-NEAT strategies address the potential issues raised by associative modelling strategies that treat materials as homogenous, with linear behaviours. Significantly, MBC and CPPN-NEAT strategies enable performance-driven adaption, material remodelling and multi-material properties, which have synergy with self-assembly processes based on material units at increasingly smaller dimensions. Significantly these adaptive abilities have yet to be fully realised within artificial 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 that have non-linear associations. 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 and how the fabrication process interacts with materials, i.e. how deterministic the fabrication process is. Additionally, logics and mechanisms within digital fabrication processes are discussed to understand how 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, p78).

Typically a linear design and fabrication process still predominates within CAD and CAM. This means that any design changes, updates or augmentations that occur to the digital model post-fabrication are not typically updated in the final structure or its materials, i.e. there is a separation between design, fabrication and materials because of the linear nature. Consequently, either limited or no feedback or mechanisms of engagement are typically instilled across the parameters of the process, in particular within the materials used. An aspect that enhances this is the typically determinist nature of CAD/CAM processes, i.e. the shapes created in CAD software are specifically fabricated using a CAM 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. Instead, they are used to impose form upon materials. A ramification of these deterministic processes is that they could limit potentially highly desirable properties from emerging or new typologies being revealed during the fabrication process, which may not have been previously conceived during initial design stages (Tibbits and Flavello, 2013). A methodology that addresses the challenge of linear fabrication processes is

'Persistent Modelling' (Ayres, 2012b), which will be discussed in greater detail in the next chapter.

To unpack the typical linear and deterministic processes further, this chapter examines multiple fabrication processes: various additive manufacturing methods (i.e. 3D printing), 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. For parallels between the fabrication processes examined and to understand how incorporating self-assembling materials could potentially enrich the abilities of the fabrication processes, they will be discussed in regards to: 1) logics; 2) material properties; and 3) 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. The literature surveyed will highlight: a) where it can or does occur; b) the mechanisms that enable material computation; c) how the mechanisms within the process can be manipulated to understand how fabrication processes can be based upon material computation; and d) how mechanisms and material computation can be guided via digital tools. It is also important to highlight fabrication technologies and processes (and later material platforms) that can be seen to explore, and could lead to, adaptive structures.

Otto's form-finding experiments established how architectural forms and urban plans can be generated by engaging with material computation. A primary benefit was in how setting up and varying the conditions (inducing stimulus) throughout the 'form-finding' process can manipulate both the material properties (local) and the form’s 3D shape (global) simultaneously. The experiments reveal how maintaining, changing and tuning stimulus can be used as the fabrication mechanism for guiding self-assembly of the materials used and emergent properties generated, which helps to envision a design and fabrication system based on tuning stimulus. 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 building’s global shape change would also be related to alterations occurring to its internal architectures, which makes them denser or more rigid if the building becomes larger, leading to greater material efficiencies. The main challenge that is prominent in Otto's analogue models was the lack of feedback between material computational processes, material formations and design information, which became especially apparent in his 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). 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 between design parameters, stimuli and material properties generated is not present; especially as systems can become increasingly complex based on even 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 that do not have the capacity to self-sense or intuitively provide feedback when subject to varying stimuli, which is used to guide material interactions.

This chapter intends to discuss the benefits of advancements in CAM processes and also to understand alternative means of how fabrication processes can interact with materials so that form does not have to be imposed on materials but can come from within the materials (DeLanda, 2004). The chapter will also form a foundation for selecting material platforms discussed in Chapter 5 that will be employed.

3.1 Searching for Mechanisms in Additive Manufacturing

The focus of this section is on current additive manufacturing processes (AM), which have recently enabled a manufacturing process that is capable of producing a structure with variable properties (Oxman, 2011b) and functional gradients (Oxman et al., 2011; Richards et al., 2017). These are material compositions and or internal architectures that do not have to be homogenous, leading to less material waste and higher degrees of customisation (Doubrovski et al., 2015). This ability to manufacture structures by discreetly controlling where material is located has allowed for physical material units to be programmed. In the case of 3D printing the material unit in some cases would be: 1) the size of the droplet from the print head; 2) the granule of material in particle-based AM, such as Selective Laser Sintering (SLS); or 3) the length of a fibre in Fused Deposition Modelling (FDM). Being able to discreetly control where material location and properties in AM have led to multi-material, 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: *first,* multi-material layer-by-layer approaches, which use light (e.g. ultraviolet) as a stimulus to change the state of the material being deposited (per layer), from liquid to solid, that makes up the product being fabricated but additionally reveals the type of material computation that occurs. *Second,* Computed Axial Lithography (CAL) highlights how AM processes do not have to be restricted to layer-by-layer logics by orientating materials around a continuously updated stimulus (light projections). *Third,* 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 reveals how material computational processes within them could potentially be further exploited by combining aspects of all three strategies, providing a basis for material probes that could create an adaptive AM design and fabrication system.

3.1.1 Heterogeneous AM: layer-by-layer

Figure 11: '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 were generated using the Data-driven Material Modelling (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 the 3D printers build volume (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.

To design and fabricate physical structures composed of multiple materials (as described in Sections 2.4and 2.5) software is typically used to digitally define where various material types/properties are positioned throughout the structure's volume. The digital structure is then sliced into layers and fabricated in using layer-by-layer additive manufacturing technologies (Bader et al., 2016a; Richards et al., 2017). 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 wavelength), which changes them from liquid to solid. Again, this fabrication approach is highly deterministic; however, before the light cures (solidifies) the various resin materials, the extremely small droplets of resin can perform material computation in the form of diffusion where neighbouring liquid droplets of resin diffuse and mix (Bader et al., 2018a). Diffusion enhances the material gradients but leads to issues of tolerance regarding visible legibility (Bader et al., 2018a) as the various materials begin to mix, which over larger volumes or areas would create homogenous materials depending on diffusion rates and material curing rates. Because the diffusion occurs on such a small scale within these processes it is highly controlled, which means that the different materials do not just diffuse and mix. Instead, the result is controlled diffusion, creating high degrees of material variation at the product and wearable scale (see Figure 11). 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 another 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 structure. The material properties can thus be gradually varied by altering the amount and composition of the mixture extruded at a given time 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 et al., 2015).

The overall adaptability of the physical artefact is limited using these layer-by-layer fabrication strategies. Overall adaptability being the degree to which the physical structure could change its global and local properties from one to another throughout its volume as well as being able to perform material computational processes based on a change in stimuli (e.g. UV light) post-fabrication, where additionally, the stimulus could be governed by a digital design tool. These AM fabrication approaches currently 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 and not used to guide its potential diffusion abilities; and 3) because of 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 new piece. Comparatively, in Otto's form-finding models, 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 in which they are manipulated. 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 could be possible if material states can be iteratively/reversibly changed (from liquid to solid) in certain locations so controlled diffusion (mixing and un-mixing) can occur throughout 3D volumes. Preventing diffusion from proliferating throughout the structures volume and resulting in a somewhat homogenous material colour or type, the liquid resin could have its viscosities manipulated or contrasting liquids incorporated to prevent mixing. Tuning the resin’s material states and properties as it cures to guide material computation could potentially result in various adaptable qualities being achieved; for example, slow diffusion rates could lead to more delicate, capillary-like structures, whereas faster rates could produce smoother, uniform material transitions.

The artist Tom Price explored how contrasting materials (tar and resin) can be combined to generate contemporary 3D sculptures in the Synthesis 1 and 2 series (see Figure 12). Tar and resin contrast visually but they also contrast in material states during the fabrication of the sculptures. 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 volumes of tar heat up and expand, which creates a multitude of colours, patterns and properties, from various colours to large dark masses to fine fissures and vapour trails (Price, 2014). The heat generated by the resin is the stimulus in this system but it is random and not controlled, 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 tar's 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 et al., 2011; Doubrovski et al., 2015). However, being able to harness and dictate the properties of stimuli (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.

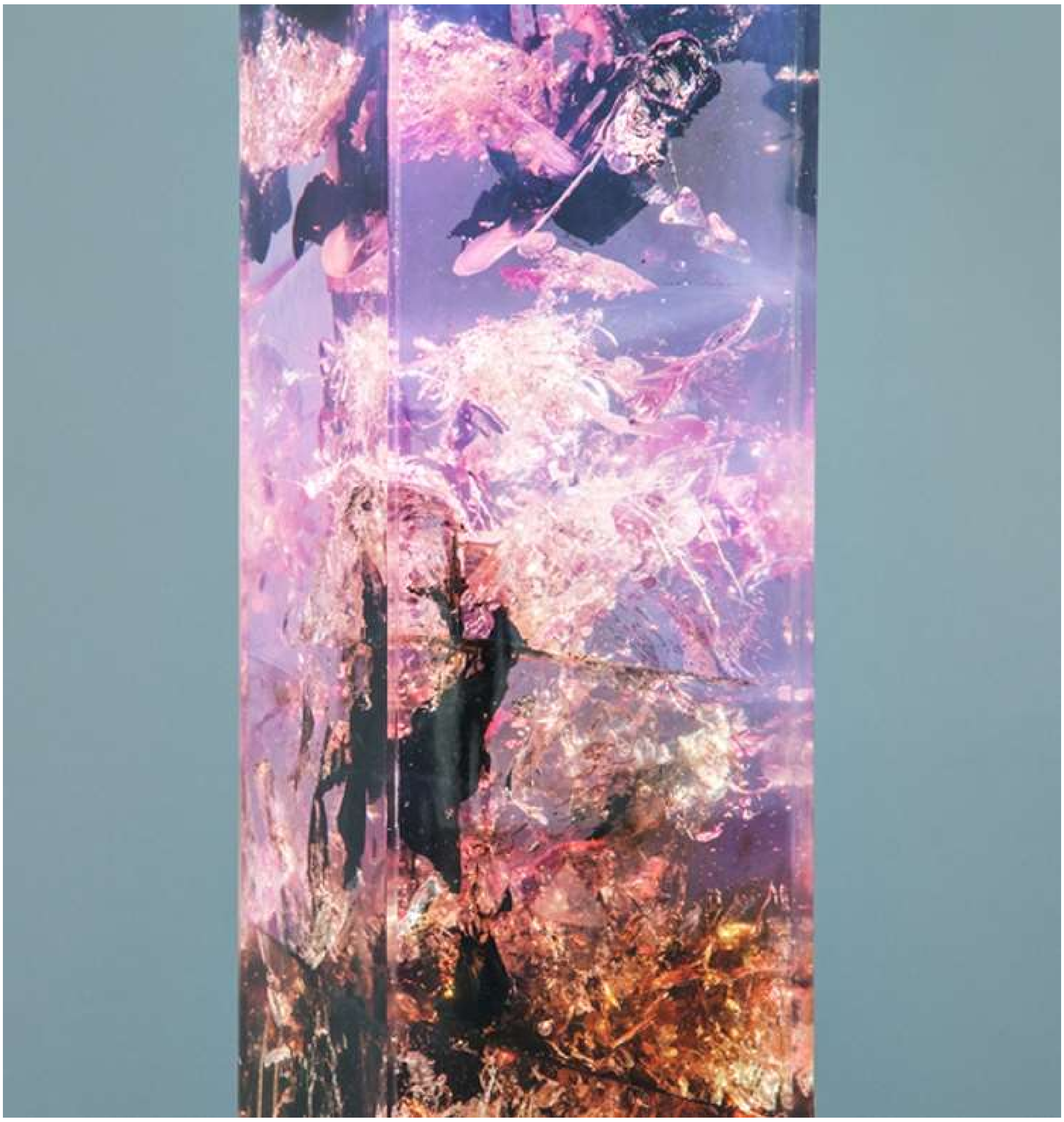


Figure 12: 'Synthesis I' by Tom Price explores how resin and tar interact with one another. As the resin heats up and cures the tar expands and creates a multitude of emergent shapes and 3D patterns throughout the sculpture's volume and at various scales from micro to macro. The patterns reveal stimulus can be used as a generative mechanism, albeit random in this context. Additionally, because the resin’s state becomes fixed along with the internal patterns, it negates the effect the heat stimulus can have on the pattern’s 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 in 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* (hereafter CAL) (Kelly et al., 2017b) and *Rapid Liquid Printing* (hereafter RLP) (Hajash et al., 2017). These additional methods of AM will be discussed very briefly and then used to speculate on the possibilities of guiding materials properties by engaging with parameters of diffusion.

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); and 2) 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 2nd points, 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 are where 2D layers of material are deposited in the X, Y and built-up layer-by-layer build-up along the Z plane. 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 volume of the 3D printer without sacrificial support material below it. Conversely, CAL is a volumetric printing process, where the light (typically ultraviolet) is projected into the volume of resin from a series of sources located at different angles. Thus, 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 of 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 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 (Kelly et al., 2017a; Kelly et al., 2019) (see Figure 13). CAL highlights multiple factors as to how the effects of stimulus can impact self-assembling material interactions:

1) The possible number of stimuli and the number of sources that generate stimuli, which additionally can vary over time.
2) The ability to combine stimuli from the various sources so they interact with one another, enabling them to be focused on different orientations and create a volumetric stimulus.
3) 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 self-assembling material interactions from an external stimulus.

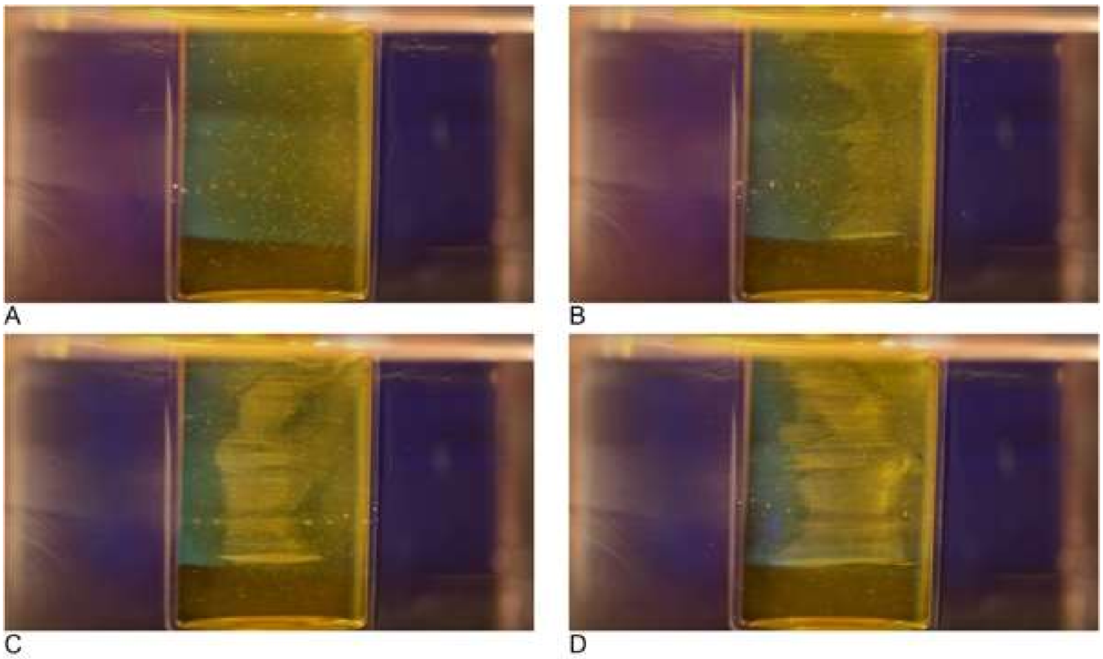


Figure 13: Series of images highlighting the Computed Axial Lithography process, where the object's (in this case 'The Thinker' by Rodin) material volume is manufactured simultaneously unlike typical layer-by-layer approaches of AM. Source: UC Berkeley, 2019, Video by Roxanne Makasdjian and Stephen McNally.

RLP also achieves the benefits of CAL but by an alternative means. RLP deposits the print material via a nozzle system into a volume of gel, which significantly, supports the deposited material (see Figure 14) (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 here because its material abilities could potentially be extended beyond using it simply as a support medium by potentially varying its properties via various stimuli (temperature, light, sound, electrical current, pressure) to enable further mechanisms, such as diffusion rates between support medium and print material. This could enable multiple surface textures without the need to digitally define them i.e. they could be materially computed and tuned in real time by changing the stimulus to which the materials are exposed. The support material could act as a *tuneable environment* to manipulate material properties within the tank. This idea will be speculated upon and imagined in the next section in combination with aspects from the other AM technologies.

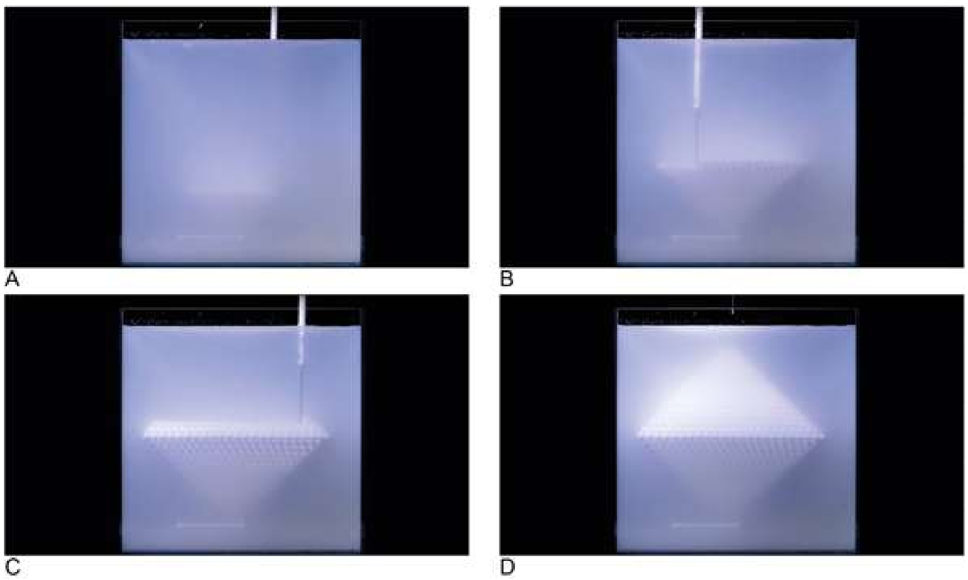


Figure 14: Series of images highlighting the Rapid Liquid Printing process where the material is extruded into a volume of contrasting gel, which supports the material deposited. Enabling rapid fabrication and not limited to layer-by-layer. Source: Self-Assembly Lab MIT, Christophe Guberan & Steelcase, 2017.

The drawback to these technologies in comparison to the multi-material printers is that the material palette for these technologies is currently homogenous. However, RLP could easily be combined with the material palettes available within FGRP or WbF to produce structures with variable material properties as the process of deposition is very similar. However, the potential amount to which the fabrication process and objects produced can be adapt is limited if subjected to varying stimuli. 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 now be briefly discussed.

3.1.3 Guiding material computational processes in AM

This subsection explores one key factor that has arisen within this section of AM processes; *how are material computational processes that occur 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 stimuli to further tune the properties of a pattern; 3) reviewing additional AM technologies, which utilise or programme materials that can respond to stimulus; and 4) discussing the implications of a possible lack of feedback between material properties and stimulus.

Combining AM processes

The presence of diffusion in the multi-material AM processes revealed that material computation occurs within AM but under very controlled conditions (Bader et al., 2018a). Additionally, examining CAL and RLP revealed how collective stimuli and contrasting conditions could be incorporated to guide properties of diffusion or equivalent self-assembling material processes to generate 3D patterns that can be reconfigured by modulating parameters of the stimuli that guide material computational processes. For instance, dropping food colouring or ink into water to create 3D ink clouds, which have various properties from fine strand-like forms to initial masses that ultimately diffuse out into the entire volume of water. Imagine being able to alter the properties of the ink clouds' diffusion (e.g. rate, location, amount). Expanding on this idea of incorporating a 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 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; and 3) adaption that can be achieved across the structures length scales (global to local) simultaneously. This raises two questions: *How could properties of material diffusion be manipulated? What forms of stimulus could be employed to create reconfigurable or repeatable patterns?*

To explore the first question and further understand the potential impacts of a 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 at various rates and scales.

Computed Axial Lithography - Continuous projection of an updated image forming a volumetric light, of various wavelengths (ultraviolet 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 stimuli could be transferred to them through the support material, making it 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, many possibilities were found. 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, Chladni examined how various sound frequencies produced many 2D patterns from sand particles placed on a Chladri board (Chladni, 1830) (see Figure 15a). The 2D sand particles can be reconfigured in real time by changing the frequencies induced upon the board, (traditionally by running a violin bow along the board's edge), which transfers set values of energy (frequencies) onto the sand particles. The patterns can reconfigure as the sand particles are not physically bonded. Significantly, set frequencies produced set patterns, which means a stimulus can be used to produce repeatable 2D patterns that can be reconfigured in real time. Jenny extended this research, calling it cymatics, by carrying out multiple experiments with various materials, such as sand, fine powders and liquids (e.g. glycerine) with different viscosities (Jenny, 2001). Interestingly, the various material platforms subjected to various frequencies showed that other properties could be achieved, from regular lattice patterns to 3D patterns as a result of the fine powder jamming and creating 3D sloped formations. Briefly, the main points of interest from these experiments and the various materials used are:

The impact the dimensions and shape of the board have on the patterns created. Thus, the container could also be used as a means of guiding material interactions along with stimulus.

Inducing sound frequencies upon glycerine created regular linear and lattice patterns on their surface (Jenny, 2001). Critically, this illustrates that the ability to change the properties (e.g. viscosities) of the materials being subject to the sound frequency stimulus could enable a greater palette of patterns. For example, maintaining a certain liquid viscosity in some areas to produce regular grid patterns and changing its viscosity in other areas via heat to create smoother patterns, could enable multi-material patterns.

It is possible to create 3D patterns by using fine lycopodium powder in layers on top of one another (see Figure 15B-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 affects the *angle of response* of the powder (Jaeger et al., 1998).

Additionally, Louviere + Vanessa, an artistic partnership founded by Jeff Louviere and Vanessa Brown in New Orleans in 2004 developed the *Resonantia* exhibition, which reveals the complex 2D patterns that are possible by inducing sound through water to guide ink diffusion patterns (Louviere and Brown, 2015).

The 2D abilities present within these series of material prototypes 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 the material at specific locations by projecting light into a volume. For example, using CAL's ability to change the RLP support material's viscosities and diffusing liquid materials through them. This could result in various surface textures being created as diffusion occurs. Imagine the print material diffusing through 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 over time based on augmentations to a digital design, which enables the physical material to reproduce any digital changes. In this way, design and fabrication instructions, as well as materials generated, could be tightly linked.

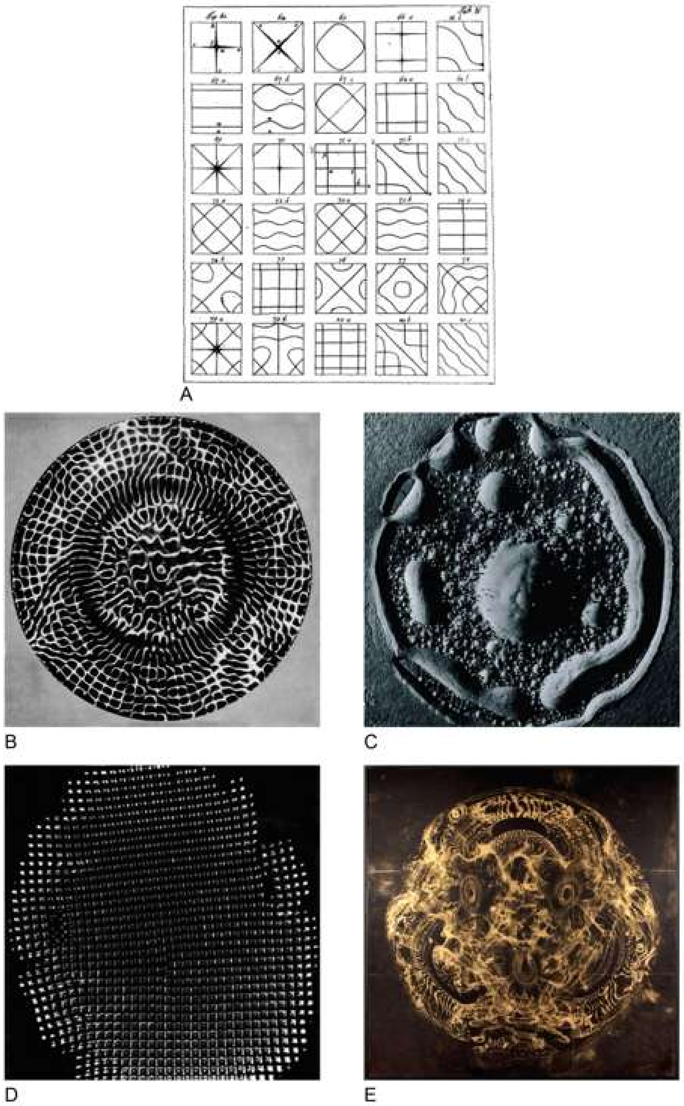


Figure 15: Various frequency / cymatics patterns. A) Various 2D Chladni patterns produced from different sound frequencies on a square Chladni board. Source: Chladni. E, Die Akustic, 1802. B) Hans Jenny document of various sound patterns that he called cymatics. The 2D patterns created by the sand particles are affected by the plate's shape. The circle's diameter is 500mm. C) 3D Cymatic patterns produced by fine lycopodium powder within a 280mm diameter. D) Regular 2D cymatic lattice patterns are produced within glycerine; no scale is given. Source B-D: Jenny. H, Cymatics: A Study of Wave Phenomena and Vibration, 2001. E) 1 out of 12 images by artists 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 photographs. 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’s multi-vascular networks (Grigoryan et al., 2019). Cronin has developed 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 structures within tanks of liquid (BEA, 2016). Grigoryan has achieved 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 (the print material), which inhibit the light stimulus of the AM process (Grigoryan et al., 2019). The fabricated vascular networks can 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 hydrogel and onto the liquids within the vascular network (as the network structure contracts and expands), causes fluids to circulate throughout the artificial vascular network. 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 Between Material Properties Generated and Stimuli Induced

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, and how they can generate desirable or intended patterns. This raises the difficult challenge of determining feedback mechanisms between material properties and conditions so they can be mapped to relevant parameters of a digital design tool so parameters of stimulus can be tuned, such as duration and magnitude of vibration frequencies or agitation to create desired material properties. The potential lack of feedback between properties of an ink cloud diffusing and design tools are similar to the issue highlighted in Otto's form-finding models, in particular, the *Occupation and Simultaneous Distancing* model, since the clusters of polystyrene chips are not monitored or used to affect a subsequent condition. For example, within this setup, the magnitude of the needles' magnetism informs the size of the polystyrene chip formations, but the cluster size and variables of magnetism are not monitored in relation to one another. However, if the material being guided by the stimuli, in this case, polystyrene chips, does not result in an effect on stimuli being induced that could be compared to one another, then feedback mechanisms between materials and stimuli become redundant and others must be determined or incorporated. In order to 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 platform can be used to establish feedback and relationships between material properties, stimulus and parameters of the digital design tool.

However, it can also be argued that being able to update material properties by continuously varying the stimulus, updated by digital design tool instructions, could also be achieved by CAM technologies and at very high level of 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

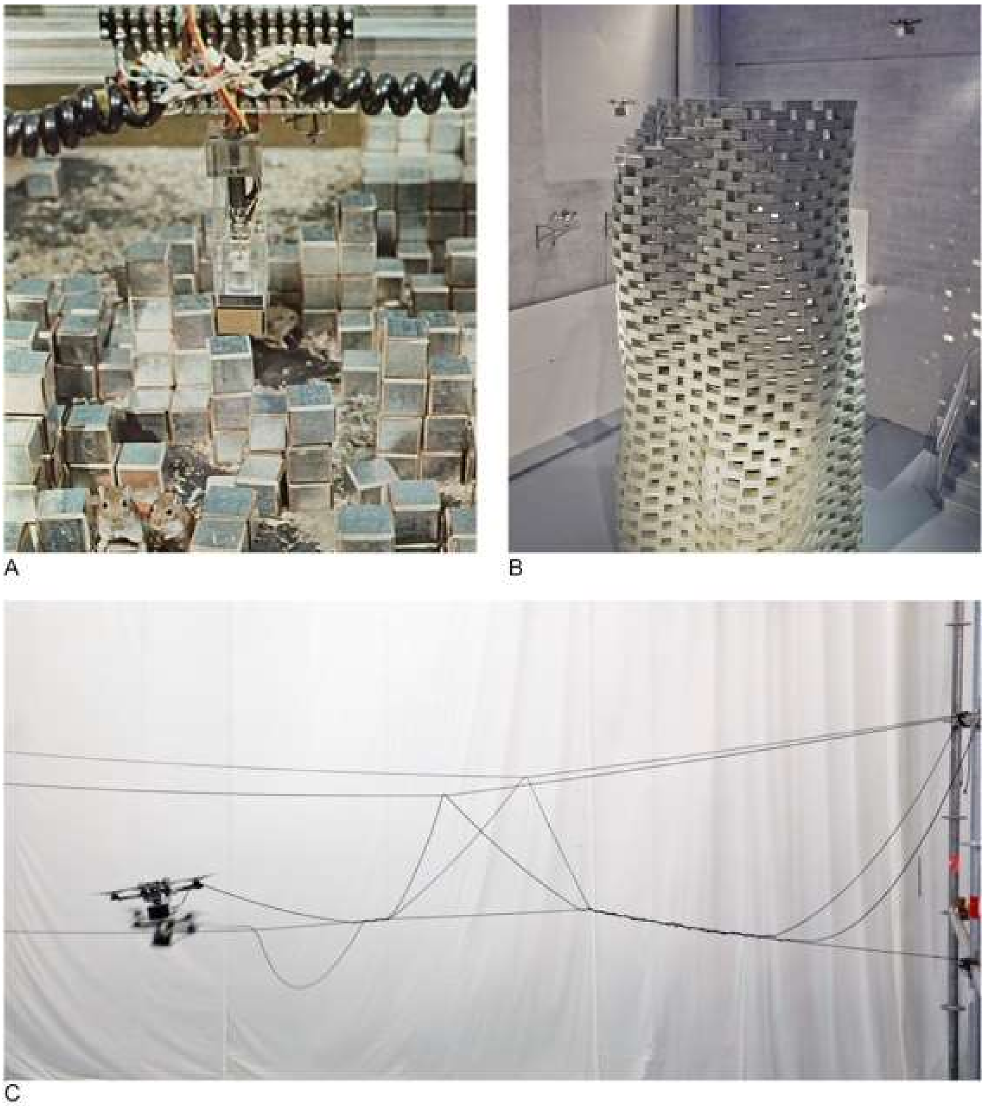


Figure 16: Various robotic fabrication processes. A) SEEK was able to adapt the 3D form of its structures based on gerbil activity with the material units but was constrained by the dimensions of the framework. Source: The Architecture Machine Group (MIT). Year: 1970. B) Flight assembled architecture; 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, as a result, the material's reconfigurations 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) analysis of material properties:

1) Digital augmentations can be used to update (in real time) the fabrication instructions of the CAM tool (Augugliaro et al., 2014; Peng et al., 2016; Sandy et al., 2016).

2) 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 material units that have designed armatures and jam together based on friction (Angelova, 2015).

3) The research project SEEK moved material units (small metal cubes) based on the gerbils' activity/interactions (i.e. user interaction data with the material units). The gerbils' interactions 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, fabrication process, material units and global form (Negroponte, 1970; Negroponte, 1975) (see Figure 16).

Typically, feedback within these robotic fabrication systems is achieved via video recording and software evaluating whether 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. However, it has been demonstrated that AM processes for depositing materials can be informed by sensor information (Sadeghi et al., 2017). Localised sensor information could become more useful for creating a distributed network of information to determine what local and global properties are needed as design demands fluctuate. However, the sensor values need to be mapped to corresponding material properties, for example, an increase in pressure being detected could result 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 object's shape in line with user analysis, without the need for completely remaking the initial product (Weichel et al., 2015). 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; second, the software determining the stacking order; and third, the robotic arm stacking the rubble (Fadri et al., 2017). Understanding the benefits of CAM fabrication processes and their relationship with materials will be reviewed by how they also bear resemblance to properties of self-assembling material platforms: 1) a distributed system; and 2) the ability to reconfigure 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 reposition the structure's materials. However, this raises the question of how feedback is achieved so that 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 16) (Ammar et al., 2014; Augugliaro et al., 2014). The multiple robotic units can act like distributed swarms, with construction and different material processes occurring in different locations simultaneously, which then converge (Augugliaro, 2013; Mirjan et al., 2014; Mirjan et al., 2016a). 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, as with SEEK's. However, this raises the challenge of communication between the multiple agents, which is required so they do not crash into one another 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, raise several interesting issues. 1) the uniform and predefined blocks used in *the flight assembled tower* (see Figure 16) (Augugliaro et al., 2014) can be iteratively reconfigured but are constrained to layer-by-layer fabrication logics as the blocks work in compression as they 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 resolution and properties of a singular block, which forms the unit of matter in this system. 3) Comparatively, the bridge structures (see Figure 16) are not limited to layer-by-layer logics as they work in tension (Augugliaro et al., 2013; Mirjan et al., 2013; Mirjan et al., 2016b). However, reconfiguration of these structures would become increasingly difficult as the structure becomes progressively interconnected and complex as material is added because the rope, which is the unit of matter, 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., 2016b). 4) Although fabrication instructions can be updated to alter the fabrication process, the process and end result is highly deterministic (Kathrin et al., 2016). Desirable traits and novel typologies that could arise are restricted and not uncovered because no deviation can occur throughout the fabrication process. Primarily, this is due to the fact the materials/units of matter are not 'active' components within the fabrication system as the processes (stacking, weaving, AM or milling) impose form upon the materials. 5) A major benefit is that the robotic units can handle material units/units of matter 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 units play a more active role in what could be seen as a fabrication process. Research into granular matter has revealed parameters (phase/state transition, force chain networks, granule shape/properties) (Radjai et al., 1996; Jaeger et al., 1998), which can be used and manipulated within robotic fabrication processes that can guide the structure's properties (global shape, packing densities, volume), composed of granular matter, thus 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, p1)

Granular jamming is reviewed because it has been employed as a material platform within digital fabrication processes, where robotic units typically pour granular material units on top of one another to create architectural structures, such as walls and columns. Significantly, the material units can be seen to play a more active role within the fabrication process, because of this, material computation is engaged with during the fabrication process (e.g. local material flow, variable packing densities) based on variables of the materials (e.g. geometries, surface area) (Dierichs and Menges, 2015; Murphy et al., 2016a), 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. Consequently, 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. To understand the properties of granular jamming and how they could be employed into self-assembly processes various aspects will be reviewed:

1) An overview of how granular jamming is created and its inherent benefits.

2) How granular materials can change phases, the interactions between materials (force chain networks) and applications based on phase changing.

3) How typically sloped granular structures can become vertical architectural structures by combining a physical force chain network with granular matter, enabling structures that are rapidly deployed, can be reversibly deconstructed and totally recyclable.

4) How typically sloped granular structures can become vertical architectural structures by designing granular morphologies, which affects material computational processes and enables walls to have functional

gradients based on light transmittance performance. This results in feedback between material properties, fabrication processes and environmental conditions being attained.

5) How local properties of the jammed architectural structures can be monitored by incorporating localised sensors, and 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; vacuums can also transmit forces (Brown et al., 2010). 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 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 that the particles are not jammed beyond this angle and behave like a fluid at the material's surface. This makes them marginally stable (Levine, 2001) as light disruptions (affecting the 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. (An example of this is the Dominus Winery structure by Hertzog and Demuro, where rocks are loosely contained in wire cages, which produce variable lighting qualities); and 3) design the shape of the material unit (Keller and Jaeger, 2016). Significantly, granular jamming can change the material's state based on *'jamming phase transitions'* (Jaeger, 2015). Granular jamming enables materials to instantly change state between solid-like and fluid-like (Song et al., 2008). Thus, granular materials can act like a liquid, where the granular material units can freely flow over one another locally, to a state 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 itself 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: 1) granules within a membrane subjected to vacuums to govern jamming phase transitions (Jaeger, 2015); 2) physical frameworks of *force chain networks* (rope) deposited by robots, which hold the structures units of matter (rocks and rope) in place; and 3) designed material units, which informs their jamming properties. Additionally, how feedback between digital simulations and physical structures 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 and reversible architectural structures (Aejmelaeus-Lindström et al., 2017), rapidly fabricated gradient-based structures (Angelova et al., 2015), and even interactive user displays with variable stiffnesses and surface textures (Follmer et al., 2012; Stanley et al., 2013; Ou et al., 2014). How these abilities are achieved will be sequentially unpacked, which will help to highlight 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 by designing the properties of the material units.

3.4 Jamming Transitions and State Changing Materials

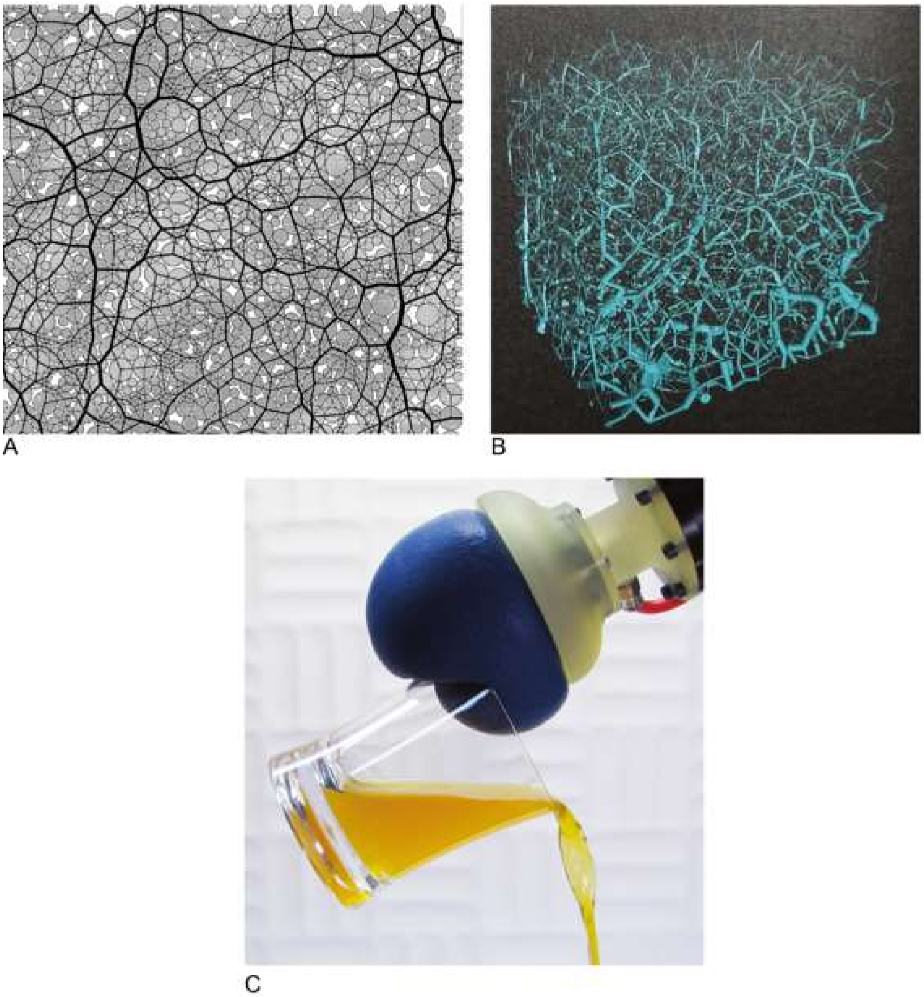


Figure 17: Granular Jamming simulations and universal gripper. A) Computer simulation of a 2D force chain network highlighting path and the network of forces transmitted between neighbouring granules and throughout their entirety, which significantly, can be reconfigured if stress is altered. Additionally, the magnitude is highlighted by the thickness of the line, 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 material's properties, from fluid-like (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 17). 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 17). This is because when the granules are not subject to a vacuum the membrane's surface enables iterative plastic/adaptive surface deformations. 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 is 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.
- 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 objects 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 materials as well as highlighting how they can develop, or have developed, into novel architectural design and fabrication processes.

- 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, dissipating energy and adaptive shape change of the membrane’s surface when the granules are in a fluid state (Jaeger, 2015). The jamming effect also opens up 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 shape of the components (Dierichs and Menges, 2016) as well as mixing materials (fibres and rocks) to help promote jamming and maintain global shapes (Aejmelaeus-Lindström et al., 2017).

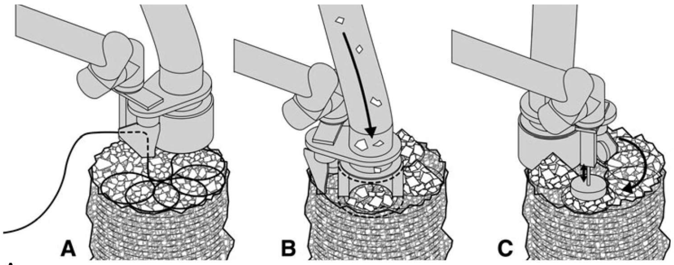
- The ability to induce and change the state of the vacuum over time and to varying degrees informs the amount the granules can locally flow over one another until a threshold is reached, which causes the granules within the elastic membrane to temporarily jam together and hold onto the object they are shaped around. The stimulus of the vacuum enables the membrane’s adaptive surface abilities.
- Interestingly, in regards 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 magnitude of the force, which has been digitally visualised in 2D (Radjai et al., 1996) and 3D (Sanfratello et al., 2009; Murphy et al., 2017a) (see Figure 17). These networks of forces are termed 'force chain networks' (hereafter FCN) (Radjai et al., 1996).
- The FCN can also reconfigure to form new network patterns when the stimulus is removed and reintroduced or fluctuates in terms of where it is induced, which enables the self-healing abilities (Keller and Jaeger, 2016).

- The variable magnitudes present within the FCN again highlight material computational abilities for generating localised variation.
- FCN reveal a means for developing a novel fabrication strategy in which the FCN is physically and continuously laid (in the form of a continuous fibre/thick string) 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 sloped formations. However, the phase transition is removed in these strategies and the structures cannot be reconfigured based on stimulus as the FCN has become materialised.

Reconfiguring formations of granular matter based on stimulus are not confined by a membrane, as illustrated in Jenny's cymatic experiments (discussed in Section 3.1.3), in which he 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, where 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 material’s *'angle of response'* 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 of 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 FCN 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 heats them 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., 2016; Dade-Robertson et al., 2017). Due to the emergent 3D patterns of FCN produced naturally within the soil, only areas beyond a threshold pressure will be bound together. This demonstrates that, 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 6 along with many other material platforms to understand the abilities and strengths for generating an adaptive design and fabrication systems.

As previously mentioned, 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 that designs the shape of the material units and the material properties they achieve when deposited via robotic units.

3.4.1 Between the Granules



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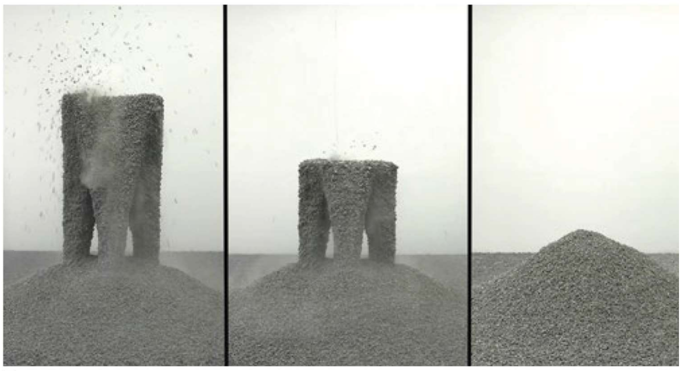

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Figure 18: Loading bearing granular jamming processes and prototypes. A) Illustration of granular jamming constructing process, where the robotic arm simultaneously deposits string and aggregates in incremental layers. The string enables structures 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 that holds the material units in position (Aejmelaeus-Lindström et al., 2016) (see Figure 18). Various aggregate types and binding materials were investigated to reveal the most suitable combination and strategy for addressing a criterion 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, p4), which investigates the primary question of stability to create viable architectural-scale structures termed; *'Jammed Architectural Structures'* (JAS) (Aejmelaeus-Lindström et al., 2016).

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 18). Here the string temporarily binds together the structure's units of matter. 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).

Direct deposition; as previously stated, granular materials 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 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 to 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; 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) since 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 embedding 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. However, in order to achieve this 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, and the variable properties they achieve, will now be discussed.

3.4.2 Designed Granules

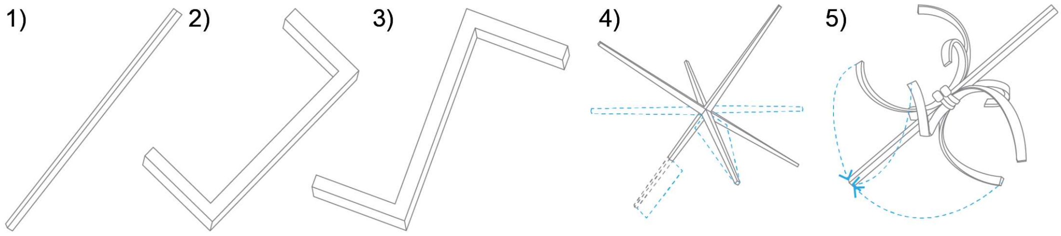
> *"Designing the individual particles of granular materials defines novel material characteristics of the overall granular system. This opens up a range of possibilities for architectural applications that are fully reconfigurable as the particles are not bound to each other."*
>
> *(Dierichs and Menges, 2017b, p90)*

There are two main aspects of interest in this section, with the first enabling the second. The intentional micro design of the material unit's 'grain morphology' (various shapes and properties of a 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 structure's macro-scale (global properties), such as functional gradients dictated by the materials units packing density abilities. The process, typologies and benefits of designing the material unit's morphology will briefly be discussed to set up 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 the structure's macro material properties. Significantly, these material properties perform material computational actions/processes to generate global properties (Dierichs and Menges, 2015). Briefly, the several benefits of designing the material unit's morphology, which achieves some of the same properties described in the previous strategy as well as additional abilities, are:

- Designing the shape of the individual material units 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 material units governs material computational processes of packing and jamming densities to create freestanding structures that have loading capacities (Murphy et al., 2016b)

- Gradient structures can be created by governing the micro properties of the material units in combination with variables within the fabrication process (Angelova et al., 2015).
- Actuated granules can further enhance packing densities and local material transformation by fabricating the units from composite materials (Dierichs et al., 2017b).
- Scalability, as the overall structure, does not have to be defined and the process involves self-assembly. Thus, 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 now be discussed by first examining the various properties and variables of the material unit’s morphology, and finally how robotic fabrication units can guide material computational processes over time to achieve variable properties.



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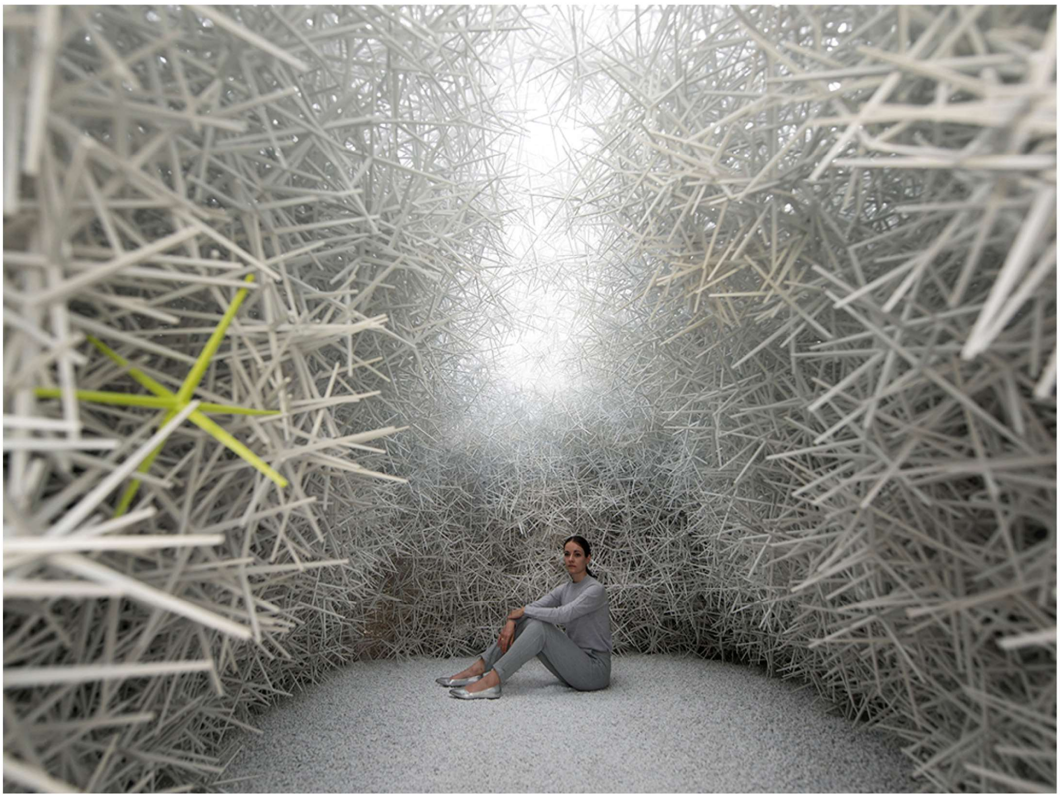


B

Figure 19: 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., 2016a), A4) X shaped. Some of the main variables of the X shape are highlighted with the blue dashed lines which are: number of arms, size of arms and length of arms. Altering these variables 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., 2017a). B) Aggregate structures with variable light properties achieved by material computational processes informing packing densities. Source: ICD University Stuttgart and 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 the structure's units of matter means that no additional binding material or formwork is required (Dierichs et al., 2015). This enables vertical structure types to be created (walls, columns) (Dierichs and Menges, 2012; Angelova et al., 2015) that have structural capacities (Murphy et al., 2016a) but allow the properties and material units to be more easily manipulated (added or removed).

The morphology of the material units (variable of the material's shape) has an impact on the global properties of the structure along with fabrication processes that guide the material unit's collective computational processes. The various shapes of the material units are highlighted in Figure 19, 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., 2016a) and X-shaped (Dierichs and Menges, 2015); and 3) *double non-convex ($ shaped)*; where the granule can form curved hooks from an initial convex state (stick-shaped) as a composite material (wood laminate) transforms and curls as relative humidity increases i.e. that granule transforms from a convex state to a double non-convex state (Dierichs et al., 2017a). The interesting aspect of the Z-shaped particles is that they enable high flowability whilst also maintaining structural capacities (Murphy et al., 2016a). The high flowability is something achieved by the $-shaped granules in their convex state, which also enables 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 greater volume (Dierichs et al., 2017a). The ability to change state addresses the problem inherent within the double non-convex state, which entangles the granules so much that they can no longer flow, and therefore cannot be poured for the fabrication process (Dierichs and Menges, 2015). An important aspect that came to light as a result of practice-based research centred around the act of making

However, the ability for the material granules to transform based on relative humidity levels endows the individual material units with the ability to perform a localised material computational process (Dierichs and Menges, 2012; Dierichs et al., 2017a), such as the material units collectively creating multiple localised openings in the structure to passively increase airflow and cool the building (Dierichs et al., 2017a).

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

The X shape has 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 structure’s global properties; *"A doubling of arm length, for example, leads to an average tenfold decrease in packing density"* (Dierichs and Menges, 2015, p88). Essentially, these material variables affect neighbouring material interactions and global properties generated from material computation. The primary material computational process in this system is packing density. Additionally, how 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 controlled by the robotic arm that pours the material units are: *"pouring speed, angle, the distribution of different particle grades as well as pouring paths"* (Dierichs and Menges, 2012, p80). Variables for an armature that grabs multiple material units and drops 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 of the robotic units in the fabrication process and the impacts of designing properties of the material units are the reasons for examining this material platform in the fabrication section; the material units are susceptible to the stimulus of gravity when poured or dropped with varying parameters using a robotic arm. However, by designing properties of the material units they have a major impact on the local neighbouring forces/interactions that affect the properties of the overall structure. By engaging with the individual material units they can induce their own local stimuli upon the material system to varying degrees, in this case, friction, as well as dissipate the global stimuli of gravity, which causes the material units to jam together and generate a compression-based structure. Comparatively, the other material platforms examined later can be deployed within a system where parameters of stimuli can be tuned and used to guide both local and global properties of a structure without designing the geometries of the individual material units.

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 the 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, p261). The aspect of interest here is that the formwork (string) also can monitor conditions, which highlights potential avenues for using the formwork/infrastructure of the material system for both inducing and monitoring local conditions to guide and determine if desired material properties have been fabricated.

- An 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 sensor's 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 the material computational process to create functional gradients that are less deterministic compared to AM processes, due to the fabrication process (Angelova et al., 2015).
- Aggregate structures with voids are 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, p68).

The *'online controlled inflated formwork'* (hereafter OCIF) is reviewed in more detail, as opposed to the *'graded light'* robotic strategy, because the OCIF uses stimulus in the fabrication process. However, the OCIF does not use sensor values to determine material properties while the *graded light* process does. Inflating balloons to various sizes within formwork has been used to create void spaces within the aggregate materials (Hensel and Menges, 2008). The ability inflate the balloons to various sizes enables them to act as a flexible and temporary formwork. The OCIF strategy is of interest because a stimulus (air pressure) is used to transform the balloon, which informs the global geometric properties of the structure. Significantly, a digital counterpart/representation of the physical material system is used to simulate the material unit's behaviours (packing, settling), which is used to govern the balloon's inflation and deflation

(Rusenova et al., 2016). Manipulating the balloon begins to link the material unit and digital model. After the initial pouring of the aggregates has 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 unstable areas, which result in the physical inflation of the balloon to temporarily support these areas and create physical voids and volumes similar to those of the digital model (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 has 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 simulation's parameters and more accurately model/represent the physical material unit's 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 the discrete element method (DEM) (Cundall and Strack, 1979). The DEM represents physical interactions that occur between the material units (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/non-deterministic 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 typical design and fabrication relationships with materials. Instead, the designer interacts with materials and observes 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; *what types of digital design strategies would be suitable for inducing and monitoring stimulus to guide processes of self-assembly with undefined units of matter?*

For this reason, several digital design strategies are reviewed in the next chapter before going on to review multiple material platforms. Examining the various digital design strategies is intended to help understand what parameters and resolution they could 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.

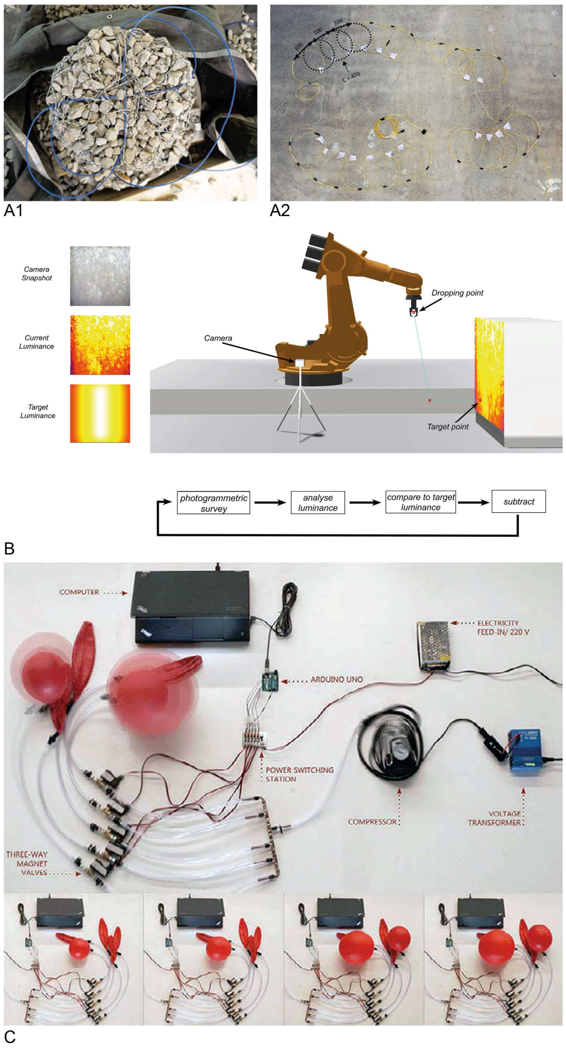


Figure 20: Sensors for 'Jammed Architectural Structures'. A1) Steel-coated glass fibre sensor incorporated into the structure as the string medium and used to determine the overall behaviour of the structure Source: Rusenova, et al. Year: 2018. A2) silicone-coated glass fibre sensor used to measure local deformations. Source: Rusenova, et al. Year: 2018. B) Optical sensor (web camera) integrated into the fabrication system to monitor real-time daylight transmittance values enabling feedback between the 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 they settle (both digitally and physically). Source: Dierichs, et al. Year: 2016

3.5 Chapter Summary

Key areas of interest from each section are briefly summarised and 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 stimuli upon materials being deposited into it so material 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 simultaneously but typically treat materials as inert.
- Robotic fabrication units with mobility enable structures to be fabricated at architectural scales. However, the properties of the material units and construction system dictate the resolution/sensitivity of possible adaptations. Typically, global adaptations can be easily, but incrementally, achieved.

Granular Jamming

- Designing variables on the micro-scale (material units) enables global properties that have variability throughout the structure, such as functional gradients.
- Variables 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.
- Designing geometries of the material units informs the degree in which they can induce local/neighbouring stimuli between units (friction), which

impacts to which degree the global stimuli (gravity) has on the material system.

- 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, relationships 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. In the following chapter, digital design platforms are reviewed to understand how they could be employed to guide interactions between materials self-assembling and at what resolution.

4 Linking the Digital & Physical

The possibility of adapting a structure's physical shape in anticipation of the inhabitants' interactions units was previously described in the SEEK research project, which produced a cybernetic, self-regulating architecture based on circular causality and feedback between gerbil activity, material components and global forms (Negroponte, 1970; Negroponte, 1975). Additionally, the proposed projects of Cedric Price describe cybernetic architectural structures and urban systems that can self-adapt to fluctuating design demands, such as the adaptive self-reconfigurable structure of the 'Fun Palace' proposal (Price and Littlewood, 1968; Mathews, 2005), or the *'Potteries Thinkbelt'* proposal, which described reconfigurable student accommodation during term time at an urban scale (Price, 1966).

All of the physical reconfigurations within these past proposals and research projects were 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 systems, such as the architectural proposals of Price. The principles of understanding and regulating these systems are 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 establishes an iterative relationship between digital design representation (parametric model) and fabrication achieved by inducing stimulus (Ayres, 2012b). Significantly, it is the ability and role 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 level. In doing so, the chapter's aim is to highlight principles within these strategies to help understand how they could be employed for further developments or iterations of adaptive design and fabrication systems, where the digital representations could be used to: 1) determine if desired material properties have been fabricated from the self-assembling materials; and 2) potentially reveal complex interrelationships that could guide more subtle material properties, such as surface texture, which may not be directly affected by a single stimulus but a collection of stimuli.

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 design's processes (sketches, models, digital models) and final physical objects are emphasised and 'persist' throughout the lifetime of the object. The relationships between the two allow for time to be accounted for, so that change can occur via feedback between the digital design representation, in this case, the parametric model, and the situated physical structure. Ayres demonstrates this concept by creating a real-time link between the digital parametric model and material units, two metal sheets welded together at the edges, by inflating the components to distort their geometry (Ayres, 2011) (see Figure 21). The connection between design and fabrication is enabled by the digital model inducing and controlling the parameters of a stimulus (fluid pressure), which acts as a global stimulus that transforms the metal component's shape. This is the major aspect of persistent modelling that is of interest. The tools induced by stimulus and monitored via design enable a continuous discourse between design, fabrication and, to an extent, material properties of the component. The variation in fluid pressure and its ability to transform the predefined metal components by expanding them (increasing its diameter when inflated), allows for iterative transformations up to the elastic limit of the metal sheets. The stimulus has discourse with the material's own computational abilities as it governs the transformation/adaptive properties. Additionally, informing these material transformations can be based on improving the structure's environmental performance by increasing its solar shading ability i.e. inflating the material units to create a larger volume shape that can block sunlight to provide varying degrees of shading, which can be tuned (Ayres et al., 2014).

These materially adaptive abilities would enable 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.

First, 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 number 3'* (Ayres et al., 2014)

Second, the transformations are limited to the material's 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 sheet's material properties (harder in some areas and softer in others) (Ayres, 2012a).

Finally, the material variation in the physical components is further highlighted as non-uniform, localised material surface textures and deformations occur during inflation, which is not accounted for in the digital parametric representation (Ayres, 2012a) (see Figure 21). Thus, a restricted discourse between the resolution of the digital representation and the physical material unit is created.

The final point is a consequence of the parametric design tools used to represent the physical model, which is based on boundary representations of geometry (b-reps) and predefined associated relationships, which are based on a linear cause and effect outcome. The assumption being that increasing pressure in the digital model X 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 homogenous (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 constraints (Oosterhuis et al., 2004; Oxman, 2010a). The separation is partly a 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 material analysis, which examines a cross-section of the material component under a microscope, revealing varied granular microstructures. Hence, localised material deformations (surface textures) are not accounted for (Ayres, 2012a).

For these two reasons, this chapter examines other possible digital models/strategies that can account for the granular nature of materials as the digital model is based on the structure's units of matter (e.g. voxels), which can be used to represent material processes that occur within a self-assembling/self-organising fabrication system. Because these digital models can represent individual material units, it may, however, 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 is not locally monitored like that of pressure in persistent modelling. For this reason, design tools are examined that could also determine or reveal potential material properties and relationships that could be mapped to locally induced stimulus as well as a collection of stimuli that produce a global environmental condition that acts as a threshold to generate other unforeseen material behaviours. Examining digital strategies capable of determining the relationships within a design and fabrication system could be used to extend the recent research area; *'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, and form generation and digital fabrication back into the digital models to create digital models that are increasingly functional and integrated (can account for multiple demands), multi-scale performance (material to global properties are performance orientated) and aesthetically novel (Royo and Oxman, 2015). These aims are potentially more potent with the incorporation of self-assembling materials as: 1) they are inherently based on material computational processes; 2) they provide a scalable process, which could heighten a design's performance and functionality; and 3) self-assembling materials can reconfigure, enabling transformation across time domains, which again would enhance a design's performance orientation as fluctuating demands (aesthetic, programme, occupation) can be accounted for.

Critically, the ability of design representations to maintain discourse with physical artefacts enabled in persistent modelling is due primarily because of stimuli, 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 workflow but one where each component is inherently linked to one another (digital model, fabrication process and material) (see Figure 22). The main intention from this point onwards is to explore how persistent modelling could be extended by incorporating materials that can self-assemble and understand other types of digital tools, platforms and strategies that could further guide self-assembling processes by accounting for various material properties that may arise (surface texture, porosity), which would enable physical adaptation with greater sensitivities. The overarching factor that connects the following design strategies is the fact that they account for, or are 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.

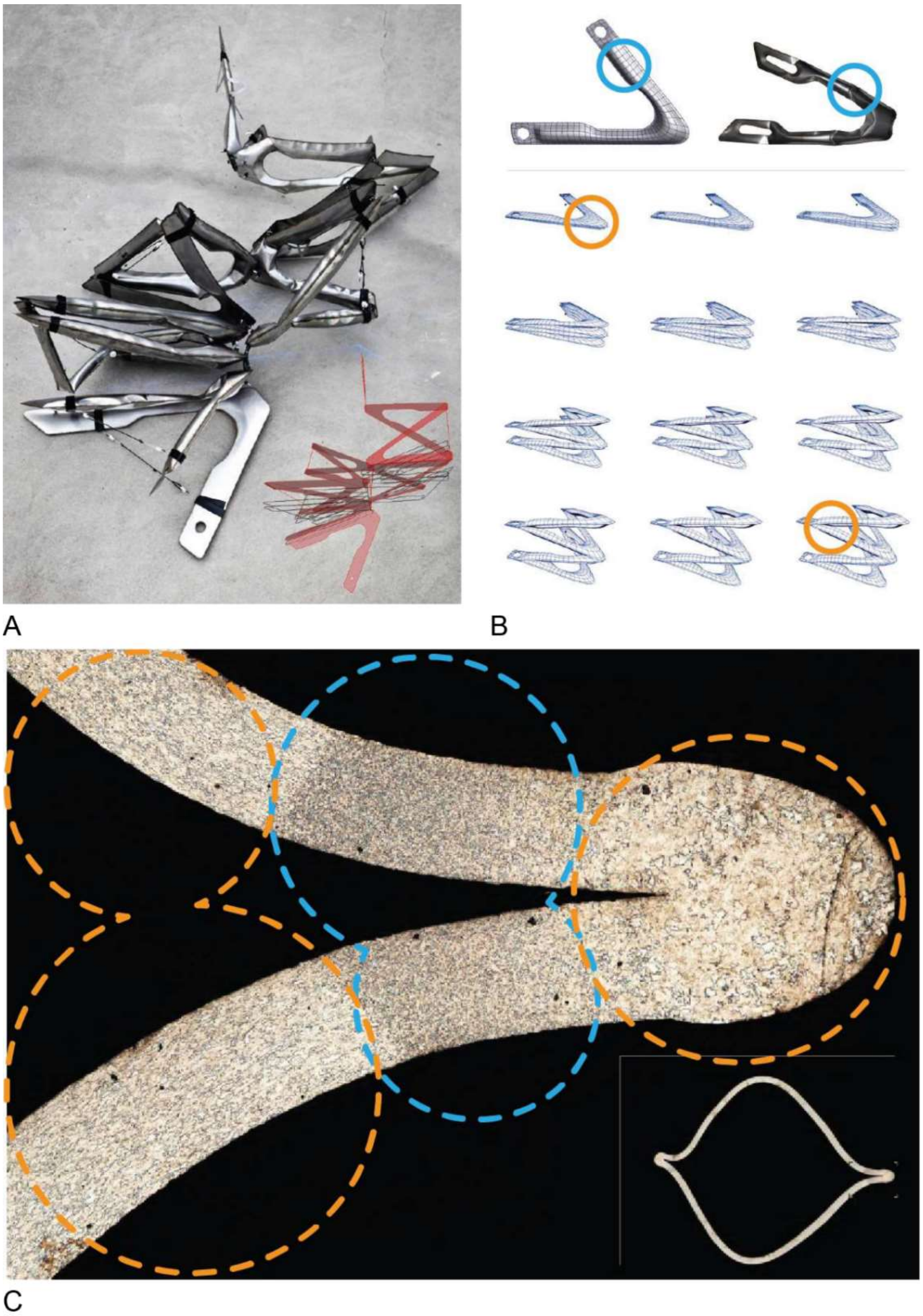


Figure 21: Persistent Model deformation and materiality. A) Transformation of digital representation linked to the physical artefact by inducing stimulus. Source: Ayres, P. Year: 2012. B) Deviations in the uniform transformation of digital model based on b-reps and non-uniform transformation of the physical 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.

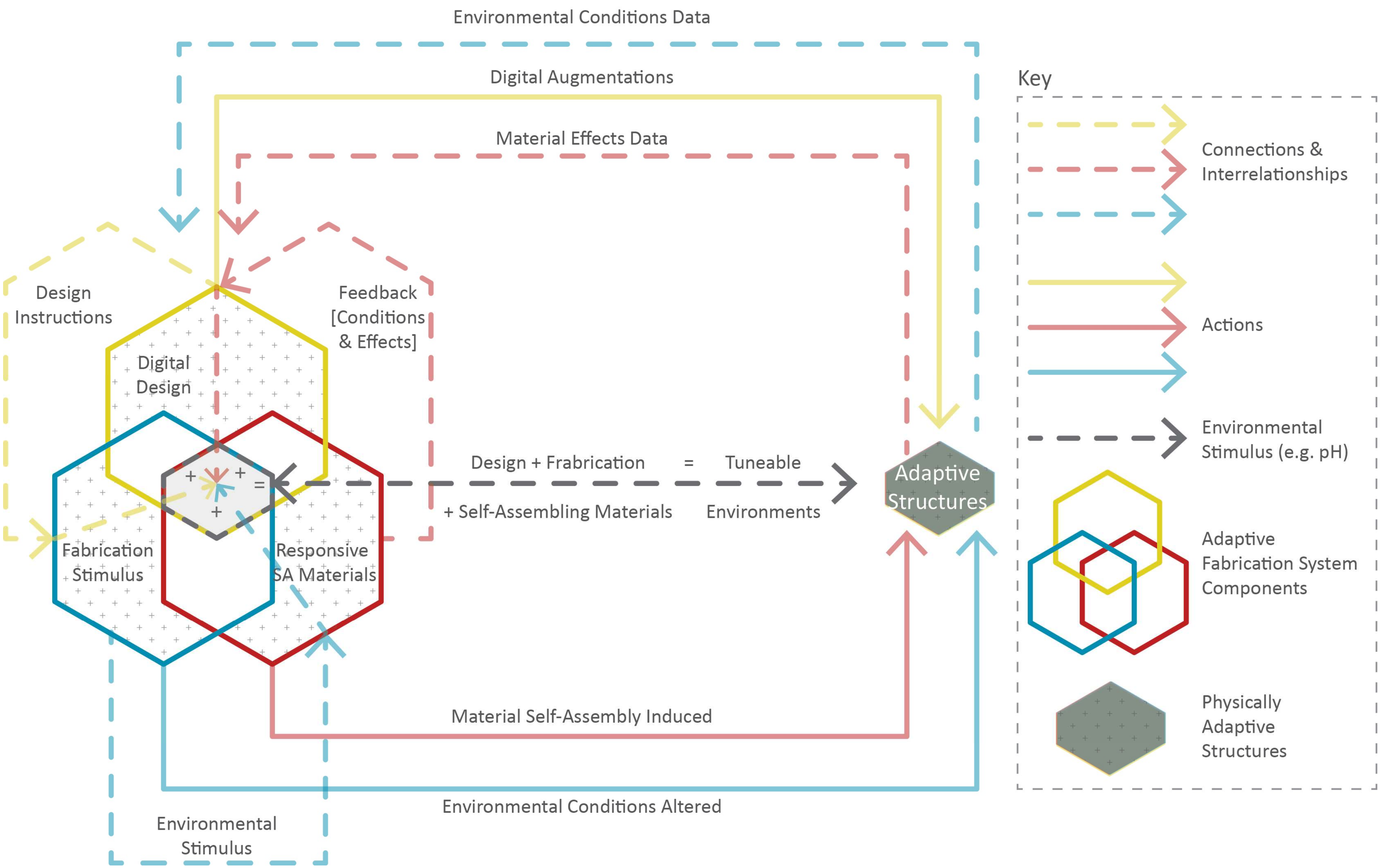


Figure 22: Aim of interrelationships within the proposed design and fabrication system enabled by utilising stimulus as the fabrication mechanisms.

4.2 Material Agents and Processes: Designing with and for Bacteria

This chapter now focuses on strategies that can generate digital models based on its units of matter and not geometry (b-reps), like those of persistent modelling. It extends and reiterates the strategies (MBDC and CPPN-NEAT) examined in Chapter 2 by relating it to how stimulus can enable feedback between design representation, physical artefact and material properties:

- Feedback can be achieved between both the global physical and digital and local (compositions, surface texture) properties.
- The granular nature of the following digital models also resonates with fabrication processes that utilise self-assembling 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 self-assembling materials guided by varying conditions/parameters that inform processes and behaviours.

As highlighted in granular jamming, it is possible to simulate a collection of material units 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) to perform desired actions (secrete bioluminescent proteins) once a threshold level is reached (Dade-Robertson et al., 2015). Essentially, the bacteria are carrying out a process they have been programmed to do.

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 that are based on the behaviour of the physical materials, for example, bacteria's behaviour in the SynthMorph simulation (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 can create 3D digital models which, *"approximate form through the behaviours of biological agents rather than through geometric rules"* (Ramirez-Figueroa et al., 2013, p52), as a result, 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 an *"ever-changing organism"* (Ramirez-Figueroa et al., 2013, p52), which could be enabled by the potentials of 'bio-bricks' (Knight, 2003; 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 stimuli/conditions will be discussed further in the following chapter. 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), in which the physical and digital experiments inform one another to understand the 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 soil's mechanical loading capacities (Dade-Robertson et al., 2016), and which results 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., 2016, p451). 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., 2018) 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 material's behaviour.

'Mushtari' is part of a series of these product scale wearables that form a speculative research project called *'Wanderers'* (MIT, 2015). The project demonstrates that speculative wearable scale products can be digitally designed based on the bacteria's activity, which creates geometrically complex and multi-material forms (variable colours and transparencies) to help support bacterial growth and guide activity within artificial vascular structures (Bader et al., 2016b) (see Figure 23). Within the *Mushtari* wearable, there is a single continuous fluidic channel that houses the bacteria. Along its length, the channel varies in diameter and 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 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 about creating a symbiotic relationship between novel types of wearable technologies and use for interplanetary space exploration enabled by the microcolonies' activity to produce habitable conditions for the wearer. The new material abilities afforded by incorporating and designing structures with bacteria as agents opens up new design potentials and relationships, which are further enhanced by speculating on future research areas or applications that are embodied in the materialisation of the design idea (Dunne and Raby, 2013).

Significantly, the digital models provide a testbed for determining parameters and creating conditions for leveraging desirable behaviour from the bacteria/microcolonies i.e. they are used to simulate behaviour digitally. Another potentially powerful space 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 digital model 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). 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. This time lag could reduce the sensitivity of dialogue when design tools are used to manipulate stimulus. Ways of addressing this issue are:

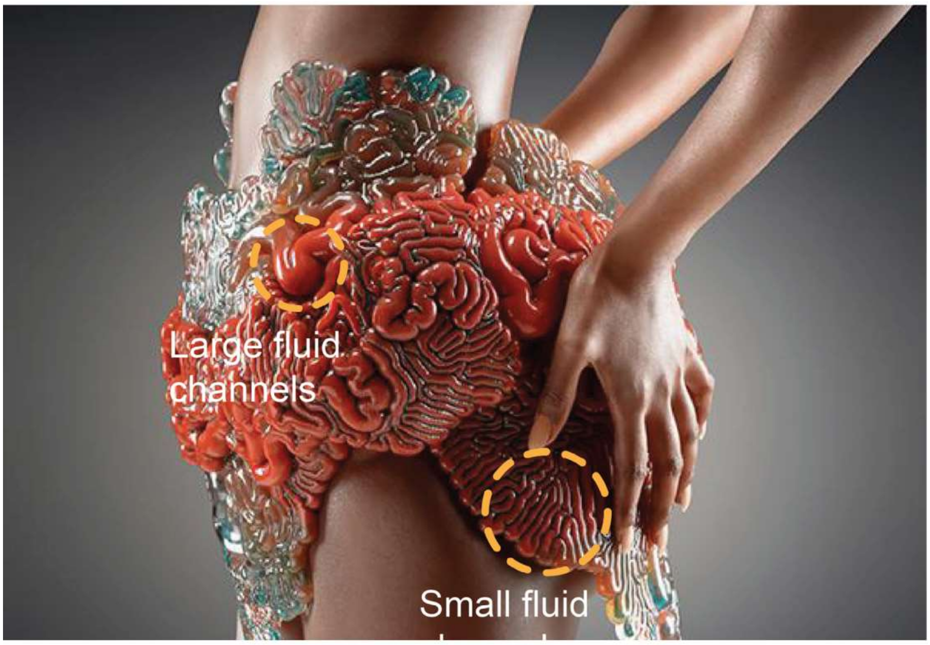
1) Utilise digital methods based on their speed of processing abilities like that of PBD which are robust enough to simulate millions of cells and their interactions (Bader et al., 2018b). Or employ the CPPN-NEAT strategy (Richards and Amos, 2015), which can generate complex designs based on compressed 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.

2) 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 types 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 – a movie's 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 the design tools'/process relationships with fabrication and materials. Instead, parameters of the design become embedded between the two, removing the separation that can occur between them when the 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 importantly, 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, Dade-Robertson et al. demonstrate that the stimulus of loading pressures, which dissipate and create 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 (Dade-

Robertson et al., 2018). These explorations are informed by carrying out both *in vivo* (in the living) and *in silico* (silicon-based computing) experiments (Dade-Robertson et al., 2016), 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 self-assembling material platform can be mapped to stimulus governed by digital design tools? How can sensor values from resultant conditions be mapped to self-assembling 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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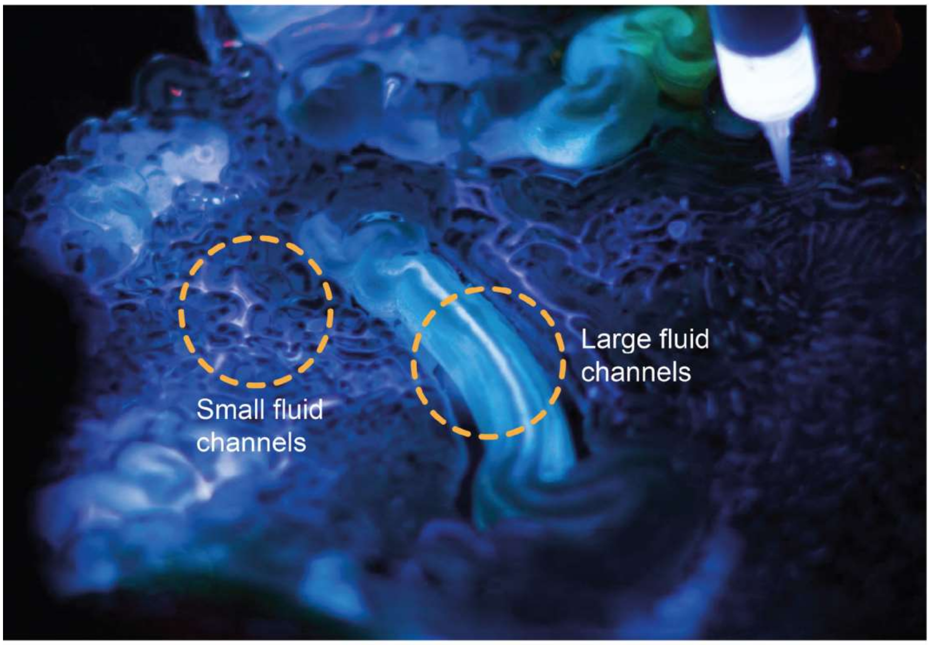


B

Figure 23: 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 biological and artificial complex systems into technological planning (Doursat et al., 2013). Understanding and leveraging these self-forming abilities through ME could have 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 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 to 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 properties of the cell (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 to govern the stimulus and material properties within an adaptive design and fabrication system have revealed three main aspects that resonate with a fabrication process based on self-assembly guided by stimuli:

- The ability to utilise simple rules and mechanisms, such as threshold conditions and concentration gradients to govern material properties (e.g. a cell’s state) could be used to 'fine-tune' self-assembly material processes and properties using stimuli that behave as gradients, which dissipate 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), for example, faster growth rates and smooth surface textures of a material that are governed by varying parameters of heat and light stimuli.
- A fabrication process based on constituent parts like self-assembling materials bears a strong resemblance to principles of ME (Doursat et al., 2013) due to the decentralised properties/agency of the materials in both. Growing materials by enabling a discourse between the processes of self-assembly and ME would be more intuitive than predefining global and local forms on the material units and then manipulating them as the materials granular nature is engaged with from the beginning. Hence, forms generated from the material units are a result of guiding them, as seen in ME.

In terms of what this would mean for fabrication processes that could grow various patterns, shapes, 3D products, and architectural structures from self-assembling materials that are guided by ME tools; imagine a trainer that could change the properties of its components parts (uppers, insoles, soles, laces) as an athlete induces different stresses upon the trainers as he/she runs across different terrains, across various time domains and at varying degrees of fatigue. Where the stresses and stimuli are sensed by the trainers' own material make-up, resulting in the material division, state/rigidity changes (hard to soft), shape and pattern changes, with these changes informed by threshold gradients based on the dissipating effects of the stresses induced at a specific location. As these mechanisms and rules are scalable since they are based on simple rules witnessed in complex 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 discussion in relation to resolution, time and varied voxel shapes (not restricted to cubes) afforded by the CPPN-NEAT strategy.

4.4 Infinite Resolution

As described 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. A reduced number of parameters can therefore 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 structures, enabling their local material composition to be programmed in relation to, and have a discourse with, global properties (shape) and demands (loading, aesthetics), creating structures that can adapt across their length scales. This is because simple information about the design's individual and or neighbourhood of voxels (x and y coordinates), which are the material units in this strategy, can be fed 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 structure's internal architecture and global shape.

In the context of utilising the CPPN-NEAT strategy for guiding interactions of self-assembly guided by stimuli, three aspects could prove to be beneficial: 1) resolution, 2) time, and 3) voxel shape:

- **Resolution**: The CPPN-NEAT strategy can potentially generate patterns of infinite possible resolution (Richards and Amos, 2017), which begins to more closely resemble a structure's physical material makeup. The ability to represent the granular nature of materials could address the restricted discourse created from b-rep digital models as highlighted by Ayres (Ayres, 2012a). Then, more nuanced relationships and finer material properties could be guided because of the higher levels 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 have their properties manipulated quickly (Richards and Amos, 2015). The increased speed of generating, manipulating and evaluating relationships of these complex structures could prove vital for guiding and determining effects of stimuli on extremely fast material computational processes (e.g. ink diffusion patterns in water or ferrofluid manipulations). Here, time may not be a limiting factor in 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, such as sand or soil, which are more spherical. The ability to more accurately represent the shape of the material increases the reliability of the digital simulation's 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 stimuli-based fabrication mechanisms point towards a convergence between digital design tools that represent granular materials and physical material computational processes, which can occur at high resolutions and potentially, at fast speeds, both digitally and physically, 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 coupled with a stimuli-sensitive self-assembling 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 adapt material properties, such as single colours, multiple colours, opacity, shape and texture by utilising the CPPN-NEAT strategy to tune stimuli-induced and monitor effects, which can be used to determine the required environmental conditions/stimuli needed to create certain image types and properties. Speculating on the idea of being able to control, tune and adapt patterns and properties of 3D ink clouds, you could imagine new kinds of TVs that are not restricted to 2D. Instead, TVs could be 3D volumes in which you could sit and the movie occurs around and interacts with the people watching it in 3D (see Figure 24).

Figure 24: Speculative image imagining people sitting within a cinema and watching a movie within a 3D physical hologram.

Beginning to attain these desirable physical material potentials, such as self-healing, adaption, and 3D physical holograms, requires suitable material platforms to be explored and an understanding of how to engage with them, to allow a material's properties to be tuned and adapted at various scales. For this reason, the following chapter examines strategies of guiding self-assembly material processes along with multiple material platforms to determine suitable platforms that can be used to develop a series of material probes that explore the idea of an adaptive design and fabrication system.

4.5 Chapter Summary

This chapter extends the abilities of digital design tool discussed in Chapter 2 as stimuli link design representation with physical artefacts as highlighted in 'persistent modelling'.

Persistent modelling

- Varying parameters of stimuli that affect material properties via digital design tools link design representations, fabrication processes and material units.
- Parametric design tools provide a sound starting point for guiding self-assembling material interactions as, initially, stimuli that have a significant impact/direct relationship with a material property (e.g. magnetism and material aggregation) can be easily mapped/associated with parameters that can be controlled via digital design tools.
- Persistent modelling could be extended by incorporating self-assembly materials so that local and global properties could be tuned.
- Induced stimuli can act as a global stimulus in as far as the transformation occurs globally with no deliberate control over local material transformations.

The following sections have been reviewed as they are all capable of representing materials on a granular level by composing them on: 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 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).

Morphogenetic Engineering

- Employing mechanisms, such as diffusion gradients and threshold values to inform the digital model's material behaviour has a strong correlation to physical processes and conditions that can be used to guide self-assembling material interactions.

- The digital simulations behave as a system of distributed parts, which again bears a strong resemblance to a fabrication process based on self-assembling 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.

CPPN-NEAT

- The CPPN-NEAT strategy can generate complex 3D structures at a high material (voxel) unit resolution and 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.
- The use of NEAT can then potentially be used to evaluate higher-level relationships created between more subtle material properties and processes.

The next chapter examines existing and current approaches for guiding self-assembly along with other material platforms that perform self-assembly without the need to predefine/design properties of the material units. Surveying these approaches and platforms will help to select a material platform that can be implemented in developing a series of material probes.

5 Searching for Material Platforms

The primary aim of this chapter is to highlight material platforms that: 1) can self-assemble when subjected to stimuli; 2) have their material properties tuned and adapted based on varying parameters of stimuli; and 3) the material platforms individual units of matter do not have pre-designed properties to generate desired patterns or properties. Highlighting suitable material platforms that meet these three requirements can then be used for developing a series of material probes that explore design, fabrication and material processes that are iterative and interrelated. Additionally, material platforms will be reviewed that may be able to establish feedback between digital design tools, fabrication processes, material properties and induced stimuli. The two main benefits that could arise from this are:

1) As established by Ayres (Ayres, 2012b), stimuli provide a means of connecting design representation and physical artefact but tuning parameters of stimuli could also provide a means of engaging with self-assembly processes to tune and adapt material interactions and properties that occur within the process.
2) Mechanisms that are part of the self-assembly process could be exploited to create a material system (Tibbis, 2017). In this way, the potentials of the material could be enhanced further if mechanisms and properties could be guided by tuning parameters of the stimuli based on feedback between them.

In a design context, Tibbits describes the three ingredients required for self-assembly: *"I - Materials and Geometry; II - Mechanics and Interactions; III - Energy and Entropy"* (Tibbits, 2016, p4). Importantly, stimuli can be seen as the energy component. Being able to tune and adapt the magnitude of the stimulus supplied to the self-assembling materials could enable the interactions between the material units 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. Understanding feedback mechanisms and enabling could be used to further enhance the abilities of an adaptive design and fabrication system as associations between desired material properties based on resultant conditions could be determined. This means that a *Closed-Loop Control System* (hereafter CLCS) could be developed.

A CLCS refers to the control action, in this case, a physical stimulus (e.g. electrical current, pH, temperature) that has feedback with process variables of the self-assembling material, such as volume, density, composition, surface texture. Exploring how feedback can be achieved between design tools, fabrication processes and material properties could be based on 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. To develop a design and fabrication process that resembles CLCS, material processes and relationships must be highlighted, which are intended to be explored through a series of material probes within this research. Furthermore, it is intended that developing iterations of the material probes will reveal design principles and challenges.

The structure of this chapter is:

First, an examination of biological processes of fabrication to understand which mechanisms dictate material adaptation and if aspects of biological processes could be applied to guide and determine self-assembling material properties.

Second, various strategies and material platforms are examined to understand how they achieve self-assembly with artificial material units.

Third, material platforms that self-assemble do not define the units of matter within the material platform and can be guided by stimuli. These highlighted material platforms will then be used (or aspects of them) for developing a series of material probes that explore adaptive design and fabrication processes based on self-assembling materials.

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, which are then broken down further. Significantly, these sections highlight mechanisms and possible resultant material effects that could be produced from stimuli, which can then be:

- Mapped to relevant design tool parameters or ultimately discovered by digital design- based tools.
- Used to determine if a desired material property has been fabricated (e.g. material volume and location).
- Could be further developed to create an adaptive design and fabrication system based on stimulus and feedback.

5.1 Biological Inspiration: Bone Remodelling

Biological fabrication processes provide the main inspiration for rethinking design and fabrication processes and how they interact with materials. The main inspiration is based on biological structures and their abilities to continually adapt their properties across their length scales to suit environmental demands as external forces and fluctuations (e.g. mechanical loading) inform material properties and deposition (Vogel, 2003). As a result, biological structures are multifunctional, materially economic and can be gradient-based. Additionally, biological fabrication processes are also scalable, robust, emergent, complex and physically adaptable/evolvable (Speck et al., 2015).

An example of a biological structure that demonstrate 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 heal micro-damages (Frost, 1990; Hadjidakis and Androulakis, 2006; AMGEN, 2012). The remodelling process 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, p385). The process occurs locally and globally (throughout the skeletal system) and it is governed by various biochemical and mechanical factors (Hadjidakis and Androulakis, 2006) i.e. external stresses (e.g. mechanical loading) inform internal stimuli (e.g. threshold protein levels) that inform the cellular activity. 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 activity of the osteoclasts and osteoblasts is in balance and prevents a certain cell activity from predominating/proliferating. Significantly, it is threshold conditions that govern the cellular activity. 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 within a self-assembling material platform. This raises a criterion for a material platform and the question; *what material platforms create fluctuating conditions when subject to stimuli to determine material properties?*

5.2 Self-Assembly: Material Platforms with Predefined Units of Matter

The self-assembly strategies examined in this section typically predefine properties of the individual artificial material units. The properties typically defined are the material unit's geometries and interface connections (Tibbits, 2014b) or the location and arrangement of the material unit's material properties (e.g. material fibre orientation, composition) (Tibbits et al., 2014). Essentially, these strategies directly programme the units of matter and instil them with construction information, which enables the material make-up of the overall structure to self-assemble when supplied with threshold levels of energy (Tibbits, 2016). Three sub-sections will be examined which employ the strategy of predefining properties of the material units:

- 1) material systems composed of pre-designed cubes that are embedded with hardware and enable them to perform computational processes, such as self-sensing.
- 2) material systems composed of pre-designed geometries and interface connections are examined as they can perform computational processes, such as self-error correction but without incorporating hardware (Papadopoulou et al., 2017). Additionally, the impact and role of external energy in guiding the interactions of the material units are also discussed.

- 3) 4D printing is examined, where the material properties of a structure are varied discreetly and controlled via 3D printing to enable it to respond to fluctuating environmental conditions, such as humidity (Correa et al., 2015).

5.2.1 Self-inspecting units

This section examines research projects based on material that can self-assemble, which have hardware (e.g. sensors, power supplies) embedded into individual material units, and also have 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.

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 and interfacing technologies of the time (Frazer et al., 1980; Frazer, 1995) (see Figure 25). 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 manually connected together both physically and electronically using a plug type interface to create 3D forms. The embedded hardware in each cube enabled 'self-inspection' for neighbouring connections between other cubes on each of its 6 sides. The information was then relayed to a computer graphic interface, which reproduced the initial physical forms created. Frazer et al. extended the system's sensing abilities and material unit’s geometries beyond the initial 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 which enable physical changes to be represented digitally. These systems did not self-assemble because:

- The material units are moved into position by hand.
- The material units’ positions are not maintained at their interface connections by the hardware-inducing stimuli.

- The interface connections are not sensitive or robust enough to connect when all of the material units are supplied with energy, which would cause them to move around in space.

Regarding the first point, Gilpin et al. partly address the issue of self-assembly, on more of a 2D level. Here a material system is again composed of cubes but on a smaller scale at 1cm (Gilpin and Rus, 2010; Gilpin et al., 2010) (see Figure 25). Again the material units have a pre-designed geometry and are embedded with hardware, which enables self-inspection and communication between a digital interface. The digital interface records and displays neighbouring connections between the cubes as well as the final shape of the assembled shape. However, in this system, the material units 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:

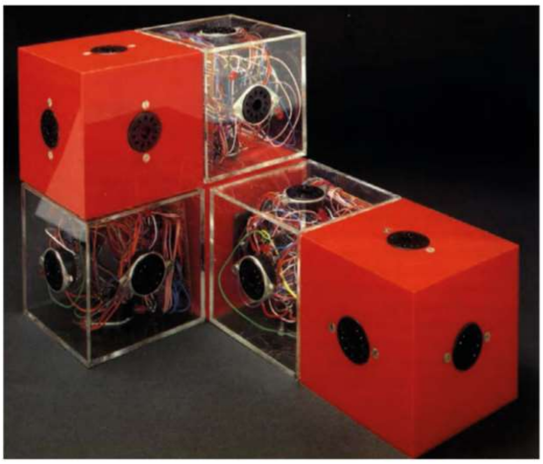
- Reproduce rectilinear/pixelated shapes that are incorporated into/arranged between the material units, due to their self-inspecting abilities (Gilpin and Rus, 2010; Gilpin et al., 2010).
- Reproduce digital shapes created using custom visualisation software, or transmit the physically generated shapes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

However, the material system itself is not overly robust and only partly achieves self-assembly as the units themselves have to be prearranged into grids so the material units' faces are aligned and they are 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 25). 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 is that 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 can 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 as the incorporated hardware dictate the sizes of the material units. Essentially, the challenge of increasing the resolution of the collective material units by reducing their size is based on the difficulties of reducing the size of electronic components and hardware that can enable movement (White, 2005). As a result of these predefined units, self-assembling multi-material structures cannot be achieved with predefined components geometries that require mechanical connections. The various benefits of multi-material structures that can have functional gradients were discussed in Chapters 2, 3 and 4, but they are mainly reduced material waste due to varied internal architectures, mitigated mechanical damage as a result of abrupt material interfaces, multi-functional structures and integrated designs.

Examined next is an alternative approach to self-assembly. These strategies can still perform computational processes (e.g. self-error correction) but without the need for embedding electronics into the material’s units.



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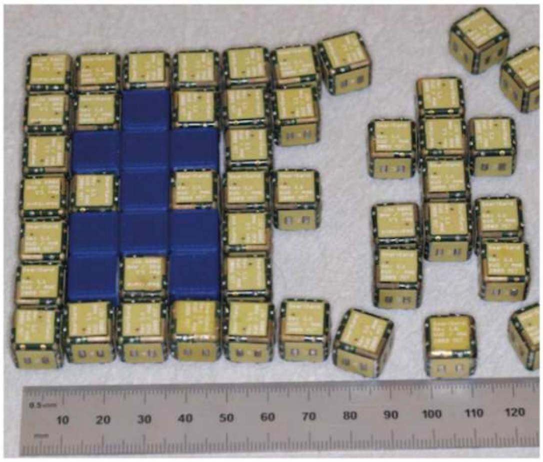

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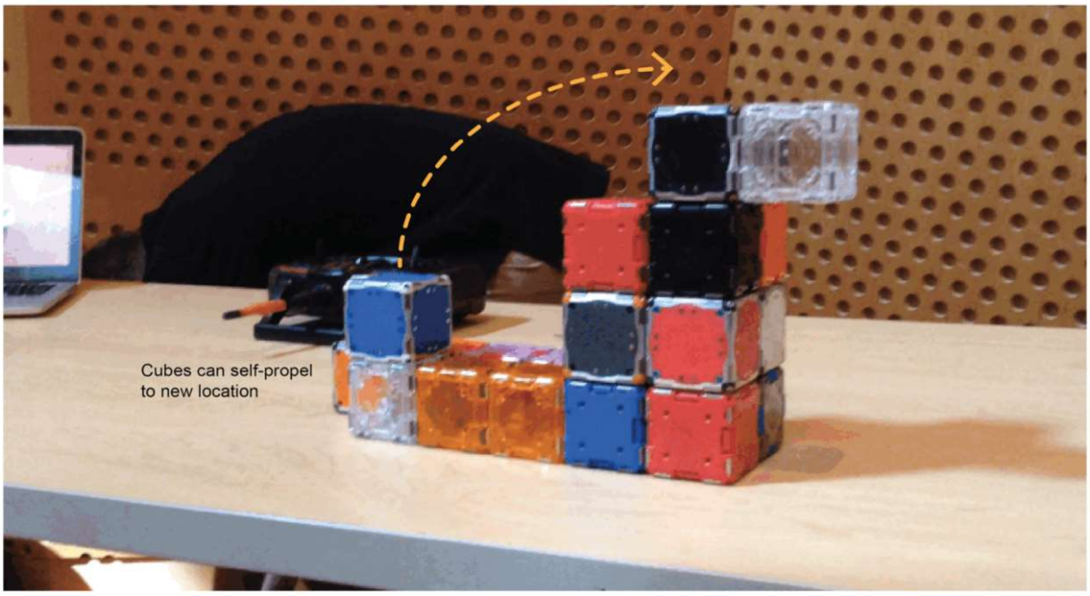

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Figure 25: Robotic self-assembling and self-sensing units. A) Cube material units that make up the three dimensional 'Intelligent Modelling System'. The units are embedded with hardware, which enables self-inspection and can then relay connection information 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 can 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 connection interfaces

This section examines strategies of self-assembly that do not incorporate electronics into individual material units. However, these material platforms and strategies are still capable of self-assembling structures as well as and performing certain computational tasks, such as binary (Tibbits, 2011; Tibbits and Cheung, 2012) and error correction (Tibbits and Flavello, 2013; Papadopoulou et al., 2017). The factors that enable self-assembly in this strategy are:

- The pre-designed geometries and interface connections of the material units
- The supply of energy (e.g. agitation) from external sources, such as pumps, which enables interactions between units to occur.

The computation abilities of these strategies are due to directly embedding the materials themselves with information, which is achieved by designing the material units' geometries and connection interfaces (Tibbits, 2011). By designing these properties, the material system's units of matter are programmed with construction information (Tibbits, 2012a). Thus, the 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 26). 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 self-assembly process as material units continually impact with one another or into the boundaries of their container. The less robust material connections are ultimately weeded out during the fabrication process, which is 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 an arrangement of magnets that repel a connection in one location (Tibbits, 2012b; Tibbits and Flavello, 2013). The 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 26). 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 self-assembling process to be, *"self-adaptive, responsive to the environment, and reversible"* (Papadopoulou et al., 2017, p31). Additionally, because the fabrication process is based on self-assembly, it is also scalable but only up to the resolution of the designed material unit. The degree of flexibility within these material systems is also dictated by the defined material units and their connection interfaces. Therefore, the extent to which a structure could adapt is dictated by the amount of information that can be programmed into a material unit as well as the sizes of the material units. Significantly, this could become problematic when unforeseen demands arise and the material units have not been directly programmed with information to account for them. Additionally, the problem with pre-designing the geometry and interfaces of the components mean recursive patterns are inherent within the material system (Tibbits, 2014b). However, this strategy produces a fabrication process that is non-deterministic and enables emergent traits and typologies to arise, which may not have been conceived during initial design processes and could be highly desirable (Tibbits and Flavello, 2013). This is due to two reasons:

1) the objects and structures being fabricated are composed of a series of distributed parts.

2) the fabrication process is not deterministic. This means, there is no set order to the construction sequence, which enables novel typologies to emerge throughout the fabrication process (Tibbits and Flavello, 2013).

However, initiating material interactions between these material units requires sufficient energy being supplied to them from an external source, such as liquid agitation. Energy is one of the three ingredients defined by Tibbits (in a design context) required to achieve self-assembly. Tibbits primarily focuses on guiding self-assembly 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). Critically, the energy's 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 an energy's threshold highlights it is as a factor that can be tuned to guide material interactions as parameters of the force can be varied over time (magnitude, location, duration).

In the research of '*modular robotic assembly,'* it has been demonstrated that desired 3D designs can self-assemble at an increased rate if the energy supplied to the designed material units is tuned (White, 2005), in which the material interactions are guided (Zykov and Lipson, 2007; Tolley and Lipson, 2010) (see Figure 26). To achieve this, 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 (Zykov and Lipson, 2007; Tolley and Lipson, 2010). In these research examples, fluid agitation is used to guide interactions between the material units. In doing so, several factors have been highlighted that increase fabrication time of a desired 3D shape: A) increasing the density of material units; B) increasing magnitude of agitation within the fluid; C) attraction strength of the binding sites; and 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 because bonds are temporary, both electromechanical (Zykov and Lipson, 2007) and friction-based (Tolley and Lipson, 2010).
- Fluid environments and components with neutral buoyancy enable 3D designs to self-assembly 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 the miniaturisation of geometrically designed components and reduced production costs and times (Tolley and Lipson, 2010).

The ability to guide material interactions by 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: *What material platforms can be used that are sensitive to tuning stimuli induced? What is the smallest size of material units that can be engaged with? How can stimuli be used to guide properties of material platforms that do not have to have properties of the units of matter designed? What mechanisms could be monitored to determine if desirable structures or material properties have been fabricated when using materials that cannot self-inspect?*

Another method of programming matter, compared to the above strategies, is to programme the material make-up of a structure. This strategy of self-assembly will be discussed in the next section to understand the role played by stimulus, and restrictions that occur from programming material properties in this manner.

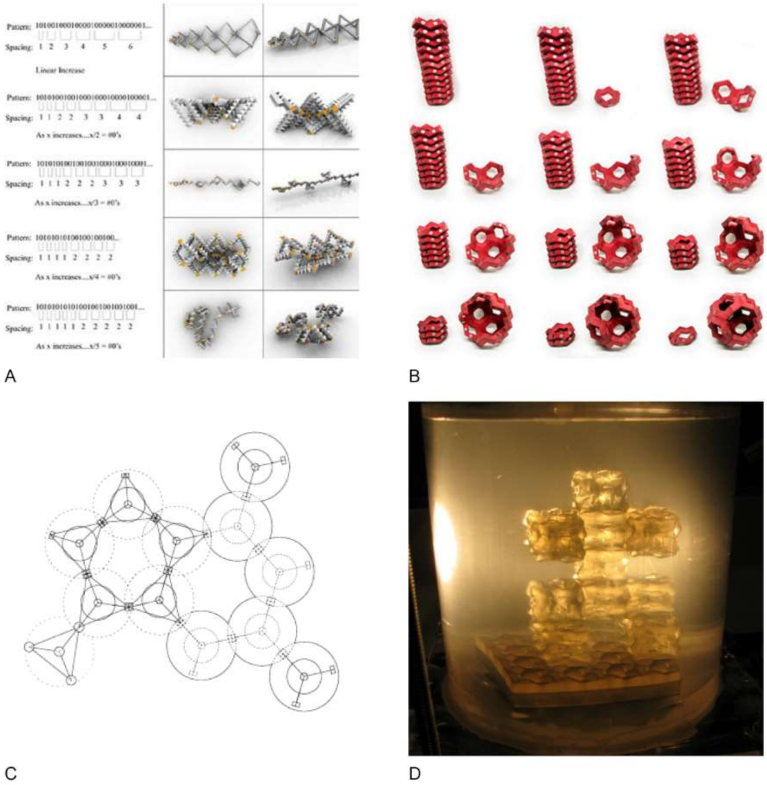


Figure 26: Geometrically pre-designed self-assembling units performing computation. A) 'Logic Matter' represents a construction material that informs neighbouring material connection locations and orientations based on binary input and logic gates. The various orientations are dictated by physical logic 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 locations 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 of 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 self-assembly or responses by governing the material composition and organisation of a structure's material properties, mainly variable material compositions (Tibbits, 2016; Tibbis, 2017). The two strategies of programming the material properties of a structure 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 self-assembly differ from the geometrically designed units as self-assembly occurs at set locations of the design itself, not from a series of distributed parts joining together to create an overall structure. The structure is already formed in these cases. Significantly, these composite materials self-assembly by responding (folding, deforming) when subjected to changes in environmental conditions. For example, plastics that can expand when submerged in water (hydrophilic polymers) will bend and deform, resulting in initially 2D shapes self-folding to form scale 3D objects and structures (Raviv et al., 2014; Tibbits et al., 2014) (see Figure 26).

It has been demonstrated that changes in environmental humidity can result in defined responses to architectural components (Menges and Reichert, 2015; Reichert et al., 2015) and scale architectural structures (Wood et al., 2016; Wood et al., 2018). Here the components respond to environmental conditions by self-deforming their shape to a certain extent based on humidity level (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 self-deform into 3D forms (Wood et al., 2016; Wood et al., 2018). In these examples, the responses are achieved by fabricating the designs from multiple layers of thin 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 27). Essentially, the material properties themselves are programmed and become actuators i.e. the materials become actuators because they can bend. The benefit of these material-based actuators negates the need for: 1) complex mechanical and heavy parts; 2) complex connection details; and 3) power supplies to the materials as they achieve movement passively (Menges and Reichert, 2015). The ability to programme material properties at this resolution has been extended by 3D printing technologies because greater control and material variation are achieved. Programming material properties to create more varied deformations by incorporating 3D printing technologies has given rise to the term 4D printing. Various benefits of utilising 3D printing technologies to programme material properties are:

- **Increased 3D geometric complexity**; designs can self-assemble into more complex 3D shapes, such as long chains representing protein folding (Tibbits, 2014a; Tibbits et al., 2014) (see Figure 26) to 2D nets (Tibbits et al., 2014) and double-curved surfaces (Raviv et al., 2014).
- **Multiple bending locations**; different locations throughout the structure can be programmed with various material compositions or material orientations to achieve multiple bending angles and shapes (Correa et al., 2015; Raviv et al., 2014; Tibbits et al., 2014) (see Figure 26).
- **Exotic materials**: It is possible to incorporate bacteria (Bacillus Subtilis), within various materials through 3D printing, where bacteria sensitive to humidity act as a nano-actuator (Yao et al., 2015a; Yao et al., 2015b), which could be further extended via the bio-brick principle to enable increased computational abilities.
- **Variable surface textures**: can be created when a component is compressed since 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 structure enables its make-up or different locations to respond at varying times or to various threshold conditions (Hu et al., 2016).

In these examples the structure's unit of matter are either: A) the sheets of fibres that make up the laminate composites, which are programmed by dictating the orientation and location of each laminate sheet (collective fibres) (Reichert et al., 2015; Wood et al., 2018); B) the individual filaments/fibres of the 3D printed wood structures, where 3D printing technologies enable control over the orientation, location and density of each 3D printed fibre (Correa et al., 2015); or C) the individual droplets of liquid resin deposited from the 3D printer's print head, where each droplet of resin can be programmed to dictate the composition, density and location of the structure's material (Guttag and Boyce, 2015; Tibbits et al., 2014). The ability to programme the structure's units of matter in these cases demonstrates a shift towards no longer treating materials as inert, as seen in typical CAM and 3D printing processes. Instead, these processes engage with and leverage material computational processes, where CAM technologies are used to precisely organise a structure's material properties and enables the structures to respond to environmental stimulus. However, a restriction that occurs in regards to programming matter with these processes is that self-assembly 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 semi-fixed material properties (orientation, composition, location) and shape (see Figure 27). The structure and material units can self-assemble but the process has become more deterministic as the global shape and material properties become set after fabrication. As a result, stimuli would not be able to force a material adaption using these strategies. For these reasons several material platforms are examined where self-assembly is achieved without designing the material platform's units of matter. Instead, these platforms have demonstrated that structures can be grown by varying parameters of stimuli throughout the fabrication process.

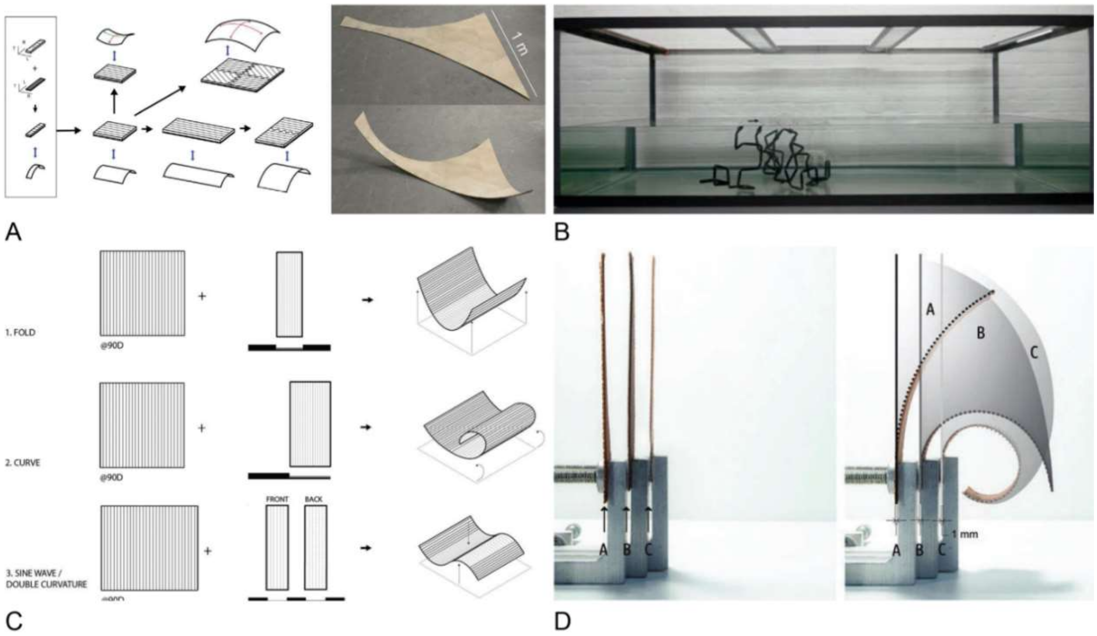


Figure 27: Programmable matter strategies and responses. A) Various wood laminate orientations producing different shape responses as humidity changes. Source: Wood, C. Year: 2018. B) A simplified large-scale protein chain created using 4D printing processes. The chain self-folds/self-assembles, when submerged in water as hydrophilic plastic located at the joints of the chain, expands when submerged in the water. This means, 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

Self-Assembly Guided by Stimulus

This section focuses on identifying material platforms that can be used to explore how an adaptive design and fabrication system can be developed based on controlling parameters of stimuli to guide self-assembly processes without the need for designing the units of matter. The main criteria for selecting a material platform are:

- The units of matter do not need to have pre-designed geometries, interfaces, properties (defined compositions and orientations) or embedded electronics to self-assemble.
- The material units and properties (location, volume, composition, surface texture, colour) that make up a structure 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 by reducing electrical current.
- The induced stimuli generate resultant conditions that can be monitored and potentially used to establish feedback between stimuli and material properties generated, which could lead to a C*losed Loop Control System.*

The two material platforms examined for developing a series of material probes 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 implemented 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, p135)

Artist Perry Hall asks the question; *how can a painting be grown?* (Hall, 2015). Exploring this, Hall initially experimented with decalcomania methods to create paintings. Decalcomania is a material process that creates a series of branching patterns that essentially self-assemble at various length scales across that painting but the subdivision process is limited when the substrate surface breaks up (Hall, 2015) (see Figure 28). The branching patterns occur when pressure is applied from one surface (e.g. a palette knife) to the paint's 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).

In these decalcomania paintings, the units of matter are the volumes of paint and its properties (composition, viscosity). Importantly, the unit of matter has not had its properties designed that define the resolution of an individual material unit or how each material unit interfaces with one another. As a result, units of matter with various sizes are generated as seen in the subdividing patterns i.e. from the smallest branch to the largest branch it comes from. The patterns are also not recursive or pixelated to the resolutions of a material unit with a designed geometry. Additionally, time becomes a critical part of the unit of matter and being able to explore the notion of growing a painting. Time is important because once the paint dries it can no longer be interacted with via the stimuli used (pressure) to generate the subdividing patterns.

Again the process engages with material computational abilities but highlights the issue of materials' changing state over time, which limit whether 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 generate patterns as various paint materials (oil, acrylic) are combined with additional mediums (ferrofluid, water) with one another that mix, partially mix, or do not mix. 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. 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 28) 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 units of matter. 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 that 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. For this reason, paints and other mediums will be used as one material platform in a series of material probes. The paint materials 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 structures that can adapt and self-assemble without having to design the individual material units. 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:

- The patterns are currently 2D.
- They are manually generated. This illustrates 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 diffusion since it can occur in 3D. Illari et al. utilise diffusion to physically simulate scale weather pattern formations (Illari et al., 2009). The materials used are dyed salty water (denser water), which diffuses and sinks throughout a doughnut-shaped volume of freshwater (see Figure 28) (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 combination with the fluid dynamics induced from the rotation creates 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).

The single units of matter in the weather system experiments are the individual pigments of ink. Again though, as the single units of matter have not had their properties designed, the system creates units of matter with various sizes and dimensions, from short, dense thick strands of ink that deform into long, thin swirling patterns due to the rotating fluid. Again, the patterns can be deformed over time but because more conditions are defined in the system (fluid density, heat convection, fluid rotation) the patterns created become similar, for example, the eventual swirling patterns. This highlights that programming less defined aspects of the material’s properties (density) and stimuli can result in semi-repetitive patterns without strictly programming properties of the individual material units.

Being able to tune and manipulate ink diffusion patterns by tuning energy supplied to them also provides another material platform for exploring an adaptive design and fabrication system. It serves as a sound material platform as Illari et al. demonstrate; the patterns generated are sensitive to altering conditions (temperature), induced random turbulence/energy (via fluid rotation) and altering material properties (densities). However, to develop the diffusion interactions into an adaptive design and fabrication system, the issue of feedback highlighted from examining Halls' painting systems must act in combination with controlling diffusion rates. This is because the rate for the dye to diffuse throughout support medium’s volume could have a significant impact on the degree or amount to which the patterns could be manipulated and reshaped iteratively over longer periods. 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 be manipulated so diffusion patterns can be tuned via turbulence over longer periods?*

A second material platform will now be examined to explore how feedback can be achieved between induced stimuli and corresponding material properties. It is the mineral accretion process.

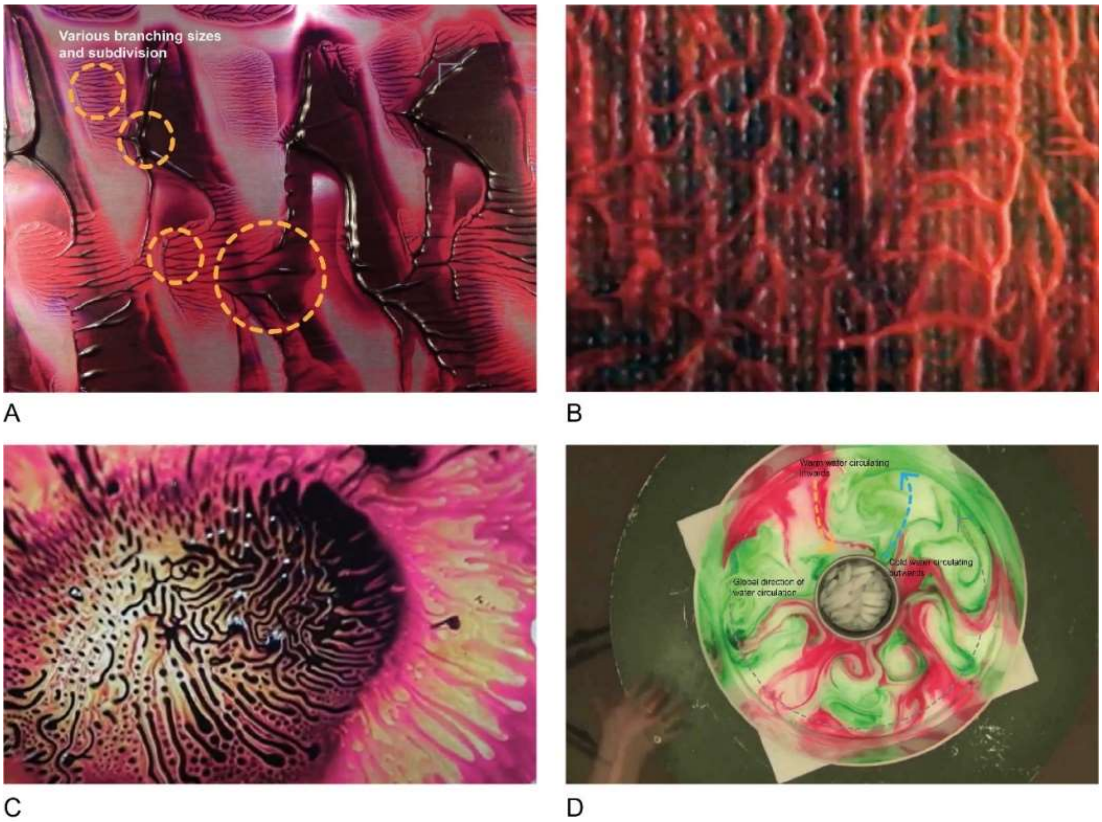


Figure 28: Self-assembling paint and ink patterns. A) 'Decalcomania 2017-4 Oil on aluminium'. The subdividing branching patterns created using the decalcomania method are a result of smooth surfaces contacting one another and the surface tension of the paints. The patterns are informed by paint viscosities, substrate texture and applied pressure. Painting Size: 12.7 x 17.8 cm. Source: Hall, P. Year: 2017. Annotations: Author. B) Decalcomania on canvas painting highlighting the branching patterns stops subdividing at the resolution of the canvas' texture. Source: Hall, P. Year: 2015. C) '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. D) Scale weather patterns physically simulated by introducing dyed saltwater into freshwater, which is cooled at the centre via a container of ice. The doughnut-shaped volume of freshwater 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 used within a series of material probes to explore how an adaptive design and fabrication system can be developed using self-assembling materials guided by stimuli.

The *'mineral accretion process'* (Hilbertz, 1978) is the electrolysis of seawater, which is a superabundant material (Hilbertz, 1991). To induce the mineral accretion process, a cathode scaffold (negatively charged) and anode element (positively charged) must be submerged within an electrolytic solution (brine or 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 on the cathode and form volumes of crystal growth (Hilbertz et al., 1977; Hilbertz, 1978). See Figure 29 for the chemical reactions and material synthesis during the mineral accretion process.

Hilbertz initially proposed that the mineral accretion process could be employed as a building construction process, which could form a type of carbon sink and ecosystem (Hilbertz, 1970; Hilbertz, 1991; Hilbertz, 1992). In this construction process, buildings could be repaired or adapted by placing them back into the ocean to (re)grow material on damaged or new areas as the fabrication process can be stopped or restarted by inducing the voltage stimulus (Hilbertz, 1970; Cureton, 2013). However, instead of employing the mineral accretion 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; Sabater and Yap, 2004; Goreau, 2012). As a result, the structures can be kept within the solution that provides the resources to fabricate materials based on stimuli. This highlights a major challenge of being able to incorporate material resources that can self-assemble stimuli and ways of monitoring material properties generated into a system, environment or wearables that humans and air- breathing animals can occupy or wear.

Additionally, the mineral accretion process 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. However, inhibiting the production of chlorine gas can be achieved by supplying a voltage between 1.23V and 1.36V, but doing this practically is challenging (Goreau, 2012). Significantly, voltage is the major stimulus that governs the mineral accretion process and, more importantly, has parameters that can be tuned (magnitude, duration and location). To use the mineral accretion as a fabrication process, the first stage would be to determine and map the parameters of voltage to various material properties it can affect, 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. Figure 30 also highlights several other factors: 1) how relationships can be created between the components of the adaptive design and fabrication system– digital design tools, fabrication stimuli and material properties; 2) where feedback is lacking to determine if a desired material property has been fabricated; and 3) how and what hardware can be used to monitor resultant conditions.

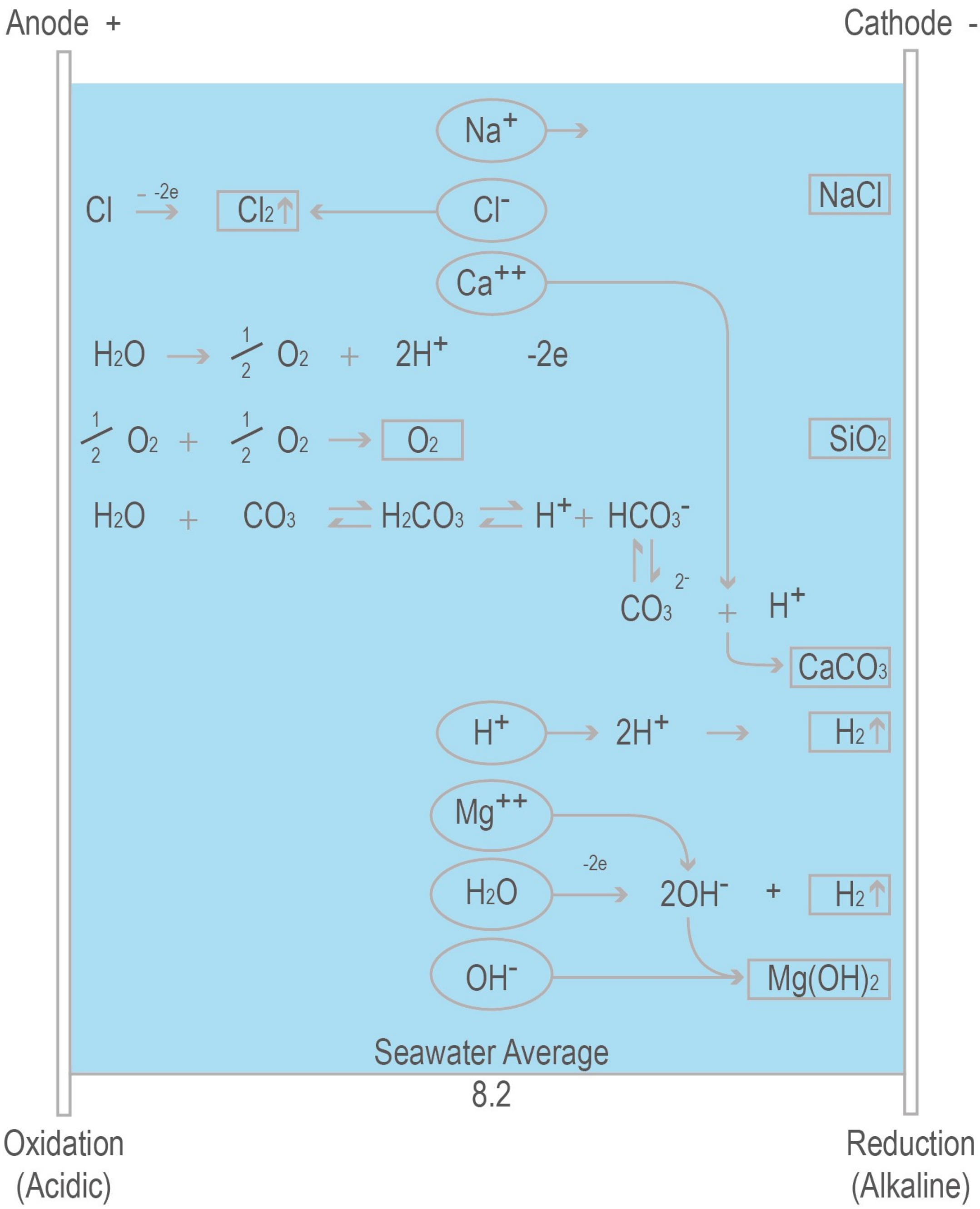


Figure 29: Chemical reaction of the mineral accretion process when anodes and cathodes are placed within seawater. Diagram taken from Hilbertz. W, 1977, and recreated by Author.

Figure 30 serves as a basis for further discussing existing research of the mineral accretion process and will help inform the development of the material probes in this research that will practically explore how various material properties can be guided via stimuli.

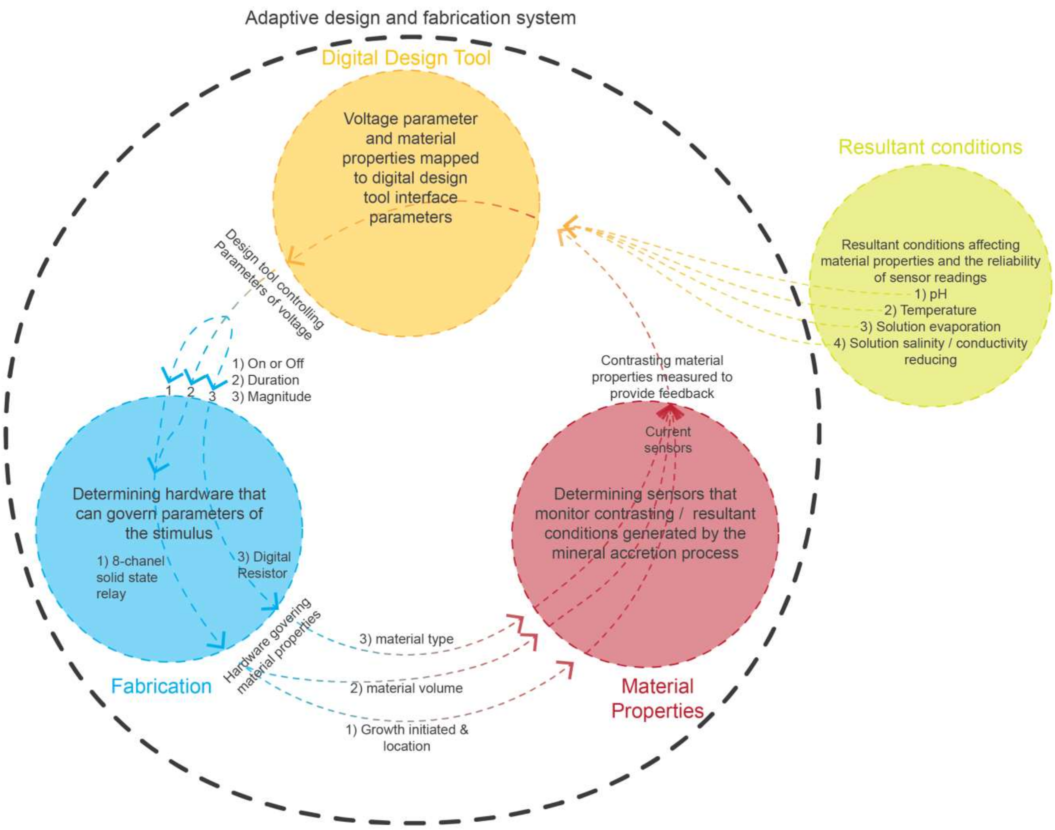


Figure 30: Initial interrelationships mapped for the miner accretion process. The relationships between the parameters of voltage (stimulus) and the resultant material properties of the mineral accretion process, which are mapped to design variables and hardware. The relationships are defined by examining 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.

The experiments of Hilbertz et al. were generally carried out in the ocean (at varying depths) (Hilbertz, 1979) and tropical reef areas (Hilbertz, 1979; Hilbertz, 1992; Goreau, 2012). These experiments generally represent an open system because external fluctuating conditions, such as temperature, are not deliberately controlled. Nor do resultant conditions created during the mineral accretion process, such as changes to the solution's pH, 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). Therefore, it was 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, several other factors and conditions impact material properties, and more importantly arise during the mineral accretion process, which could be explored to understand how feedback is established between them and build towards a CLCS.

To understand the relationships within the mineral accretion process, its variables have been mapped and discussed below. The variables of the mineral accretion process 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**); and D) an environmental condition that effects material growth but is predominantly due to the nature of the experiment's open system (e.g. temperature) (**ENV**). These variables and relationships are then further discussed in regards to: 1) how they impact (if at all) the set-up of past experiments; 2) if the variables and stimuli could be governed or induced via hardware; and 3) if the resultant conditions can be monitored via sensors to determine feedback. The several stimuli, conditions, resultant conditions and their parameters are:

Voltage (IS): voltage is the primary stimulus that governs the mineral accretion process and the material properties that grow upon the cathode scaffolds, which 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 result 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 predominates 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 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 insulation in two instances of past experiments.

First, Goreau highlights that if a portion of material decays or is broken off the cathode 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 system’s ability to self-heal.

Second, Hilbertz et al. demonstrated that material growth rate and volume can be monitored because of its 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 they 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 form of sensor and mechanism present within the material system to determine feedback between material properties (type and volume) and stimuli supplied. The mechanism is the reducing electrical current detected as material growth increases. This highlights that 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 to guide material properties. These parameters are:

1) *Voltage amount*: informs the type and rate of material grown, which could be altered at any time during the fabrication process using an

analogue potentiometer or digital potentiometer i.e. 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 electrical current 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. *How can localised material growth be controlled using the mineral accretion process?*

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

pH (IS-REC); during the mineral accretion process, the pH of the seawater solution becomes alkaline (Hilbertz et al., 1977). 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 added to off-set the rising pH levels in a closed system (Goreau, 2012). At a pH of 9 (alkaline), magnesium hydroxide and calcium carbonate materials are grown. At pH levels, less than 9, calcium carbonate predominantly grows (Hilbertz, 1981). 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. *How can pH levels be monitored and tuned over time to guide the material type grown?*

Solution conductivity (IS-REC); during the mineral accretion process, magnesium and calcium ions are removed from the seawater solution, which causes the solution’s conductivity to decrease 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 result in unreliable readings for voltage and electoral current differences being created, which could be used to determine material growth volumes. *How can solution* *conductivity be monitored and maintained to enable reliable voltage difference readings?*

Cathode design and anode properties (IS-REC); Three main properties of the anode and cathode effects material properties:

- The shape of the cathode structure and its local properties, such as sharp bends, affect material properties as the sharp bends result in concentrated electrical fields, which results in initial growth predominating at these locations (Goreau, 2012).
- 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).
- 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 ceases (Goreau, 2012). *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). This factor would again produce unreliable results for determining desired volume growth based on voltage and electrical current 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 occurs faster in warmer tropical water temperatures (Goreau, 2012), which typically range between 20 - 28°C (Hilbertz and Goreau, 1996). However, as solution temperature has an effect on conductivity it will have to be maintained at a reasonable constant within 20 - 28°C to again 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 variables mentioned above provide a solid basis for being able to tune them over time to guide material properties. The mineral accretion process will be used as a material platform to develop a series of material probes that explore how an adaptive design and fabrication system can be developed using self-assembling materials for several reasons:

- It is robust and initially inexpensive to set up in the laboratory as seawater is a superabundant base material.
- The materials self-assemble without having to programme properties of the individual material units themselves (Hilbertz, 1979; Goreau, 2012). Instead, stimuli can be used to guide various material properties and developed as a strategy for programming materials without fixing their properties.
- The unit of matter that the stimuli engage with is the fabrication of calcium carbonate or magnesium hydroxide molecules, which are formed from the chemical reactions highlighted in Figure 29. Vast and varied numbers of these molecules then join together to form individual calcium carbonate or magnesium hydroxide crystals.
- It is a multi-material system with variable material properties. Calcium carbonate ($CaCO_3$), which is hard, or magnesium hydroxide ($Mg(OH)_2$), which is brittle (Hilbertz, 1979) can be grown depending on the voltage supplied and the environmental conditions within the system.
- Data, resultant conditions and growth rate of the mineral accretion process in an OLCS have already been determined (Hilbertz et al., 1977), which highlights the possibility that feedback between material properties and stimuli (voltage) can be created to develop a CLCS, where design tools govern the parameters of stimuli.
- A limitation is the slow material self-assembly rate that can take days to grow large amounts of material (Hilbertz, 1978). Being able to adapt and tune material properties will take a long time compared to instant or relatively fast alterations/adaptations that occur within the corresponding design representation.

An issue that might be significant with the mineral accretion process in regards to the overall amount a structure could adapt its global properties (e.g. global shape) is that the material growth is constrained to the global shape of the scaffold. This is not a problem in approaches to self-assembly established by Tibbits, where the system can be based on a collection of distributed parts with defined geometries and interfaces and if the final overall shape of the unit's make-up is not defined. This is demonstrated in the project's *logic matter* (Tibbits, 2011) or *fluid crystallisation* (Tibbits, 2014b). However, as mentioned before, a trade-off is that these strategies can lead to recursive global and neighbourhood patterns being produced (Tibbits, 2014b)

Conversely, it has also been demonstrated that material systems based on chemical molecules are capable of generating complex, 3D nano-crystal formations without the need for scaffolds (Grinthal et al., 2016; Kaplan et al., 2017) or designing properties of the individual units of matter. Interestingly, the various shapes (flower, coral, helical) are created by tuning and altering stimuli (temperature and pH) and their parameters (magnitude, location, duration) when they are imposed upon the solutions in which the self-assembling crystal formations grow (Grinthal et al., 2016; Kaplan et al., 2017). Significantly, this demonstrates: 1) the possible nano-resolutions that can be achieved when the units of matter do not have designed geometries or interfaces; 2) how stimuli can be used as a way of programming the materials units, which enables multiple properties of the structure to be tuned and adapted during its' lifetime; and 3) the potential of creating associations between parameters of stimuli, design parameters and material properties.

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: protocells and synthetic biology

It is worth mentioning briefly several other material platforms that could potentially be used for 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 through a bacteria's DNA, so they can perform actions when a threshold condition is reached.

Protocells

It has been proposed that protocells can be used as architectural fabrication agents (Hanczyc and Ikegami, 2009; Armstrong and Spiller, 2010; Spiller and Armstrong, 2011b). Protocells are artificial chemical units that are 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 is based on the ability to programme them individually, enabling them to: 1) change shape (Čejková et al., 2018); 2) move on top of a liquid's surface to the centre of concentration gradients (Hanczyc, 2011) or through 2D maze structures (Cejkova et al., 2014); 3) self-divide, self-sort and amalgamate (Čejková et al., 2017); and 4) deposit different material types (Beesley and Armstrong, 2011; Cronin, 2011a).

These abilities have highlighted the potentials of utilising protocells as fabrication agents, which could enable structures fabricated by them to adapt their properties and self-heal (Armstrong and Spiller, 2010; Spiller and Armstrong, 2011b; Armstrong, 2014). This is because protocells can deposit both colourful carbonate materials (Armstrong, 2011; Beesley and Armstrong, 2011) and carbon non-tubes (Cronin, 2011a). The materials can then be deposited at desired locations as protocell movements can be governed by concentration 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:

- **Movement**; protocells can be programmed to move to locations of high concentration gradients and could be used as a means of directing multiple protocells as well as governing their activity to deposit material where it is needed (Hanczyc and Ikegami, 2009; Armstrong and Spiller, 2010; Cronin, 2011a).
- **Adding and Removing Protocells**; It has been demonstrated that various protocells can be added or removed from the system over time via the use of an automated syringe as protocells can be assigned bright

colours, which allows for differentiation (Gutierrez et al., 2014). However, the scale of this is limited to the size of the robotic gantry and the degree/distance to which the camera can measure the protocells' activity and location.

- **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; Čejková et al., 2017). This means numerous protocell types could be used as a semi-permanent moveable framework to guide those that deposit material.
- **Shape changing**; protocells can also be programmed to change shape after certain durations when exposed to threshold conditions (Cejkova et al., 2016; Čejková et al., 2018), which highlights a possible application for them as 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 restricted durations (minutes - hours) if the chemical system reaches equilibrium (Hanczyc et al., 2007; Armstrong, 2014; Cejkova et al., 2016). The ability to introduce turbulence and controlled stimulus into these systems could prevent the activity from ceasing.

Synthetic Biology

Synthetic biology is an area of research that programmes bacteria by altering their DNA so the bacteria respond to and carryout desired activities when threshold environmental conditions are reached (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 threshold conditions (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, and over time the bacteria can alter the properties of the support material to change its colour, surface texture, shape, and elasticity (among others) as environmental conditions change (Smith et al., 2019b).

These alternative platforms were not chosen as they are complicated to reproduce, can require expensive equipment, can be highly sensitive, and require expertise in chemistry or synthetic biology.

5.4 Chapter Summary

This chapter examined various self-assembling material platforms that could be guided via stimuli and employed for developing a series of material probes. The key aspects from each section are:

Predefined components and material properties

This strategy predominantly guides self-assembly by 'programming' the individual material units or the material properties that make up a structure. Some of the challenges and benefits are:

- **Self-sensing units**: embedded electronics restrict the size and number of material units due to cost and production time but enable discourse between materials, digital design platforms and fabrication.
- **Pre-designed components**: embed constructions' logics into the material units but this can restrict the resolution of the system and generate recursive patterns.
- **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

Self-assembly processes guided by stimulus opens up to the possibility of guiding units of matter that do not have to be pre-designed. However, this raises challenges of feedback and robustness, which are aspects the pre-designed material units' strategies begin to address.

- **Paints and mediums**: by 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 the system material computational processes and resultant effects.
- **Mineral accretion process**: the mineral accretion process demonstrates large-scale structures can be grown and have their material properties programmed by inducing and varying parameters of stimuli. Additionally, as stimuli are induced, resultant effects are generated, which could be monitored to determine feedback between stimuli, material properties and design parameters. These relationships and associations could result in an adaptive fabrication system based on stimuli.
- **Tuneable energy**: governing the energy supplied to the units of matter without pre-designed properties establishes that stimulus can be used as a way to programme matter or guide self-assembling material interactions.

Alternative platforms.

Alternative material platforms examined illustrate their main abilities and how they could be used to explore the development of an adaptive design and fabrication system.

- **Protocells**: can be programmed, which enables them to act as fabrication agents because they can: sense, move, self-divide, amalgamate and deposit various materials at locations dictated by stimuli to which they are programmed.
- **Bacteria**: 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 the research within this thesis has been carried out using *research through design* (hereafter RtD) as an approach and why the prototypes created within this research have been termed *'material probes'*, which is based upon Gaver et al.'s use of the term *probes/cultural probes* (Gaver et al., 1999). Significantly, no set research question(s) have been defined at the outset of this thesis as the intention is to explore and iteratively develop design and fabrication processes and relationships that incorporate self-assembling material platforms, including how they can be guided with no technical or prior practical knowledge. Instead, the intention is to identify and investigate research questions and areas of interest that emerge following each iteration of a material probe, which build towards an adaptive design and fabrication system. Consequently, summaries, reflections and questions will be made following each material probe and have been documented in Chapters 7 and 8, which explore the RtD process.

The chapter is structured as follows:

1) Possible research methodologies that could be employed to develop and explore the research aim of this thesis are discussed

2) Why and how RtD has been employed as an approach.

3) The reflections and design decisions behind the development of each material probe, which are presented as a flow diagram. The logic for terming the prototypes as *material probes* as well as the additional methods (sensing and actuation) employed to help develop and create insights within the series of material probes are also discussed.

4) How and why annotated portfolios have been used as a means to document the material probes as a collective whole, which will be presented within the Conclusions chapter of the thesis.

5) The limitations of employing a RtD methodology.

6) An overview is given of the material probes and the material platforms used within them (mineral accretion, paints and inks), and how engaging

with their properties helps to explore the development of adaptive design and fabrication system.

7) The material analysis employed to compare and determine material properties generated during and post-fabrication.

The exact set-up details and components of each material probe along with how it was fabricated and developed are discussed in more detail in the relevant sections of Chapters 7 and 8. These two chapters essentially document the explorative and iterative design process, key findings generated from each material probe, and the development of the subsequent material probe.

6.1 Possible Research Methodologies

This research aims to investigate and reimagine design and fabrication processes that can maintain relationships with materials. Selecting an appropriate research methodology will be informed by several criteria:

1) The intention of carrying out research by physically making i.e. practice-based.

2) No prior practical knowledge of the material platforms used.

3) Not rethinking design and fabrication processes based on incremental developments of existing technologies and processes so the research is not constrained to current practices or perceptions. Instead the research is intended to be explorative and reflects on design iterations.

The intention and primary means of investigating this aim is through making. Essentially the research will be explored through an overarching practice-based approach and processes. The act of making (i.e. the design and fabrication process) is of interest as it means design proposals and ideas become physically materialised, which is essentially the main aspect of this research being explored in regards to how design proposals become materialised so they can change their properties over time. The main aim of this research, therefore, is to investigate the seemingly open-ended relationships between the design and fabrication processes, techniques and materials and how they inform the materialisation of a design concept. The point of not constraining the research to current incremental developments is to enable novel applications' areas and potentials to be understood based on properties generated from the research and prototyped systems. A summary table is used to understand and select a suitable research methodology that facilitates the exploration of this research (see Table 1). The table provides a brief overview of various methodologies, their potential strengths and limitations.

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

Research Method	Overview	Benefits	Limitations
Design Research	"Design research methodologies can be seen to be comprised of multiple methodologies, mainly, research *through*, *into* and *for* design" (Frayling, 1993).		
Research Through Design (RtD)	"Research Through Design: often describes an *approach*, *a practice, a process, a framework,* a method, or a technique… It frequently describes: a product, an application, a system, a technology or an interface and these are likely to be – multi-media, smart, new, unexamined or emergent. *The work is usually an exploration*" (Blythe, 2014, p3).	Typically employs the design process as a means of enquiry (Forlizzi et al., 2009) and usually generates artefacts. Bowers discusses that the artefacts generated embody design thinking that is highly *'varied, multi-faceted, heterogeneous',* which can be documented and unpacked through the use of *annotated portfolios* (Bowers, 2012). Additionally, the artefacts can be used as *probes* to engage, explore and reveal areas of interest (Gaver et al., 1999). Importantly, the design the process does require a set answer to a particular problem based on prior knowledge or defined hypothesise like traditional scientific modes of enquiry. As a result, the design process can be developed into a personal approach that is highly flexible, intuitive and enables areas of varied areas of interest to be explored (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 an RtD and it not being centred around specific challenges this could raise problems in developing a design and fabrication process that can accurately guide material computation processes. However, Cross discusses the ability of design being compatible with the sciences to varying degrees (Cross, 2001), which could help to refine material processes within a non-deterministic fabrication process Additionally, it could be seen that the probes and prototypes developed are 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.
Research into Design (RiD)	*"Primarily contextualises design as a practice in relation to the world and other fields of study. It conforms to the canon of academic research in that it often produces knowledge and makes theoretical contributions about design"* (Findeli, 2004).	In the context of this thesis, design research can be comprised of and carried out through a series of *probes*, which play an active role in generating knowledge and theory construction (Forlizzi et al., 2009; Bang and Eriksen, 2014) typically this forms a *research through design* methodology	The advancements generated from RiD typically "lack relevance for the processes inherent to design itself." (Findeli, 2004)
Research for Design (RfD)	*Research for design* is based on a variety of activities that generates theories designers can use to improve design practice (Forlizzi et al., 2009).		RfD could lead to initially adopting generalised theories and approaches that are not intuitive to the individual carrying out a practice-based design process and may not be compatible when exploring novel processes.
Critical Design	Critical design rejects affirmative design by critiquing current norms and embodying alternative social, cultural, technical or economic values within a physically designed object (Dunne and Raby, 2001). It is a *research through design* methodology that foregrounds the ethics of design practice, reveals potentially hidden agendas and values, and explores alternative design values (Bardzell and Bardzell, 2013).	It can highlight future possibilities without being constrained to current market and industry trends. It is liberated from these constraints to creatively explore a variety of possibilities, which can highlight preferable futures (Dunne and Raby, 2013). Significantly, the issues explored are enhanced and contextualised by physically making artefacts (Dunne and Raby, 2013).	The research outcomes centres around rethinking larger-scale social implications based on the design intervention/artefact. The social implications of rethinking design and fabrication processes are not the main interest at this stage.
Design Fictions	Is a relatively new approach with RtD and was initially defined by (Sterling, 2005) with Bleecker discussing and expanding on it as a practice (Bleecker, 2009). More recently, it has been defined in relation to *diegesis*, which is the narrative of plot within a film the design fiction/fictional world the artefact is situated with. *"The deliberate use of diegetic prototypes to suspend disbelief about change... It means you're thinking very seriously about potential objects and services and try to get people to concentrate on those – rather than entire worlds or geopolitical strategies. It's not a kind of fiction. It's a kind of design. It tells worlds rather than stories"* (Bosch, 2012).	Similar to critical design, design fiction is an RtD method used for creating alternative future possibilities to highlight social, technical and cultural implications (Stead, 2020). Additionally, design fiction centres around future 'worlds' and associated narratives based on the *materialisation* of the ideas as artefacts.	It requires fictional worlds and a narrative to be built around the design proposals/artefacts (Bleecker, 2009; Stead, 2020). As a result, challenges that arise from prototyping systems could become abstractions but the success of the artefact is dictated by how compelling the narrative is. At this stage, the main aim is to only explore the design and fabrication process, not the future implications of a developed/speculated upon approach. However, future work could employ design fiction to explore the future potentials of adaptive design and fabrication could be and then used to inform the next stages of practice-based research.
Action Research	A way to produce new knowledge through the concrete actions and interventions taken by the researcher (Brydon-Miller et al., 2003)	It is a generative process which creates change. The generative process facilities exploration and practice-led process of making based on previous experiences and knowledge (Swann, 2002; Dick, 2007). Importantly, the process is based on *cycles of action* and *cycles of reflection (Stead, 2020)*	The specifics of the research (e.g. process, aims, outcomes) are unique to the researcher based on their own experiences and prior knowledge (Huxham, 2003). Resultant actions occur after an event and are based on cycles of reflection (Stead, 2020), which is rigidly adhered to could hinder and limit the emergent and responsive nature of the design/research process (Pollastri, 2017).
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).	Regarding guiding processes of 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 the 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 primarily encompass has helped to inform which methodology is most appropriate at this stage to begin exploring and prototyping an adaptive design and fabrication system. The most appropriate methodology to be employed at this stage is *design research* methods as they 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.

6.2 Why Research through Design and How it has been Employed?

Table 1 highlights the various methods of *design research*, which 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, as outlined by Forlizzi et al. (Forlizzi et al., 2009, p2892):

"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 produce theories in the area of research for design."

As mentioned previously, the main intent of exploring and developing an adaptive design and fabrication system is to physically make and iteratively prototype multiple systems. This means that how the research is carried out is rooted in making, and by doing it this way, design and fabrication processes themselves are investigated and the challenges are understood, as well as the properties and processes needed to guide self-assembly without previously imposing form or properties upon the individual material units. However, the research process that explores the development of the adaptive design and fabrication system is done based on an individual perspective and the use of making is not done as part of co-design, which typically informs *Research for Design* methods (Sanders and Stappers, 2014). This individual-based perspective of developing the research and the mode of enquiry has led to RtD being employed as the research methodology.

The main reasons for and benefits of employing an RtD methodology are that the research is investigated *through* the act of designing a new design process and fabrication processes that are based in incorporating self-assembling material platforms, which aligns with the intention of wanting to physically make these systems/prototype i.e. practice-based research. Essentially, the problems of materialisation within typical design and fabrication processes and their relationships can be explored by *making* new design and fabrication processes. RtD facilitates the *'hands-on'* engagement of interacting with these materials' abilities (Frayling, 1993; Koskinen et al., 2011; Gaver, 2012), which can help facilitate a further understanding of the implications, principles and challenges based on a personal preference of working. Furthermore, 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.

Significantly, the main benefit of employing an 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 particular 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 reimagine novel design and fabrication processes is enabled by RtD and is central to the aim and the material probes developed in this research. An additional reason for employing RtD is that it could help situate this research within the body of architectural research that is growing in regards to self-assembling architecture and responsive architecture, as highlighted in Chapters 2 – 5. This is because it could be said that, generally, the architectural forms of research documented within these chapters employ RtD methodologies based on the various material probes and physical artefacts made and the processes involved to investigate and envision novel architecture potentials.

The intention of developing a series of material probes will be a result of combining multiple, more common, design (e.g. digital design) and fabrication processes (e.g. 3D printing processes) to create new processes by incorporating various hardware components (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 is that it could lead to interdisciplinary research, which can be further facilitated by an RtD method due to the artefacts generated. 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. This is because the multiple material probes can 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 material probes/artefacts can provide a platform for creating a common language to enable interdisciplinary collaborations between chemistry, engineering, computer science and electrical engineering.

The next section will discuss why RtD has been used as an approach.

6.3 How RtD is Employed

Blythe (2014) and Storni (2015) have both discussed separately how RtD can be employed as an approach:

“In brief, Research Through Design often describes: an approach, a practice, a process, a framework, a method, or a technique... It frequently describes: a product, an application, a system, a technology or an interface and these are likely to be – multi-media, smart, new, unexamined or emergent. The work is usually an exploration but if it does not explore then it will: consider, discuss, investigate or reflect.” (Blythe, 2014, p706).

Whereas Storni’s notion of RtD can produce different forms of knowledge as an approach, but this is based on several factors; *“different forms of knowledge in* *different ways depending on research questions, epistemological stances [and] ways of operating"* (Storni, 2015, p74).

In regards to Storni's notion, no set research question(s) have been set at the beginning of the research. Instead, as Gaver et al. discuss, research can be based on an artist-designer approach that can be openly subjective and seeks inspiration, and which is guided by a loose objective (Gaver et al., 1999), in this case, the aim of exploring an adaptive design and fabrication process. That said, regarding the ways of operating, which is a personal preference of practice-based and iterative design processes, the intention is to highlight specific research questions after each design iteration. However, these research questions will be based on personal and subjective areas or aspects of interest that will be explored further in subsequent iterations. Effectively, the research questions will emerge as the research develops. This emergent nature aligns with an *Interpretivists* ontology stance discussed by Hudson and Ozanna (1988). This acceptance of an emergent process is well suited to using RtD as an approach based on insights into design and fabrication processes within architecture but with little prior practical knowledge of the properties of the material platforms to be used (Hudson and Ozanne, 1988). The ways of operating, how the material probes are framed, and aspects explored from each iteration are discussed in the next section. However, the specific research questions and personal aspects of interest generated from each iteration along with their repercussions are documented and discussed in Chapters 7 and 8.

Framing RtD as an explorative approach will help in developing novel design and fabrication processes that are not concerned with incrementally developing known products or processes. The subjectivity of this approach is a factor that could be seen to raise concern if the focus is based on defining a set method and generating theory for developing new forms of adaptive design and fabrication processes based on guiding self-assembly via stimuli (Zimmerman et al., 2010). However, this subjective factor is accepted based on the explorative nature and a personal position that sides strongly with Gaver and Bowers (2012), who discuss the benefits of not constraining design research to seek methodological '*rigour*' by aligning it with more traditional modes of scientific research or defining set methods of carrying out research*;*

“Methodological frameworks promise rigour but jeopardize the possibility for designers to invent ad hoc approaches, or draw inspiration from unorthodox sources, or take inexplicable imaginative leaps” (Gaver and Bowers, 2012, p42). It is these imaginative leaps, inspirations and ad hoc-ness that will be vital in developing new forms of design and fabrication. If these aspects of creative practice became constrained then the nature and intention of the research would not be able to drastically rethink current design and fabrication approaches.

The next section will discuss the practice-based nature of this research and why the prototypes are framed as *material probes.* Following this is a discussion of the reason for employing annotated portfolios, which primarily help to document the explorative nature of this research.

6.3.1 Material probes

This section initially discusses why the term material probes is used to identify the making carried out in this research. Second, the challenges raised and feedback from each of the iterations of the material probes are documented as a flow diagram to represent the aspects explored further and the overall research and insights generated from the research. Finally, the design journey is represented as a diagram to highlight the subjective nature of the process and the selective aspects explored along with some alternatives that could have been explored.

Because the material platforms used in this research can be seen to be more commonly placed in scientific research, in particular the mineral accretion process, framing them as *experiments* is avoided because of the preconceptions that comes with it. Essentially, experiments require repeatability and strongly defined methods, which conflict with the explorative nature of this research. This rules out initial thoughts of terming them as *design experiments*. Furthermore, terming the *‘design experiments’* as *prototypes* creates some tensions and again does not fully align with the term and nature of *prototypes* in certain contexts. Sanders and Stappers (2014, p6) define the role of prototypes within RtD:

- *“Prototypes evoke a focused discussion in a team, because the phenomenon is ‘on the table’.*
- *Prototypes allow testing of a hypothesis.*
- *Prototypes confront theories, because instantiating one typically forces those involved to consider several overlapping perspectives/theories/frames.*
- *Prototypes confront the world, because the theory is not hidden in abstraction.*
- *A prototype can change the world, because in interventions it allows people to experience a situation that did not exist before.”*

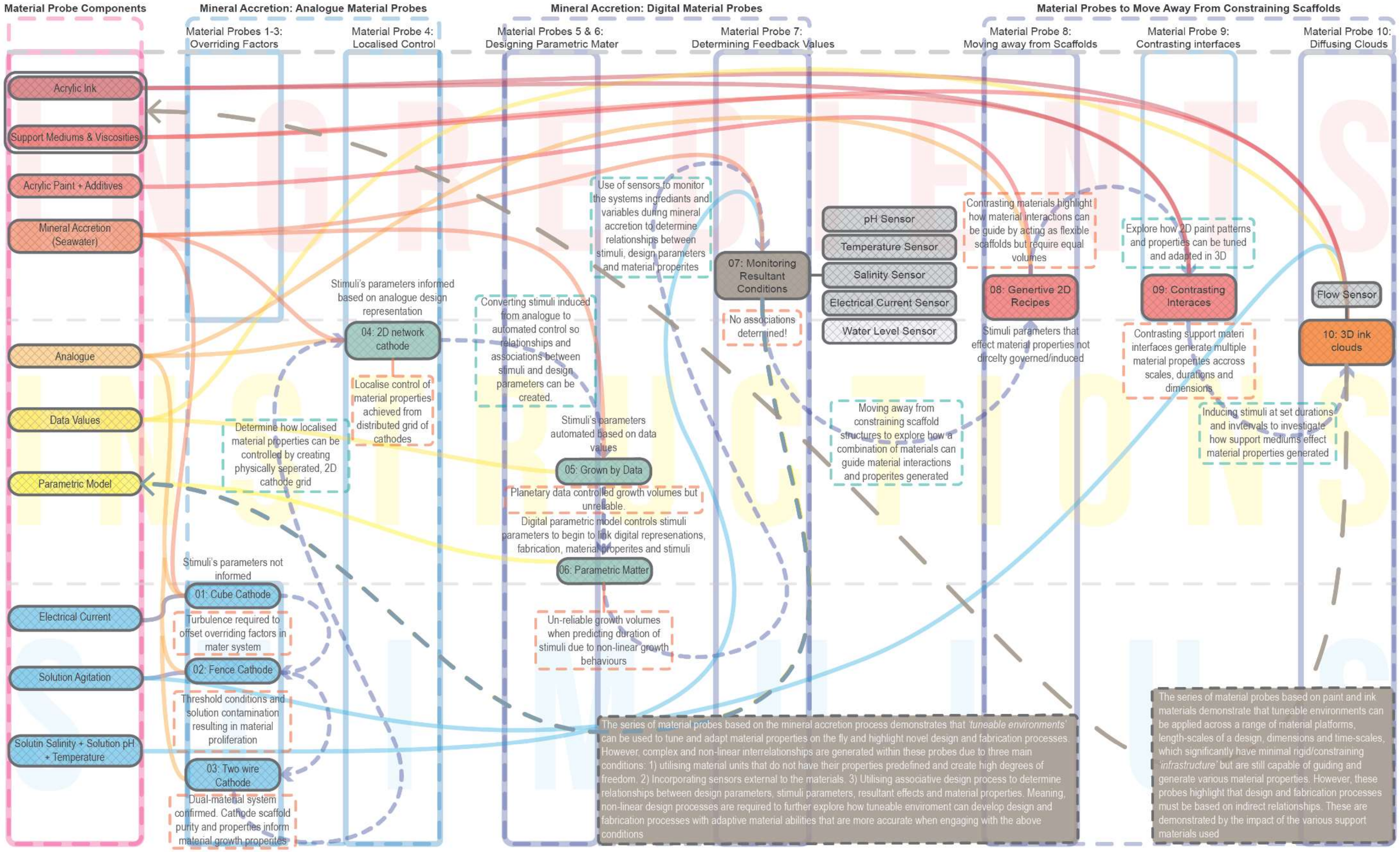
Furthermore, Sanders and Stappers describe how prototyping follows on from the initial *‘fuzzy front end’* of design and prototyping is used in a ‘*traditional design development process’* (Sanders and Stappers, 2014) i.e. in order to prototype something the concept, challenges and areas have already been defined during the first stages of the design process. In these initial stages, probes and generative toolkits are used as the means to explore concepts. Because of these associations, the terms design experiments or prototypes are not used. Instead, the research and series of iterations are termed as *material probes.*

Sanders and Stappers developed a map to illustrate the ‘*landscape of design research and practice*‘ (Sanders and Stappers, 2008), where probes *“originated in the design-led and expert-driven corner of the map”* (Sanders and Stappers, 2014, p7). Although probes are typically used within co-design practices this is not the case for the material probes developed in this research, which are based on a personal and subjective perspective. It is the design-led and creative nature of probes that lends itself again to the explorative process of this research. Terming the series of outputs in this research *material probes* is based on the use of *probes* developed by Gaver et al. to carry out design research (Gaver et al., 1999). Importantly, using this term facilitates the explorative approach of this research as they enable responsive modes of working (Gaver et al., 1999). The explorations are not constrained based on preconceptions and requirements that can be associated with terming the research outputs as a series of *design experiments* or *prototypes.* Instead, at the heart of probes they are intended to be playful, uncertain and explorative (Gaver et al., 2004, p53);

“Beyond this, however, the Probes embodied an approach to design that recognizes and embraces the notion that knowledge has limits. It’s an approach that values uncertainty, play, exploration, and subjective interpretation as ways of dealing with those limits”.

However, the iterative stages of the material probes need to be highlighted to unpack the research findings and document: 1) what the series of material probes have developed when exploring the development of an adaptive design and fabrication process based on self-assembling materials; 2) their subjective nature; and 3) the aspects that have been explored. Figure 31 is used to provide an overview of the iterative process of the material probes, a notion of what questions were raised and the aspects that have been explored in subsequent interactions. Additionally, Figure 31 is used to highlight the explorative and *Interpretivist* nature of this research, along with other possible aspects that could have been explored instead. Framing the research as a series of material probes aligns with the uncertain nature of how it was going to develop without devaluing the insightful principles, issues and future opportunities that have been generated from this research. Further details and the development of the material probes are detailed in Chapters 7 and 8 via annotated portfolios.

The next section discusses briefly how annotated portfolios were adopted in hindsight after carrying out all this research as a useful and intuitive way to document the material probes.



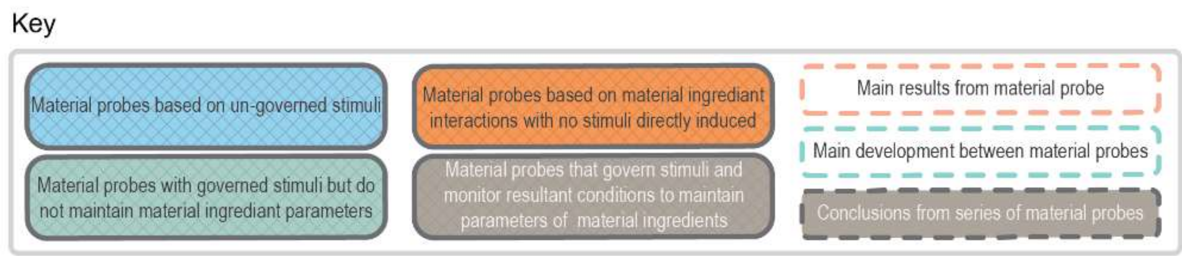


Figure 31: Flow diagram highlighting the reflections, sequence and development of the material probes used to explore and develop tuneable enviroments, which are explored by employing a research through design approach. Annotations between the probes document the process, properties and conclusions across their development.

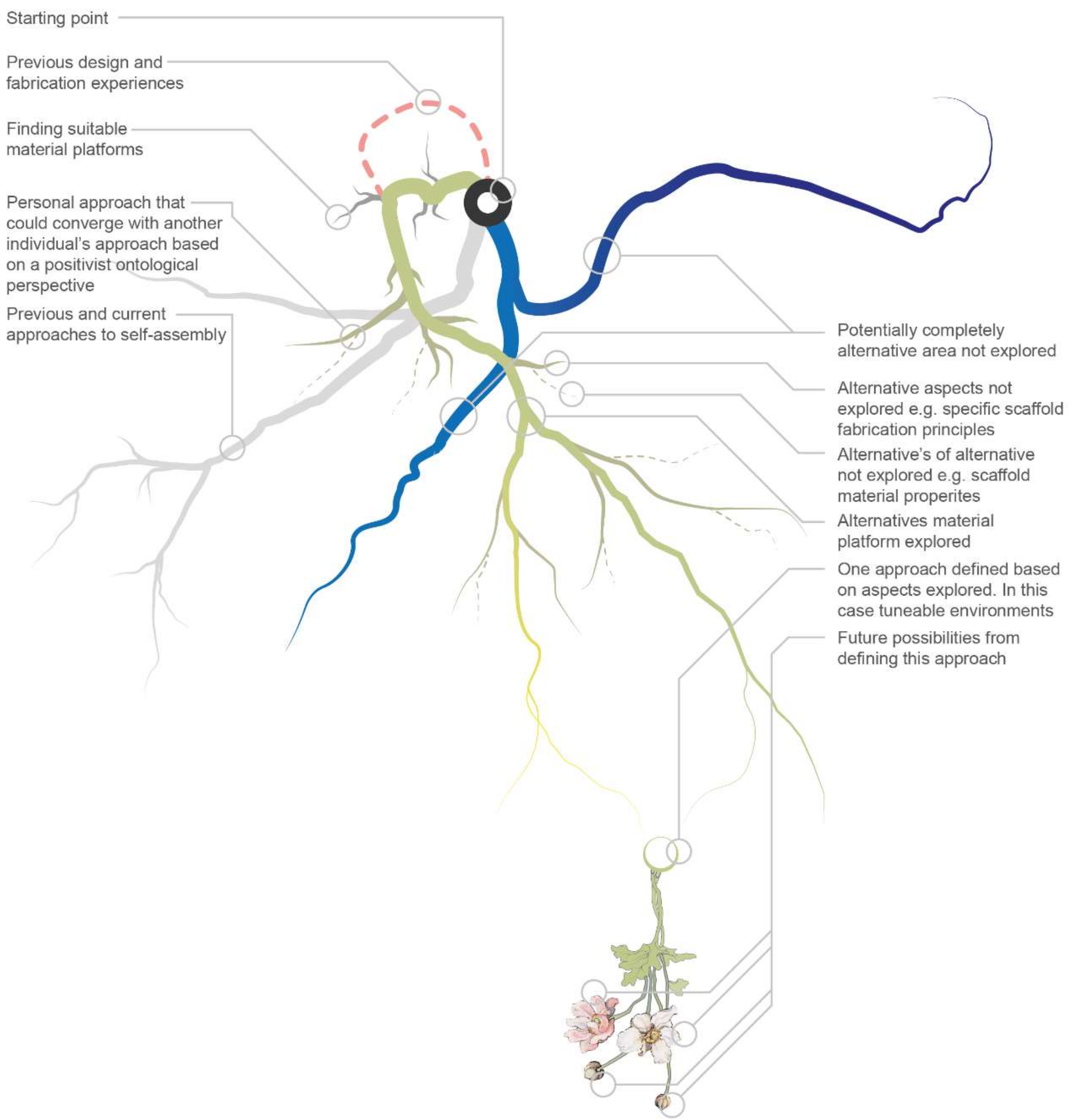


Figure 32: Diagram depicting the design/creative journey of the research based on its explorative nature. Significantly, alternative approaches within self-assembly are highlighted as well as alternative branches that could have been explored through the material probes but were not in favour of other areas of personal interest. The endpoint of the journey highlights one possible approach (tuneable environments) and the potentials that could arise.

6.3.2 Why annotated portfolios are employed to document the material probes

"If a single design occupies a point in design space, a collection of designs by the same or associated designers – a portfolio – establishes an area in that space." (Gaver, 2012, p944)

Within this research, RtD is implemented as an explorative approach by creating a series of iterative material probes. As a result, the collection of material probes forms a *body of work* or artefacts generated from personal design practice that explores aspects for developing an adaptive design and fabrication process. As Frayling states, these artefacts can be seen as the embodiment of design thinking (Frayling, 1993). However, Gaver and Bowers comment on the trouble of representing design practice and that a body of work as *research* is tricky without constraining intuitive practices to generate theory;

"The problem is that novel products alone do not seem sufficient to count as research, and even a stream of locally innovative designs may not seem to add up to much. But strategies for generalizing beyond practice to produce a body of work recognizable as research seem equally fraught with difficulty" (Gaver and Bowers, 2012, p42).

This is because the design thinking, processes and imaginative leaps cannot be directly read from the artefacts i.e. the material probes themselves (Gaver and Bowers, 2012). For example, a second designer looking for precedent and inspiration would attempt to elicit these aspects by only observing the artefact where generate knowledge and theory would lead to *abstractions* (Löwgren, 2013). It is these certain levels of abstraction I find it difficult to engage with, mainly abstraction that is based on a secondary interpretation and have become more distanced from the artefact(s) themselves as they can be purely descriptive theories, and no visual references to the artefacts or incremental stages of the design process are tangible. To address the problem of trying to elicit theory, knowledge and design thinking from an artefact(s), Gaver and Bowers suggest the development of *annotated portfolios* as they build on existing practices within design and can be seen as a way to *'legitimate the* *designer's activities'* (Gaver and Bowers, 2012). Löwgren (2013) discusses how the use of annotations begins to occupy this space of abstraction (between artefact and general theory) and this space is called *intermediate level knowledge* (Höök and Löwgren, 2012). However, this makes the annotations a form of abstraction themselves in Löwgren's opinion but in a more simplistic and accessible format. Conversely, Bowers (2012) states that the annotations are inherently linked and contextualised with the artefacts (indexical). Additionally, Bowers (Bowers, 2012, p71) provides an overview of annotated portfolios based on seven features (constitution, relationships, communication, perspective, mutual informing, shaping and materiality):

- **Constitution**: *"Annotations make a collection of designed artefacts into a portfolio. They bring together individual artefacts as a systematic body of work."*
- **Relationships**: *"Annotations capture family resemblances between designs in a mesh of similarities and differences."*
- **Communication**: *"Annotations communicate the nature of the portfolio and enable its comparison with others."*
- **Perspective**: *"Typically a portfolio can be annotated in several different ways reflecting different purposes and interests and with different audiences in mind."*
- **Mutual informing**: *"Annotations and the designs they annotate are mutually informing. Artefacts are illuminated by annotations. Annotations are illustrated by artefacts."*
- **Shaping**: *"Annotations can shape how artefacts are used, how they might be appreciated and understood, and what scientific and aesthetic value artefacts can have, as well as suggesting future research and design possibilities."*
- **Materiality**: *"Any material form can be considered for an annotated portfolio including an illustrated monograph, a scientific paper, a curated exhibition and so forth"*

This research aligns itself with Bowers on the role and nature of annotations as the collection of material probes within this research is centred around exploring an iterative process of developing an adaptive design and fabrication system.

Furthermore, the annotations within this research centre around the *constitution, relationships, communication and shaping* as well as material properties generated.

By building a body of work from a similar collection of artefacts, in this case, a collection of material probes, and documenting them with annotations enables: 1) a body of work to be formed into a portfolio and help to communicate the research and nature of the research in intuitive, less abstracted ways; 2) comparisons to be made between material platforms and other related areas of research.; 3) the logics, process and working in the development between iterations as well as possible future speculations to be captured; 4) a domain to be established that can help inform and build towards future visions within a research area and the challenges, processes and properties involved in the development towards it (Gaver, 2012); and 5) opinions to be made and contextualised for the future development of aspects explored (Gaver and Bowers, 2012).

Within this research, the use of annotated portfolios has been used in hindsight once all of the material probes had been developed and carried out as tools of exploration. Once compiled together, the multiple facets of the practice-based process, challenges, aspects of interest explore, iterative stages of development, design thinking, speculations and making were not conveyed. From a personal point of view, employing annotated portfolios felt extremely intuitive and agile, which has helped to succinctly capture these initially lost properties, the explorative nature and richness of the research embodied within the collection of material probes. The details and revised annotated images are provided in Chapters 7 and 8 with an overall annotated portfolio provided in Chapter 9 to portray the whole research process, which helps to explain the contributions.

Additional methodologies have been employed to explore aspects of interest emphasised within the material probes and to further understand the parameters and interrelationships generated within an adaptive design and fabrication system. These supplementary methodologies are discussed below.

6.3.3 Employing additional methods

As mentioned, 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 helps to inform the parameters and interrelationships of the research. The additional method is *actuation and sensing.* Essentially, within the material probes 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 material probes and are used to explore how feedback between these parameters can be further understood so adaptive properties can be guided more accurately. Additionally, the incorporation of hardware to induce stimulus and monitor its impacts enables an aspect of repeatability and accuracy within the material probes. For example, the consistent control over the magnitude, duration and time intervals of stimuli induced. This repeatability also enables a form of quantitative comparative analysis between material probes based on the same material platform and highlights: 1) the impacts on pattern/material property generation when a parameter is altered; for example, the impacts of altering the support solution viscosities and densities in the ink material probe; and 2) the role altering parameters can play in developing tuneable environments in regards to interrelationships.

Actuation and sensing can be seen as being more commonly used 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 material probes as they provide more refined control to help accentuate some tangible properties (analysis and data) and inform/define parameters of a framework for developing an adaptive design and fabrication system based on interrelationships. Thus, 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.

6.4 Limitations of RtD

Primarily, employing RtD has enabled a discourse and feedback to be achieved between digital design tools and the material properties of material 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 the material probes. For example, the material porosity, surface texture and tubular forms generated within the mineral accretion material probes are not defined or under precise control across any of the material probes. As a result, the methodology becomes limited in regards to the accuracy within the proposed 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 units to grow complex 2D patterns and 3D shapes via self-assembly. Examples of these processes 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 show that specific patterns can be 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 that 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 beneficially, an increase in interdisciplinary collaboration.

6.5 Overview of Material Probes

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

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

6.5.1 Overview: mineral accretion material probes

The key principle for the series of mineral accretion material probes is to explore how feedback can be understood or generated between digital design models, fabrication, stimulus and material properties, where patterns/material volumes are generated when employing self-assembly when the units of matter do not have predefined properties.

Designing and carrying out each material probe revealed key parameters and principles that need to be addressed 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 generated contrasting properties when inducing stimuli, which revealed an area to be explored as a way to generate feedback loops between the interrelationships and lead to a *closed-loop control system*. Critically, RtD helped to engage with the parameters of this material system through practice-based processes and reflecting on the limitations of each material probe.

6.5.2 Overview: 2D generative paint material probes

The key principle of both the 2D generative paint recipes and 3D ink diffusion material probes is to understand how to move away from the restrictions of the cathode scaffold structures, which are required within the mineral accretion material probes, while still examining the role stimulus can play within these material platforms. Neither of these material probes are intended to establish or explore the feedback mechanism between design, fabrication or material properties. However, specifically to the 2D paint material probes, no stimuli or resultant conditions are monitored via sensors.

The 2D generative paint material probes explore how multiple 2D patterns can be generated by changing the ingredients and ratios within the paint mixture recipe, resulting in the various patterns generated being 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 illustrate what the effects of the ingredient are as well as the impact of how the paint recipe is deposited on the canvases. These material probes 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 material probes into less defined material systems and interactions as it highlighted parameters and material properties that can guide 2D pattern generation.

6.5.3 Overview: 3D ink diffusion material probes

The ink diffusion material probes are investigated as a means of extending the 2D paint material probes into 3D volumes. These material probes explore how volumetric ink diffusion properties can be manipulated by only varying the viscosity and density of the liquid into which they are deposited. 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 of the liquids that are evaluated, and how the impact on the ink’s volumetric properties, such as diffusion rate, dispersion rate and the forms are generated. The inks will be deposited into 5 litres of various liquid mediums: 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 alter material properties of the support material. However, RtD within this material probe 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 or prosthetics could be rapidly grown around a patient's limb and, significantly, tune and adapt their properties as the patient grows or moves to enhance comfort, recovery rate and avoid adverse effects.

Various material analysis techniques are used to understand some of the more general parameters and material properties that are generated within the material platforms, and these are discussed next.

6.6 Material Analysis

Generating data from the results of each material probe 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 platforms.

6.6.1 Mineral accretion analysis

For the mineral accretion material probes, 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 material probes, it is important to confirm if the set-up can grow either calcium carbonate, magnesium hydroxide or a combination/mixture of both and what conditions result in a certain material property of type to proliferate. 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 can determine the composition or predominant type of material grown by comparing peak value wavelengths to known 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 scraped from the cathode and then placing it in the machine. This gives an overall evaluation of material composition. Alternatively, SEM analysis can 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 with material growth on them, which is then analysed by placing it in the machine. Again, peak values of material composition are generated, but from specific areas. Additionally, SEM analysis is 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 the mineral accretion material probes, final growth volumes 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

are manufactured by Qualtex,[1] which can record readings up to 100th of a millimetre. Figure 33 displays how the intended location's growth volumes will be measured based on the various cathode typologies. However, only cathodes that have generated sufficient material growth will be recorded using the digital Vernier, otherwise, growth properties will be based on visual inspections.

- **Live growth volume and rate:** To determine growth rate over time as it is occurring, time-lapse photography will be used. Essentially, a series of photographs, at set intervals, will be taken to document material growth. The time intervals for the photographs will be noted in the relevant material probes that use this technique. Growth volume will be established by comparing it to a known distance, in this case, the diameter of the cathode.
- **Environmental conditions:** The significant conditions that vary during the mineral accretion process, which have a major impact on the material growth properties and 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 setup of material probe 07. The accuracy of the individual sensors will be noted in the annotations for each of the material probe's set-up diagrams.
- **Determining adaptive growth:** As material grows on 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 calcium carbonate or magnesium hydroxide increases. This highlights that, a *resultant change* or *contrasting effects* to the induced stimulus is

[1] https://www.appliancespareswarehouse.co.uk/6-inch-digital-vernier-caliper-150mm-mis400.html

measured and used to determine growth volumes in real time. For example, if the electrical current decreases as material volumes increase these properties could be associated with one another. Significantly, the electrical current values are recorded with timestamps, which can then be corresponded to 'live' growth volume data determined via time-lapse photography. The electrical current sensor used is noted within the setup of material probe 07.

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

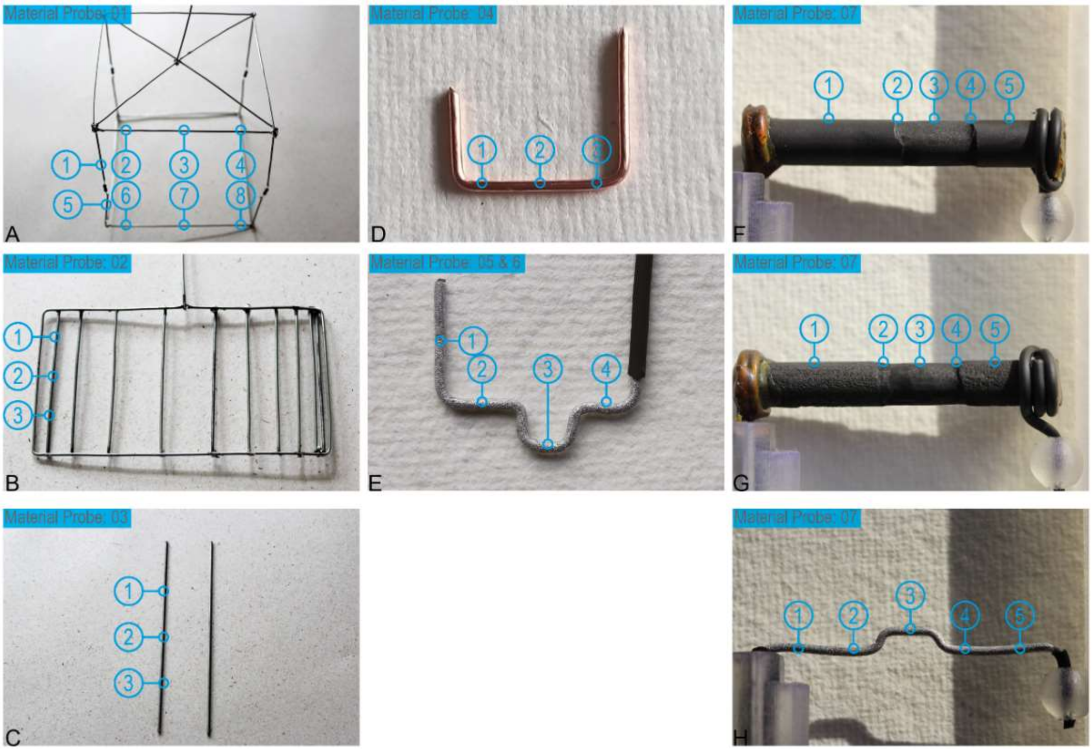


Figure 33: Collection of cathode typologies used within the mineral accretion material probes documenting the intended locations at which material volume growth will be measured. Consequently, sufficient growth only occurred on material probes: 02, 04, 05 and 06 to allow for Vernier measurements.

6.6.2 Generative paint & ink diffusions analysis

For the 2D generative paint and 3D ink diffusion material probes the material analysis is through: 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 choosing each 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 display material interactions occurring over longer periods of time. Time-lapse photography is used within the 2D generative paint material probes during the drying time of the paint as this takes a long period, which highlights slower material interactions and effects.
- **Videography (using a macro or a zoom lens):** Used to capture real-time material interactions and pattern generation in both the paint and ink material probes 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 material probes to highlight the effect increasing liquid viscosities have on the flow rate of the pumps. Specifications will be given in the diagram demonstrating this material probe's set-up.

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

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
Canon 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 lists the material probes as well as the significant properties of each. For example, if the material probe is analogue and what type of material analysis will be used to generate results.

Table 3: Table of material probes and their properties

Material probe №	Material Platform	Nature	Feedback	Material Analysis
Mineral accretion Material Probes				
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 Material Probes				
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 Material Probes				
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

6.7 Chapter Summary

This chapter discussed why and how a RtD methodology approach is employed, and why the explorations are termed ‘material probes’, which are documented through the adoption of annotated portfolios and the material analysis techniques used. The key aspects from each section are:

Why RtD and How it is Employed

Employing RtD as an approach was determined and applied based on the following factors:

- It enables exploration guided by a loose objective/aim and flexible freedom within a design process that does not have to be constrained to incremental developments of known technologies.
- The ability for RtD to address the weaknesses that arises from the approach can be addressed as the material probes can act as *boundary objects* to facilitate interdisciplinary collaboration.
- The flexibility of RtD enables concepts to be developed so that design and fabrication processes can be based on inducing stimulus and monitoring ‘*contrasting effects’/resultant effects*
- RtD is employed through practice-based processes that generate a series of material probes where the development is iterative

Material Probes

The reasons for terming the series of artefacts material probes are:

- The explorative and playful nature is captured by terming the series of artefacts material probes without constraints associated with other terms, such as *experiments*.
- The subjective nature qualities are also captured by terming them material probes and the fact that they do not look to set a defined method.

Annotated Portfolios

The use of annotated portfolios has been used, with the benefit of hindsight, for several reasons:

- They felt familiar and were an intuitive way to capture the development of the design process and design thinking
- They capture the design thinking and material properties of the material probes without abstracting one another i.e. they are seen as indexical.

- They do not constrain the embedded research within the artefacts to perceived methodologies that promise *rigour.* Instead, they can elicit it with more tangibility
- They can coordinate the series of material probes to allow for comparison as well as define an area that the *body of work* of material probes represents and is exploring.
- The annotated portfolios and reflections of each material probe are provided in the following chapters to provide more context and detail.

Material Analysis

Various material analyses used to determine and compare material properties are discussed:

- **XRD, XRF and SEM**: determine the material type and composition of the materials grown from the mineral accretion material probes.
- **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 during and post-fabrication.

Chapters 7 and 8 now present and discuss: the details of material probes' set-up across various material platforms; the iterative development of the material probes; results generated from each material probe; and the challenges and potentials that arise when engaging with and guiding material computational processes to generate structures that can tune and adapt their properties.

7 Mineral Accretion Material Probes: Investigating Adaptive Design and Fabrication Processes

This chapter presents and discusses each of the material probes carried out within this research, based on the mineral accretion process, which has facilitated the understanding of how to develop an adaptive design and fabrication system based on interrelationships by employing *'tuneable environments'*. Here, tuneable environments can guide units of matter that do not need to have the properties pre-designed to inform properties (shapes, patterns, material volumes, locations and compositions) of the structure. In this case of mineral accretion material probes, the units of matter are molecules of calcium carbonate and or magnesium hydroxide. Furthermore, the material probes aid in the understanding of how feedback mechanisms within the systems can be generated based on variable interrelationships of the mineral accretion process between induced stimuli, resultant conditions and material properties generated.

The chapter first presents a series of material probes that uses the self-assembling mineral accretion process. The development and challenges addressed throughout the series of Material Probes are presented in Figure 34. This series of material probes are used to understand how an adaptive design and fabrication system can be created when using material self-assemby by altering parameters of stimuli to guide material interactions and properties generated. The system and its adaptive abilities are developed based on interrelationships. Following the mineral accretion material probes, the 2D generative paint material probes are then presented, followed by the 3D ink diffusion material probes. Both the 2D paint and 3D ink diffusion material probes explore how material self-assembly can be guided without the need for restricting scaffold structures. They do not attempt to establish feedback. All the material probes are either presented as a collection or individually based on their nature. For example: if the material probes are analogue; if the material probes can achieve localised variable material properties (volume, composition, type); if the material probes show parameters that can be used to establish feedback between design tools, fabrication, material properties and stimulus i.e. can the material probe lead to *Closed-Loop Control System* based on how the sensors are incorporated into the system?

The series of mineral accretion material probes are presented as follows:

First, material probes 01 - 03 are presented as a collection since they are all analogue in nature. Additionally, they have fundamentally the same cathode properties.

Second, material probe 04 is presented. This material probe is also analogue but it is presented individually as its cathode properties differ from the first three material probes.

Thirdl, material probes 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 material probe 05. The stimulus is then controlled using a parametric design tool in material probe 06.

Fourth, material probe 07 is used to generate data by incorporating sensors external to the material to determine how feedback can be established between design, fabrication, material properties and stimulus.

At the end of each set of material probes, specific questions will be stated that will be explored in the flowing iteration, as well as reflections on the design process and insights. Chapter 7 finishes by discussing the key findings across all the mineral accretion material probes, which bring to light future fabrication potentials based on tuneable environments.

7.1 Set-up Overview and Development of Mineral Accretion Material Probes

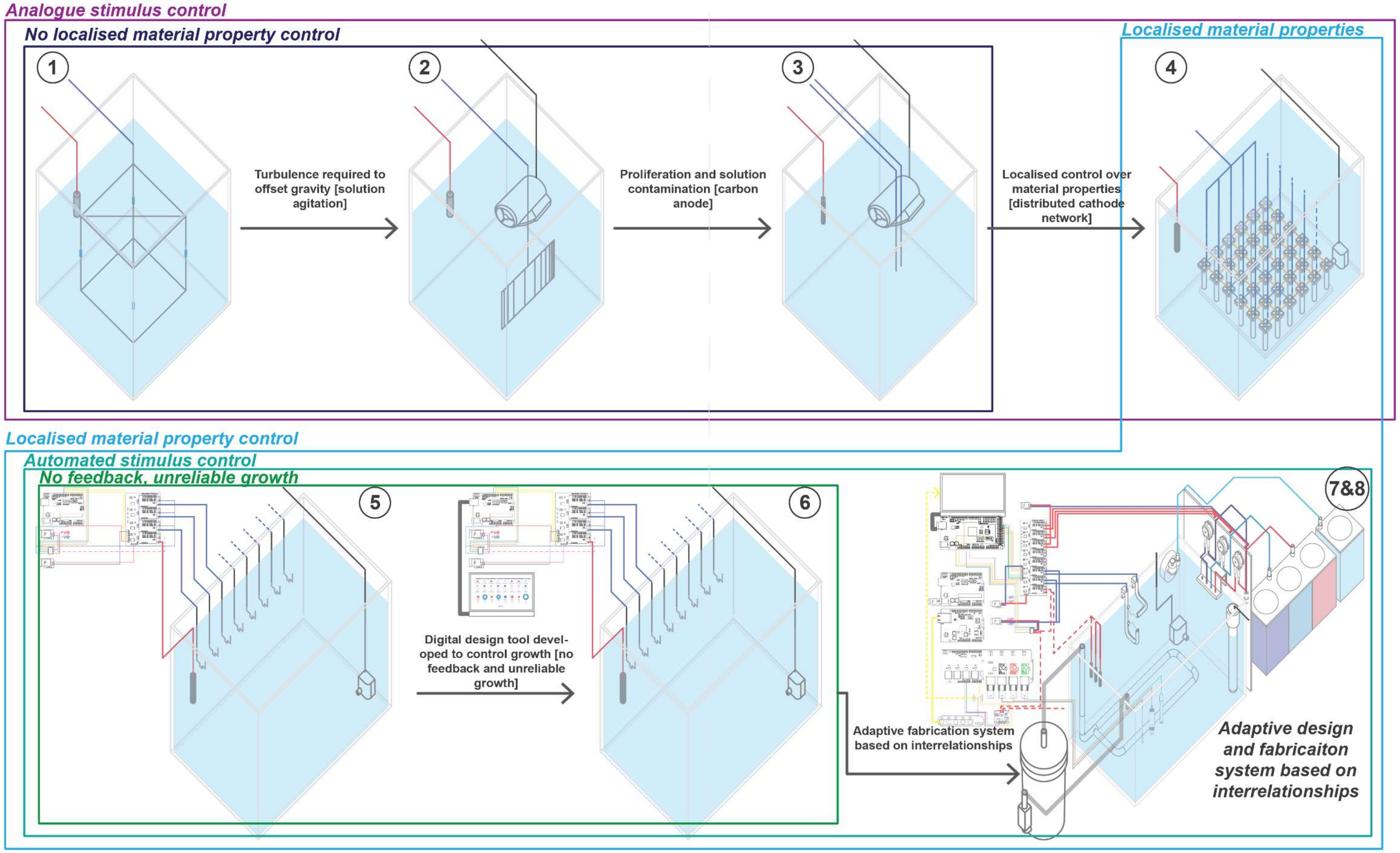


Figure 34: Overview and development of the multiple mineral accretion material mrobes. The material probes are iteratively developed in four stages. First, analogue material probes (1-3) with no localised control over material properties. Second, an analogue material probe (4) with localised control over material properties. Third, automated material probes which incorporated hardware to control parameters of stimuli to grow desired material volumes by predicting growth durations. Finally, a material probe that incorporates sensors to understand how feedback between stimuli, resultant conditions and material properties can be developed, which inform how an adaptive design and fabrication system can be created based on interrelationships.

7.2 Mineral Accretion Overview

Before discussing the development and results of each material probe, a brief summary of the mineral accretion process, its parameters and the variables it engages 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 calcium carbonate or 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 electrolyte solution (e.g. seawater or brine) and then supplying a potential difference (i.e. voltage/direct electrical current) between the anode and cathode. 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 calcium carbonate or magnesium hydroxide that can be affected by conditions within this process are volume, type, rate and composition. The main parameter dictating these material properties within this research is the voltage supplied between the anodes and cathodes. Importantly, the voltage supplied can be modulated in regards to duration and magnitude. A break down is now given of how voltage variables inform material properties:

- **Volume** – typically, the longer the cathode and anode are supplied with voltage the greater the volumes of material are grown as long as the solution is electrolytic or saline. However, the volume of material growth in previous experiments by Hilbertz (Hilbertz, 1981) and Goreau (Goreau, 2012) has resulted in somewhat uniform growth across the whole of the scaffold, which indicates 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 to the anodes and cathodes is one factor that informs the material type grown. Calcium carbonate typically grows at lower voltages closer to values of 1.23 volts and

magnesium hydroxide grows at higher voltages. Hilbertz et al. do 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 cathode’s distance from the anode, and time also impact the material growth. Time can also affect material compositions as Hilbertz and Goreau state that percentage amounts of magnesium hydroxide becomes less prominent overtime with calcium carbonate percentages increasing (Hilbertz, 1979, pp108-109), due to further chemical reactions as a result of material build-up (Goreau, 2012, p282). This factor will not be monitored within the series of material probes carried out within this research. Instead, favourable conditions for generating calcium carbonate and or magnesium hydroxide production will be monitored and varied, which are tabulated in Table 4 based on a survey of literature by Hilbertz et al., Goreau and Streichenberger.

- **Rate** - calcium carbonate typically grows at a slower rate than magnesium hydroxide. Typically, the conditions for growing calcium carbonate are lower voltages/electrical currents and pH levels (Goreau, 2012). 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 magnesium hydroxide or calcium carbonate 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 lie outside 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**. 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 those with a diminishing impact towards the right. Past literature showed that experiments using the mineral accretion process were typically carried out within the open ocean i.e. in open systems, which means conditions would fluctuate over the course of a day, such as temperature fluctuations, which affect solution conductivity. The material probes within this research will be a closed system and will, therefore, need to be able to account for these factors and others 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. Understanding the relationships between induced stimuli and resultant conditions is intended to uncover feedback mechanisms and inform material adaptation parameters.

Table 4: Conditions for calcium carbonate or magnesium hydroxide production

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

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

The first three material probes presented are used as a basis for understanding the main parameters of the mineral accretion process and what their impacts are in regards to developing a fabrication process based on modulating stimuli parameters that inform material aggregation, which results in a non-deterministic fabrication process as materials and material properties are not specifically defined. Each material probe, its results and the key findings are then discussed. The key findings highlight the challenges that need to be addressed in the subsequent iteration 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 material probe's overview, set-up, components, results, factors and key findings are discussed in individual sections. The development of the material probes is iterative and has helped to inform: 1) how they impact on design and fabrication processes; 2) what are the key challenges or the overriding factors that arise and need to be addressed to achieve localised material properties and build towards creating an adaptive design and fabrication system; and 3) how the key findings point towards new forms of *'living architecture'*, which could behave like '*material eco-systems'*. These material eco-systems can be made possible by engaging with and guiding the computational abilities of materials.

7.3.1 Material probe 01: cube cathode. properties, predictions and analysis

This initial material probe sets out to provide a proof-of-concept that controlled crystal deposition could be achieved using electrolysis of seawater (mineral accretion), and what are the requirements of a cathode typology to achieve localised control over material properties. Figure 35 highlights the material probe's set-up. Briefly, the cube cathode is placed within 4 litres of seawater, which was collected from Morecambe Bay. The seawater solution was not replaced throughout the duration of material growth. The cathode was then supplied with 1.6 volts at 0.14 amps for a total of 240 minutes. A steel anode was used and a consistent voltage supplied using a bench power supply.[2] The set-up resembles an *open-loop control system*.

Properties

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

[2] Aim-TTi Digital Bench Power supply, 130W, 3 Outputs, 0-30v 2Amps

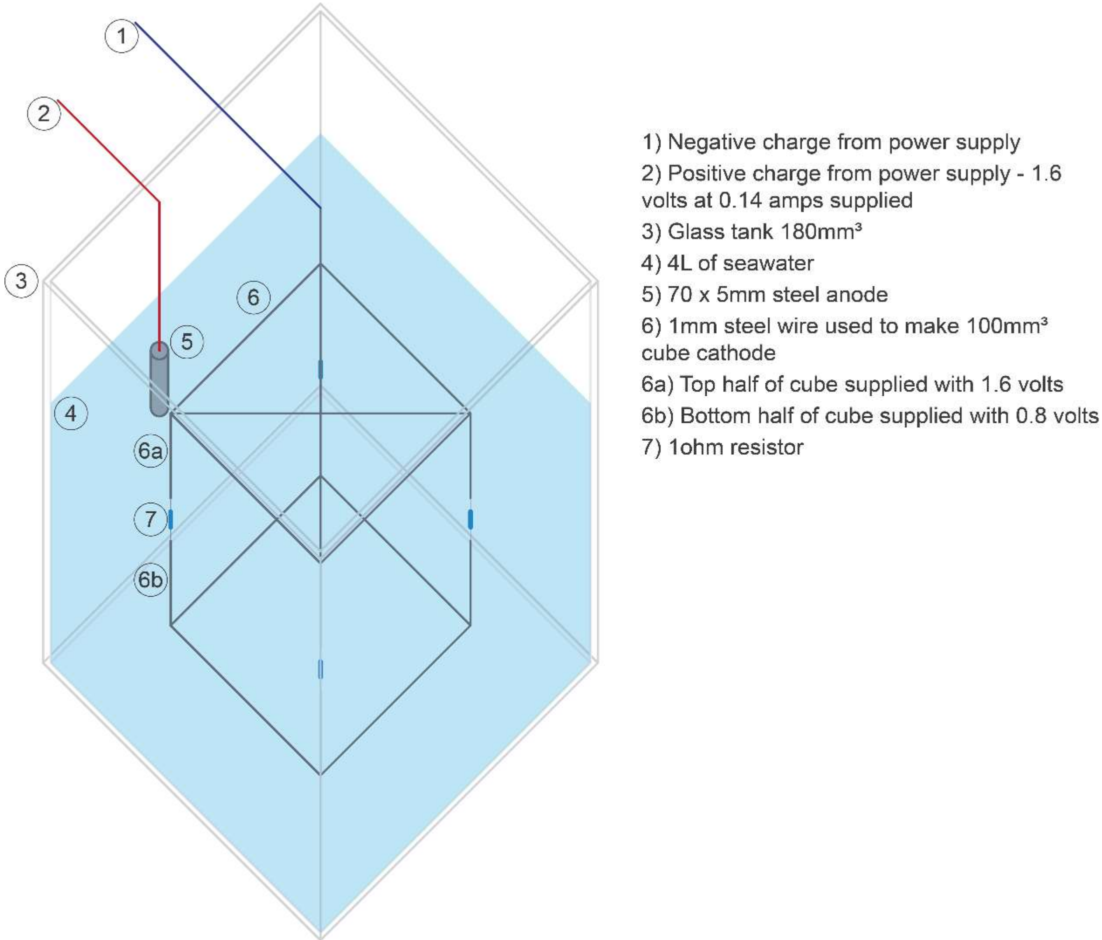


Figure 35: Material probe 01 set-up of the initial cube cathode. The material probe is used to understand the initial properties of the mineral accretion process. The resistors that separate the cube cathode are intended to create a drop in voltage, so the top half grows magnesium hydroxide (higher voltage) while the bottom half grows calcium carbonate (lower voltage).

Predictions

The predicted material results for this cathode typology are: more material to accumulate on the top of the cube and to be predominantly composed of magnesium hydroxide compared to less material growth on the bottom, which should be predominantly composed of calcium carbonate.

Analysis

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

The results of this material probe will be discussed with those of material Probes 02 and 03. material probe following the discussion of the properties of material probes 02 and 03.

7.3.2 Material probe 02: (Fence Cathode) & 03 Two-Wire Cathode: properties, predictions and analysis

Two further material probes 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 material probe 02 and two individual wire cathodes for material probe 03.

Properties

For material probes 02 and 03, both are suspended in 3 litres of a controlled consistent solution. The solution is created by dissolving 100g of marine salts[3] in 3 litres of tap water at 25°C. Both material probes are supplied with 2.0V and 0.07Amps for 24 hours using a bench power supply. 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[4]. Additionally, the salinity of the solution

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[3] Red Sea Coral Pro Salt

4 WM-2000 Mini Aquarium Wavemaker by all pond solutions

was monitored by analogue means using a Fluval salt sea hydrometer. Figures 36 and 37 present the set-up of the material probe.

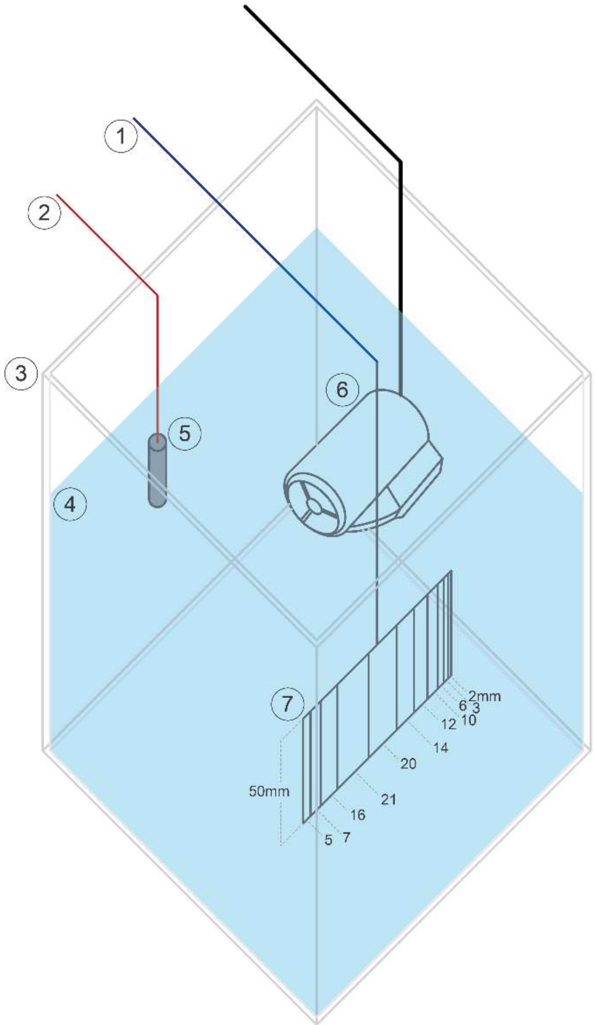
Predictions

The fence cathode is composed of vertical members that are spaced irregularly; Figure 37 shows the spacings 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 material probe as the cathode itself has not been designed to have any particular qualities, and so, provides a base-line. For this, it is only predicted that a composite material of calcium carbonate and magnesium hydroxide will be grown.

Analysis

XRD material analysis will be carried out on the fence cathode whereas material that is grown on 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.



1) Negative charge from power supply
2) Positive charge from power supply - 2.0 volts at 0.07 amps supplied
3) Glass tank 180mm³
4) 3L of solution made from dissolving 100g of marine salts in 3L of water at 25°C
5) 70 x 5mm steel anode
6) Aquarium wave maker (2000L/hr)
7) 1mm steel wire used to make fence cathode with various spacing between vertical members (spacings noted on diagram)

Figure 36: Material probe 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.

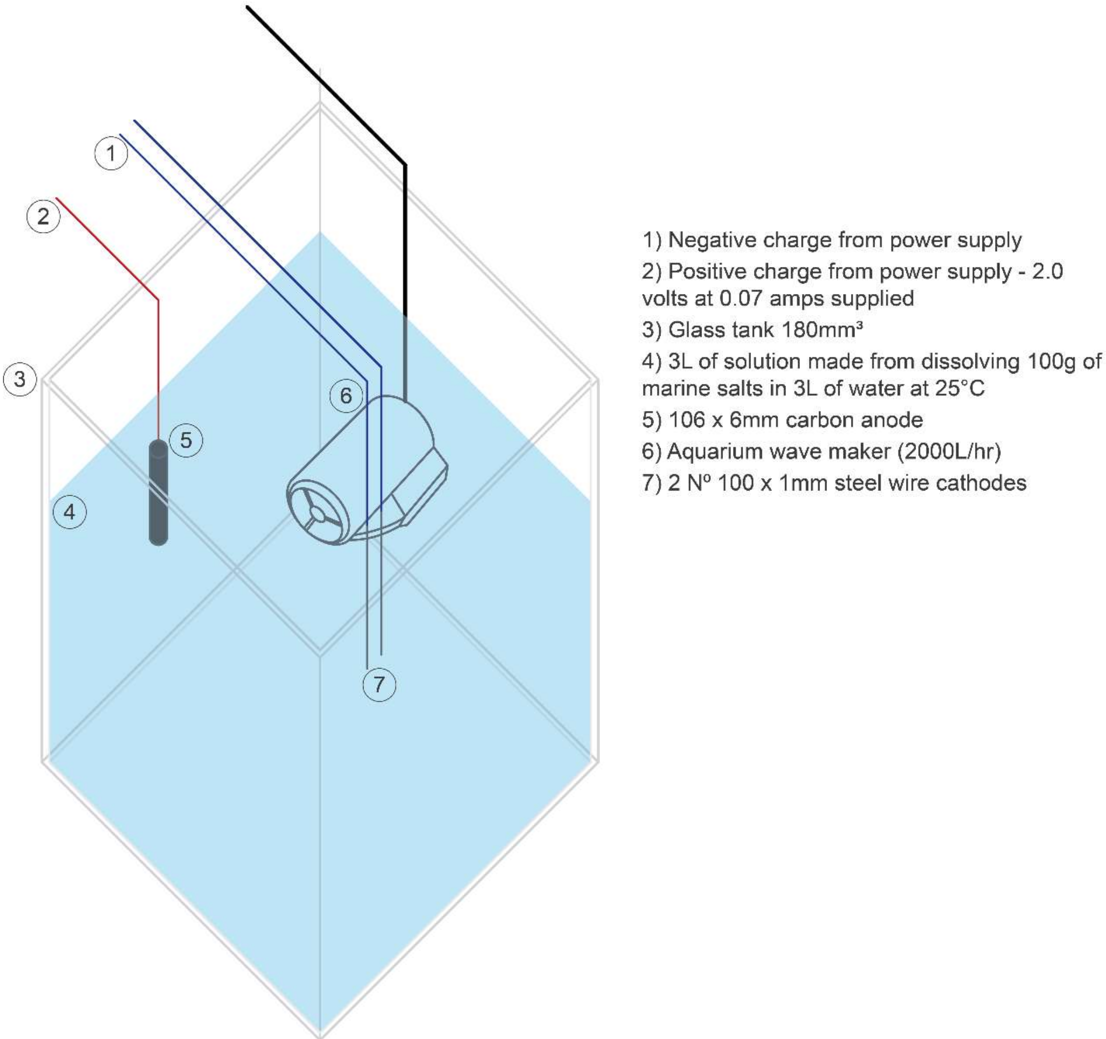


Figure 37: Material probe 03 set-up of two individual wire cathodes. The Material probe is carried out to undertake SEM analysis and understand the impacts of the cathode material itself.

7.3.3 Material probe 01, 02 & 03: Results

The results from each material probe will now be discussed through increasing scales of resolution i.e. from macro to micro. *First*, data will be discussed based on anything visible to the naked eye, which is captured via macro photography. *Second*, 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 cathodes will be discussed.

The factors governing or generating these material results from each of the material probes are then discussed in the conclusion of this section. Additionally, research questions and reflections are defined to inform the following exploration in the next material probe iteration, which is guided by the loose aim of developing an adaptive design and fabrication process by guiding material self-assembly processes.

7.3.4 Macro Results

Figure 38 is a series of photographs, which reveal two main factors in regards to cathode typology: *first,* the impacts cathode typology have on material properties grown. *Second,* the varying and emergent material properties generated from each of the material probes. 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 material probes discussion, which focuses on the necessity of *turbulence* within the system and the impacts of *proliferation*.

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

Fence cathode: the photographs reveal several interesting factors:

First, 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 the proliferation of another material type. However, iron oxide growth only proliferated after the initial white material growth. These orders of growth indicate: A) threshold concentrations of the solutions material must be reached before proliferating; and, B) the solution’s dissolved materials/ions can be manipulated over time to grow various composite materials.

Second, material growth is uniform as a result of turbulence induced by the wave-maker.

Third, material unification of iron oxide occurred between the closer vertical members. The ability to unify materials as they grow reveals the potential of self-healing structures and components that can change their properties to meet demands e.g. solar shading, privacy.

Finally, emergent variations in surface textures are generated, from smooth to porous; where the material porosity increases the closer the vertical member becomes.

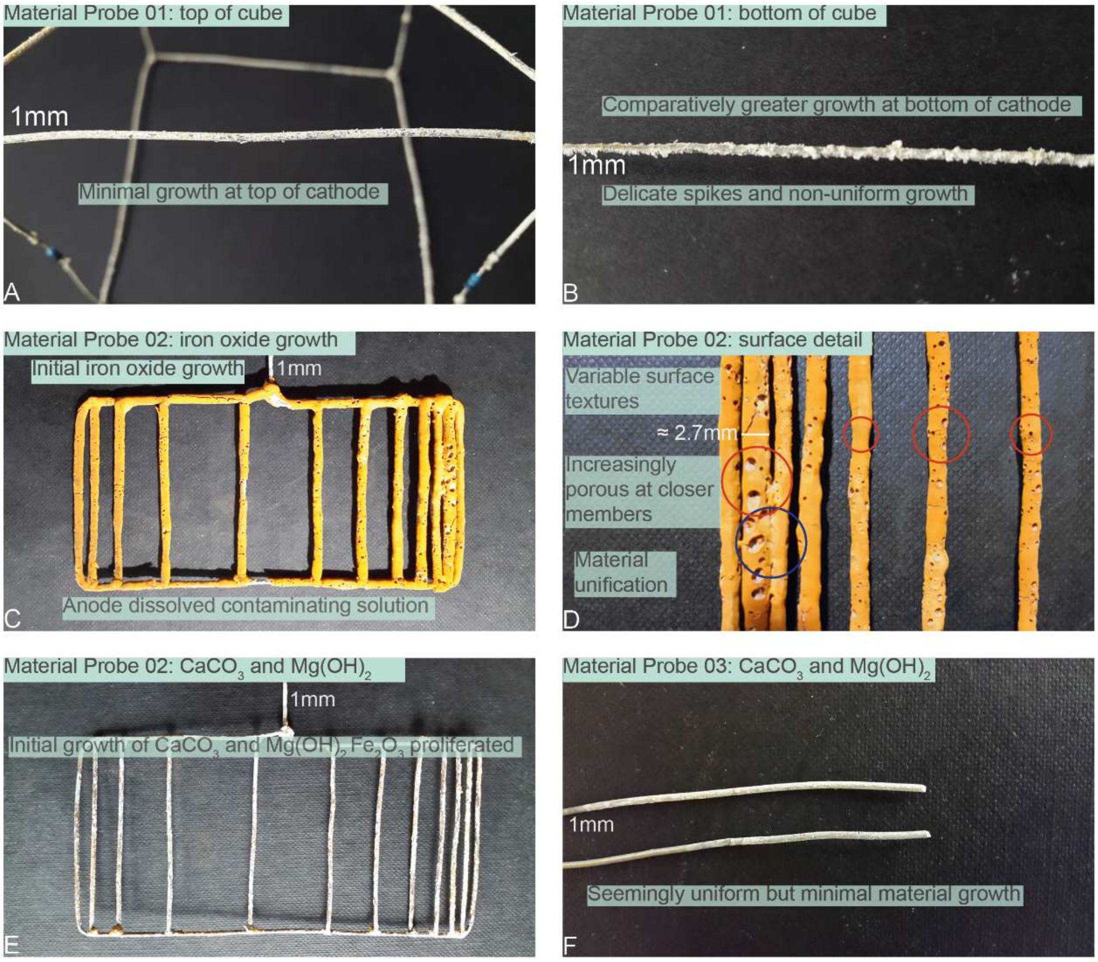


Figure 38: Material growth results from material probes 01 - 03 photographed. A) The minimal growth that occurred at the top of the cube cathode in comparison to B) the bottom of the cube cathode. This exhibits the significant impact of gravity, which needs to be offset. C) The effect of the solution being contaminated from the anode dissolving and the uniform growth achieved as a result of inducing turbulence. D) Material unification and the emergent surface textures generated during growth. Surface texture porosity increases as the vertical members become closer. E) Illustrates that the solution must have threshold amounts of materials/ions 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 that magnesium hydroxide is more predominant at the top of the cathode compared to the bottom, demonstrating that the resistors had minimal to no effect on dictating the material properties grown within this set-up (see Figure 39). However, XRD of the white material deposited on the fence cathode reveals both calcium carbonate and magnesium hydroxide are present, this establishes a multi-material system is possible using the mineral accretion process. As a result, the current cathode typologies need to be updated to govern localised properties. Additionally, SEM analysis also confirms these results (see Figures 40 and 41).

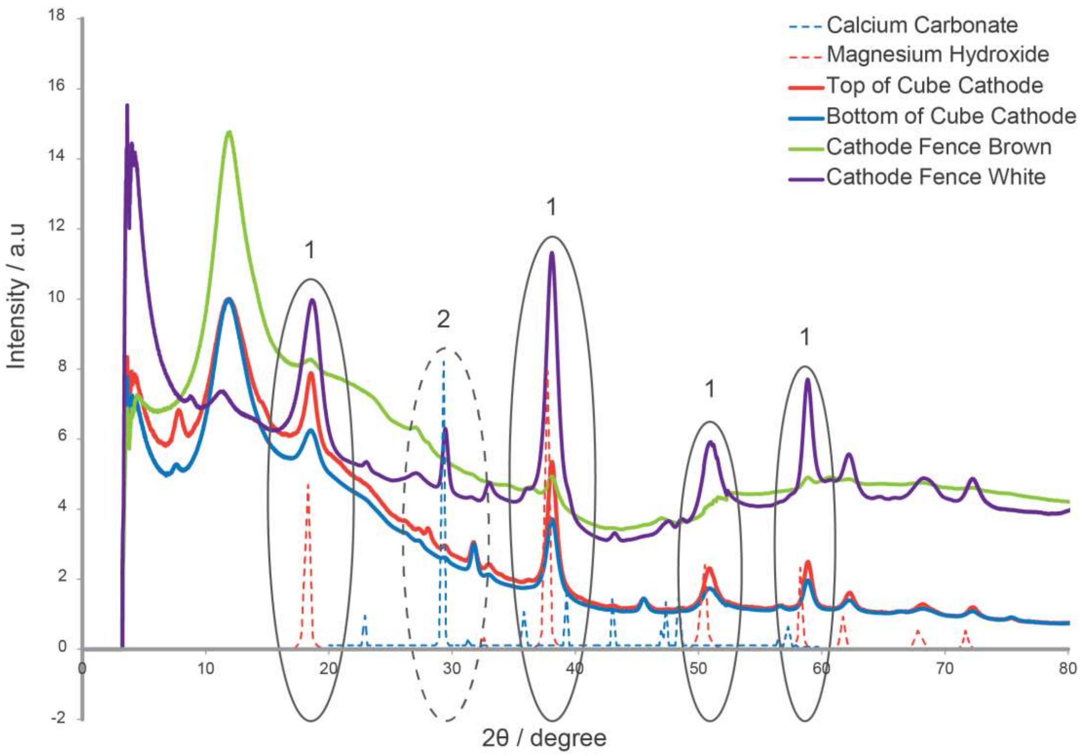


Figure 39: XRD material analysis graph from material probes 01 and 02. The results establish that a multi-material system is possible using this material platform.

7.3.6 Micro Results

The images generated from the SEM analysis (Figure 40) in combination with the graphical analysis (Figure 41) reveal the impacts of cathode purity. Cathode purity informs the material type deposited, as the purity informs current uniformity. The images display various surface textures, which also reveal an emergent, clearly defined ‘7’ shape. Additionally, the images show the various material compositions highlighted by the different crystal shapes, where the needle-shaped ones are calcium carbonate and the dandelion shapes are magnesium hydroxide.

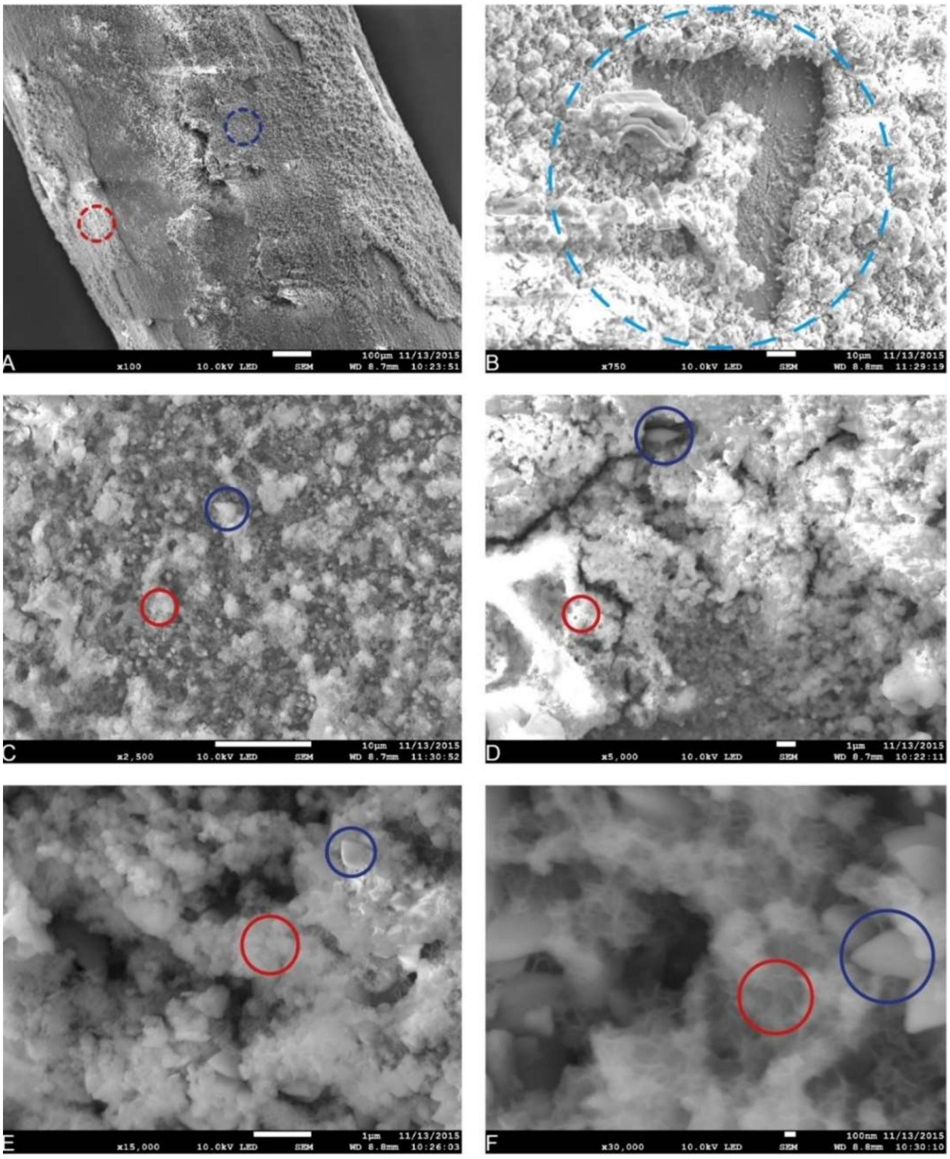


Figure 40: SEM images from material probe 03. The images sequentially increase in magnification. A) SEM revealed the effects of the cathode's purity as varying amounts of calcium carbonate and magnesium hydroxide crystals depending on analysis locations. Sample location A is highlighted by the central 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 magnesium hydroxide, highlighted with red circles compared to the calcium

carbonate highlighted with blue circles. 100 x 1mm diameter steel wire cathode used the two individual wire cathodes.

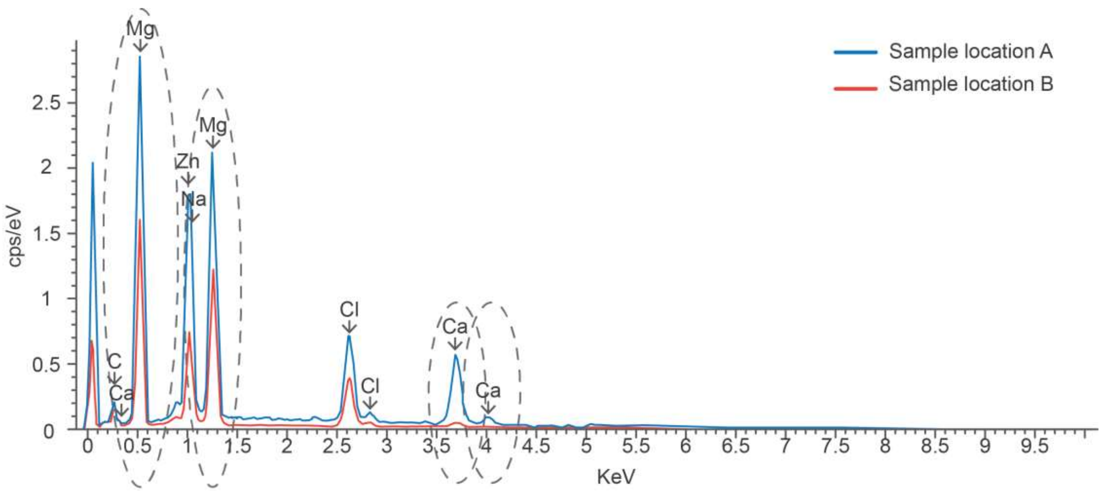


Figure 41: SEM peak value data graph showing the materials present. In particular, calcium and magnesium have varying peak values depending on the location of analysis. These variable values establish a multi-material system can be achieved by tuning the voltage supplied.

7.4 Material probes 01, 02 & 03: Conclusions, Discussions & Developments

Overall, the initial results from all three material probes 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 material probe iteration are broken down into three sections.

7.4.1 Development: cathode typology

This first series of cathodes highlighted one key question: *What cathode typologies can lead to localised control over material properties so a defined* *shape can be grown?* This question will be further explored in the following iteration of the material probes.

However, the results from the first three material probes provide insights into how to explore this question. The main points raised that begin to address this question are: 1) cathode typology; cathode elements need to be physically separated by an insulating material to enable control over electrical current location and localised material properties. Additionally, localised control could be further improved by incorporating a form of a switch to turn off or on the electrical current supplied to individual cathode wires; 2) resistor types; electrical current bypassed resistors that are within the cathode due to the seawater solution. Consequently, variable resistors, e.g., potentiometers (analogue or digital), are needed and placed within the circuit outside the solution. These would allow for the electrical current supplied to the cathodes to be varied over time so different material types and compositions could be grown.

7.4.2 Development: 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. This raises the question: *What type of anode materials will not dissolve and prevent solution contamination?* Carrying out a brief literature review revealed that using a carbon anode could prevent solution contamination.

7.4.3 Turbulence

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

The results and key factors of this series of material probes (01 – 03), are part of the paper; *Adaptive materials: Utilising additive manufactured scaffolds to control self-organising material aggregation*, published at the 2015 RDPM conference (Blaney et al., 2015)

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

This material probe iteration aims to explore the questions raised from the previous three Material Probes. The main aims to be explored are: 1) how a defined heart shape can be grown (Figure 42); 2) how a defined shape can be composed of locally variable material properties i.e. grow materials with varying volumes/thicknesses and of varying material type or composition; and 3) how solution contamination and proliferation can be prevented by using a carbon anode.

The aim of material probe 04 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

Material probe 04 is composed of a 2D 6 x 6 cathode grid. The grid is composed of 72 individual U-shaped copper cathode wires with a 1mm diameter. Figure 43 presents the set-up for material probe 04. Material build-up on the cathode grid will be 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 44 shows this 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.

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 to create a heart shape. 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. This material probe intends to determine whether it is possible to indirectly create a specific shape with varying material thickness and what effect varying voltages have 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 those supplied with 3.0 volts and every 2 hours for the half supplied with 4.7 volts. 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 to the human eye. Once all 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 calcium carbonate compared to other materials present and growth rate), 12 wires were supplied with different voltages, and each individual element supplied with a set voltage for 2 hours. The material probe was run 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.

For the solution, 300g of marine salts were dissolved in 6.5L of tap water and the 2D cathode grid was then submerged in 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 second part of the Material Probe, which supplied individual cathode elements with varying voltages. One carbon anode of radius 6.3mm and length 75.0mm was used to determine if this material type prevents significant solution contamination.

Notably, as discovered in the first series of material probes (01 - 03), 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, it was found from these tests that agitation of the solution with the grid-shaped cathode structure produced detrimental effects to the early growth of crystals, causing grown material to fall off the structure during agitation intervals. To avoid material decaying away from the cathodes because of agitation, this material probe did not agitate the solution to counteract gravity as material was growing. However, for material probe 04, it was believed that the effect of gravity would be less significant because all 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.

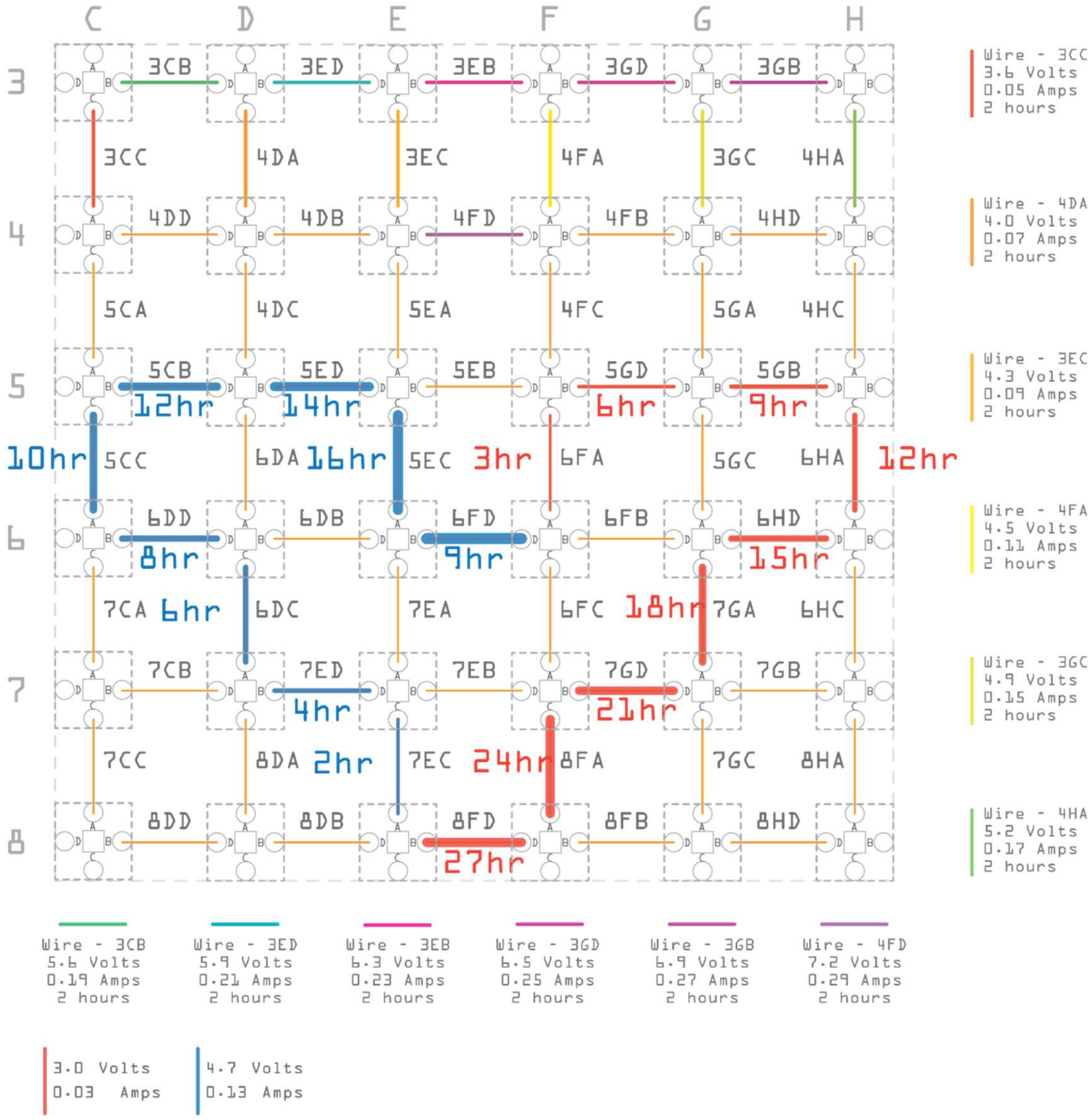


Figure 42: Pixelated heart shape is drawn on the 6x6 cathode grid with the corresponding wire reference to be connected. The heart shape is split in two and supplied with different voltages, each element of the heart is grown for varying durations. Individual elements are supplied with varying voltages to determine their effects on material composition and properties.

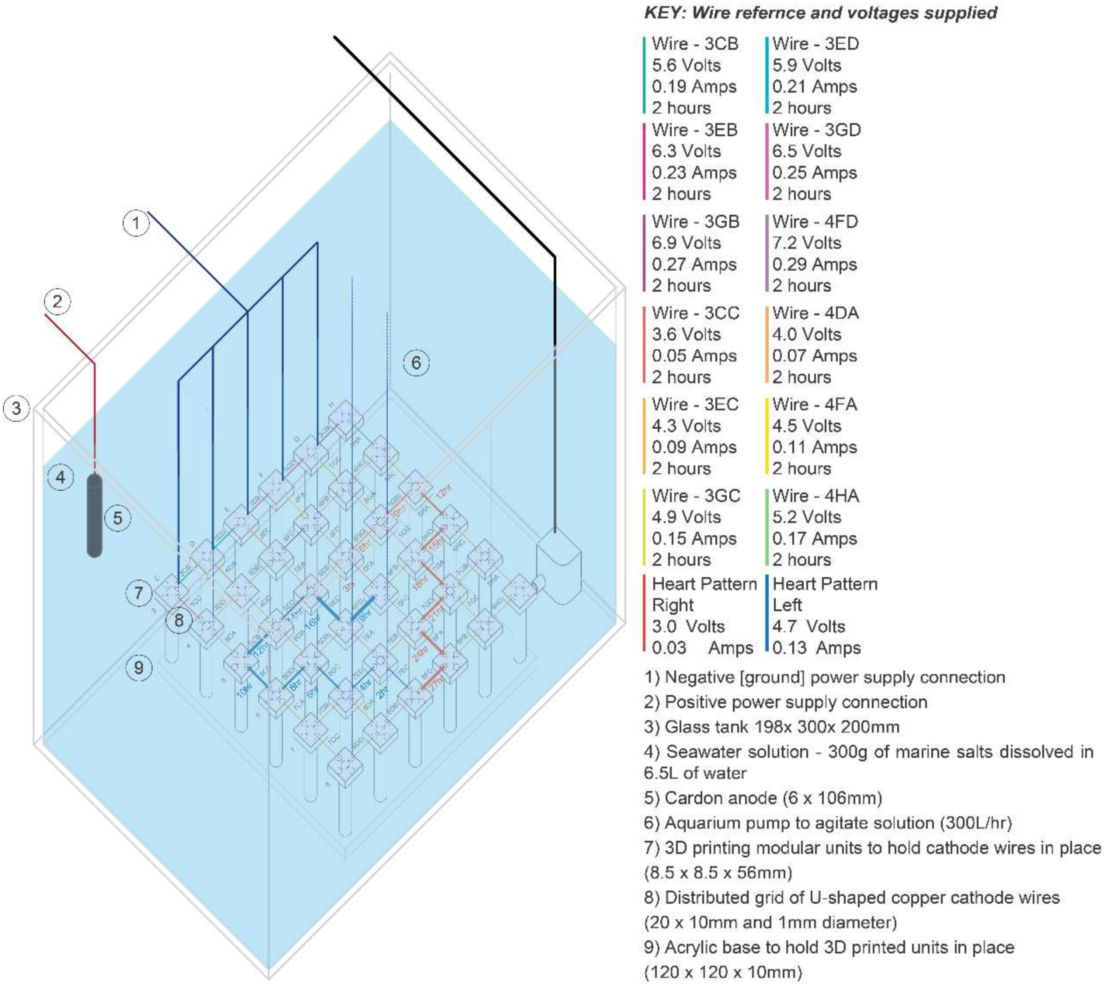


Figure 43: Material probe 04 set-up of the 2D distributed cathode network. The material probe is carried out to understand how to control localised material properties so a desired pattern can be grown.

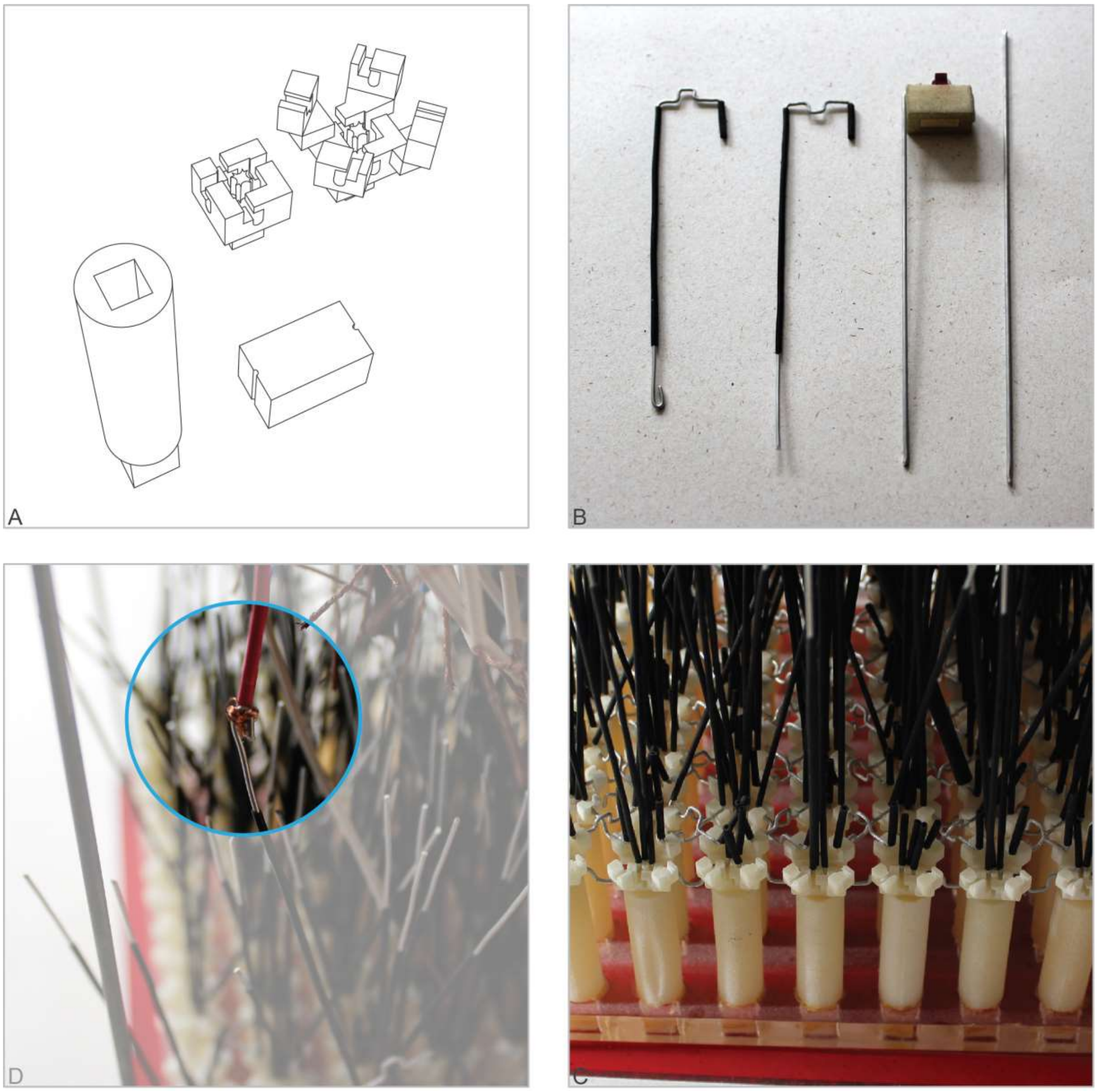


*Figure 44: Fabrication process of cathode scaffold for material probe 04. **A**) Digital design of modular component used to hold the copper/aluminium cathode wires in place. 36 of them were fabricated using selective laser sintering (SLS) a form of 3D printing. **B**) Copper and aluminium wire (1mm in diameter), bent by hand around a jig to create cathode wires that have approximately the same dimensions. Copper wires are used in material probe 04. **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**) The network of wires placed within the 3D printed head of the components within a square grid.*

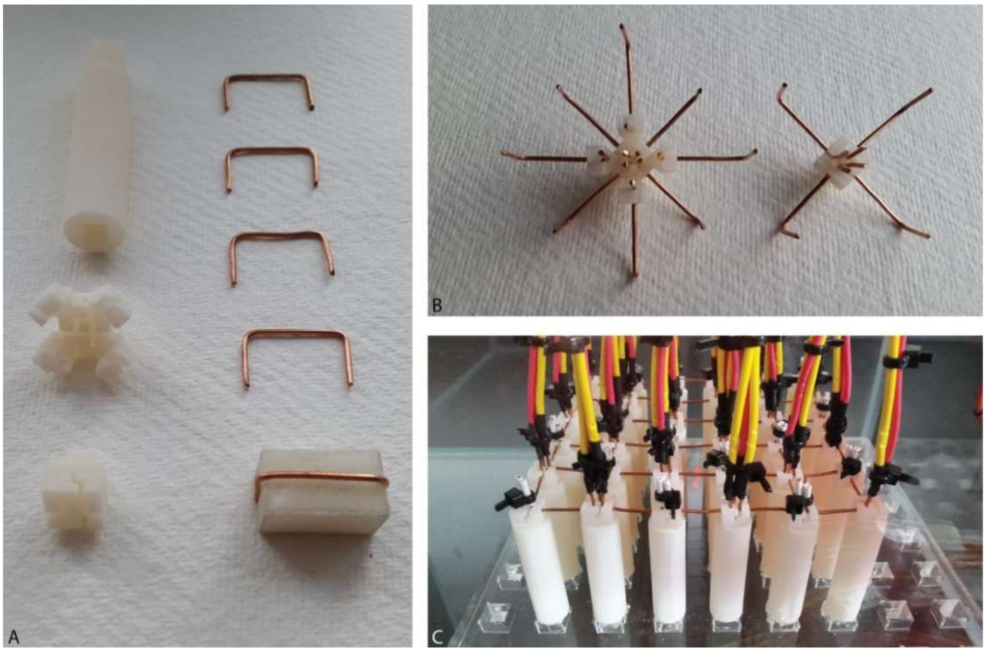


Figure 45: Assembly of 2D grid scaffold. A) AM was used to fabricate modular nodes made to physically separate the cathode elements. B) Two different heads were fabricated as an option to increase the resolutions of the 2D grid. C) Final 2D 6x6 grid with 4 cathode elements.

Predictions

Predictions for the 2D grid cathode design is that it should be able to grow a clear heart shape upon 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 shape supplied with 4.7 volts is expected to generate a faster rate of material growth, with greater volumes of material aggregation on elements that are supplied with electricity for longer durations.

Analysis

To determine the material composition, X-Ray Fluorescence (hereafter XRF) is used to analyse the results of this material probe. 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. Details of the digital Vernier are supplied in Section 6.6.1.

7.6 Material probe 04: Results

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

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

7.6.1 Macro Results

These observations are separated into three main areas: 1) the results of the overall heart-shaped pattern (global properties)*;* 2) local surface texture qualities; and 3) uniformity in material growth.

Figure 46 reveals the completed growth of the heart shape. Establishing this cathode typology can 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 the electrical current for longer durations resulted in an 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 46 also highlights two other emergent material properties, which are generated at various stages and conditions:

- *Varying surface textures* on the heart shape elements supplied with 3.0 volts. A smoother texture was produced on elements supplied with electrical current for longer durations compared to an initially granular texture produced from shorter durations. Uniform surface texture was created on the half of the heart shape supplied with 4.7 volts. 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 durations (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.

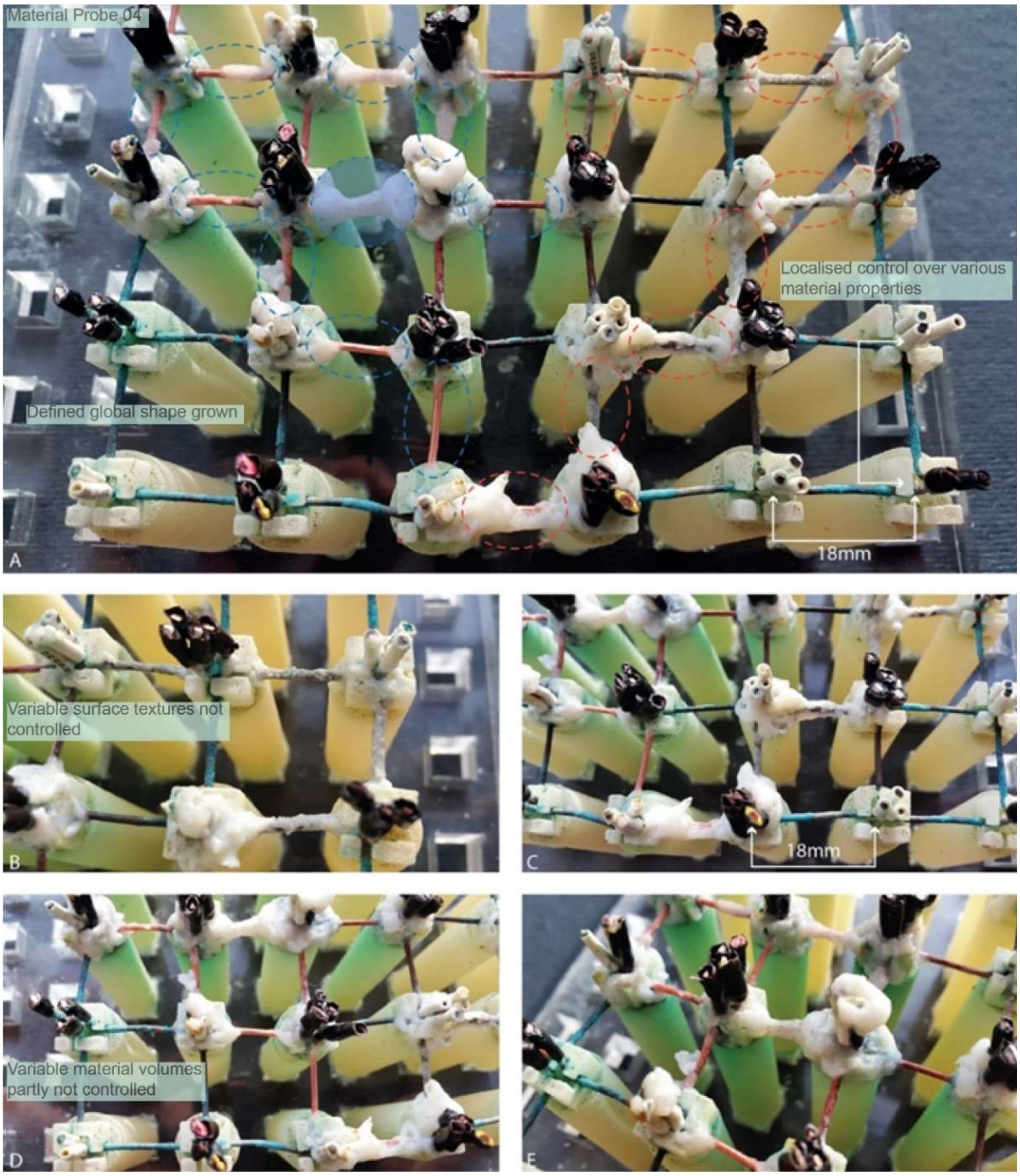


Figure 46: Material results material probe 04. A) The final heart shape growth reveals material growth location and amount can be controlled. B & C) Reveals varying surface textures and varying growth location over time when supplied with 3.0 volts. D & E) Reveals a smooth surface texture was produced 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 47 delineates plots of material deposition over time and 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 that 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, as a result of increasing voltages, which results in an increased amount of hydrogen being produced at the cathodes, appears to have prevented material deposition. Additionally, the growth rate for both voltages (3.0 and 4.7 volts) is quite similar, with both increasing over time.

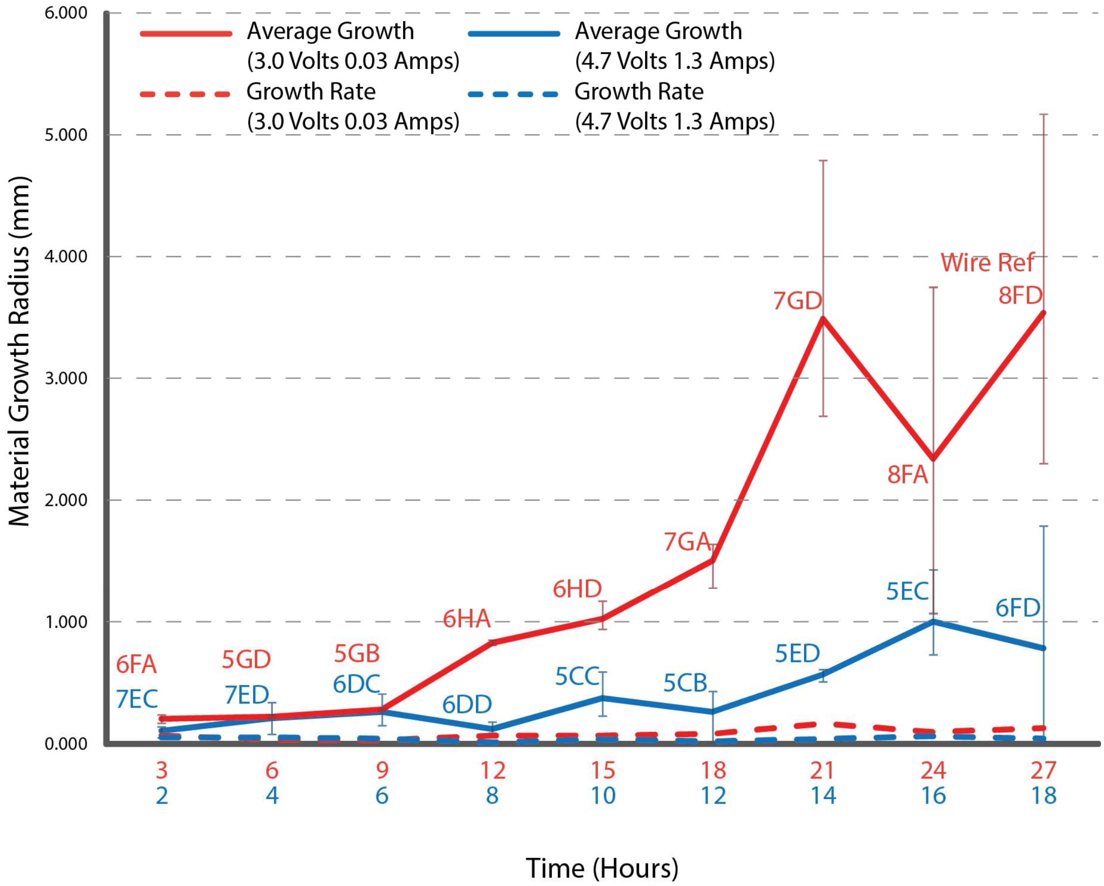


Figure 47: Graph of material growth volumes and rates for material probe 04 exhibits an increase for both 3.0 and 4.7 volts the longer the cathode element is supplied with electrical current. Error bars highlight the range between average growth and minimum and maximum growth at points on each cathode 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 48 shows an initial trend of increasing material growth amount corresponds with increasing voltages between 3.6 – 4.5 volts (0.05 - 0.11amps), which then falls off.

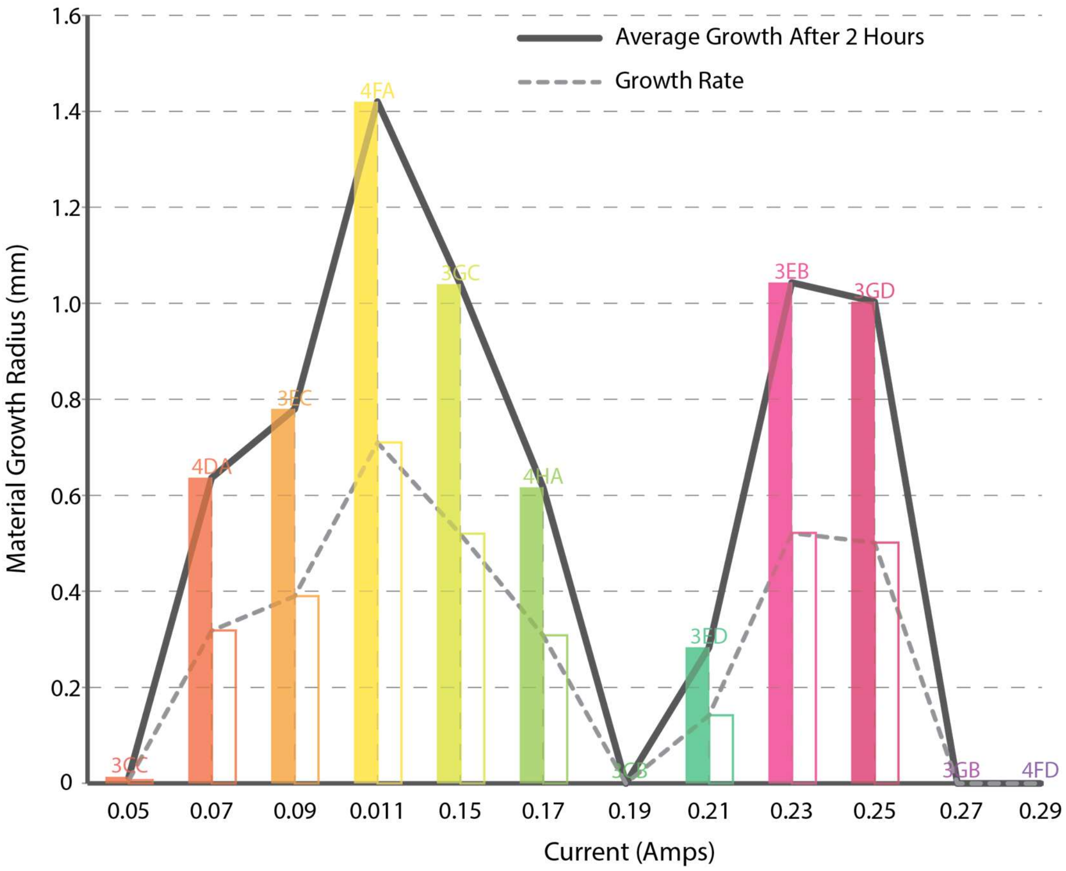


Figure 48: Graph reveals an initial trend, in which material growth amount and rate increase as voltage/current increases, cannot be sustained due to the material's increasing fragility.

7.6.3 Material composition & decay results

Comparing growth rates with the material composition graph obtained from XRF analysis (see Figure 49) 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 49 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 50 shows that *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 48 with Figure 49 reveals *varying mechanical strengths* and *compositions* are achieved as a result of varying voltages supplied to the cathode elements. As the 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. Additionally, this fragility was further revealed as the material deteriorated once it was taken out of the tank as a result of the solution’s surface tension. The varying material resiliencies and rate of decay establish that varying material qualities and functionalities can be achieved by altering the environment (voltage) as materials grow.

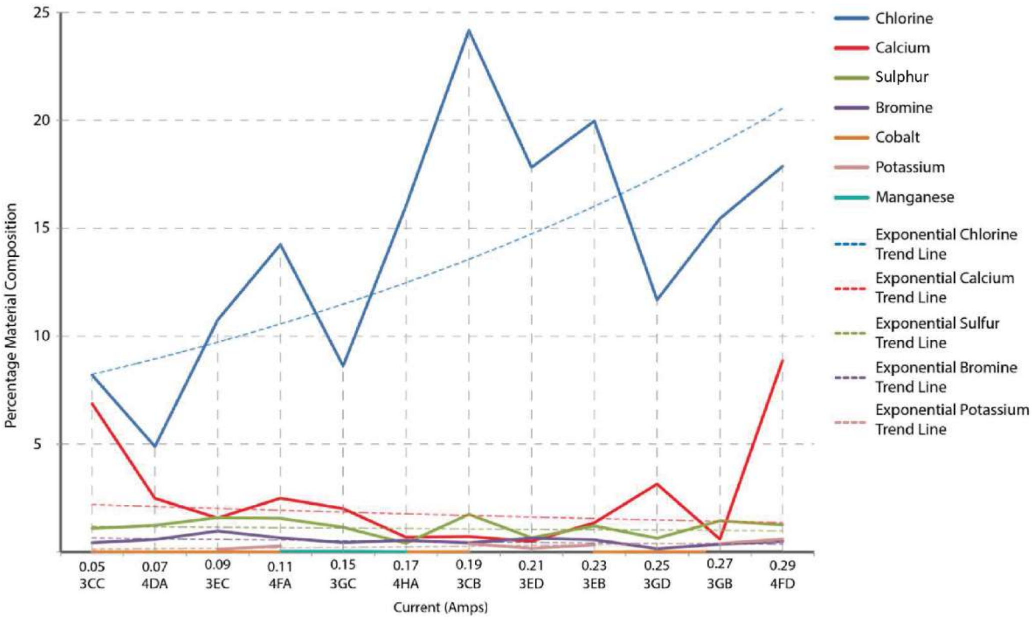


Figure 49: XRF analysis graph for material probe 04 shows the cathodes supplied with varying voltages reveal that the material composition can be tuned by varying voltages. An increase in voltage results in an increase in chlorine with the reduction of all other materials.

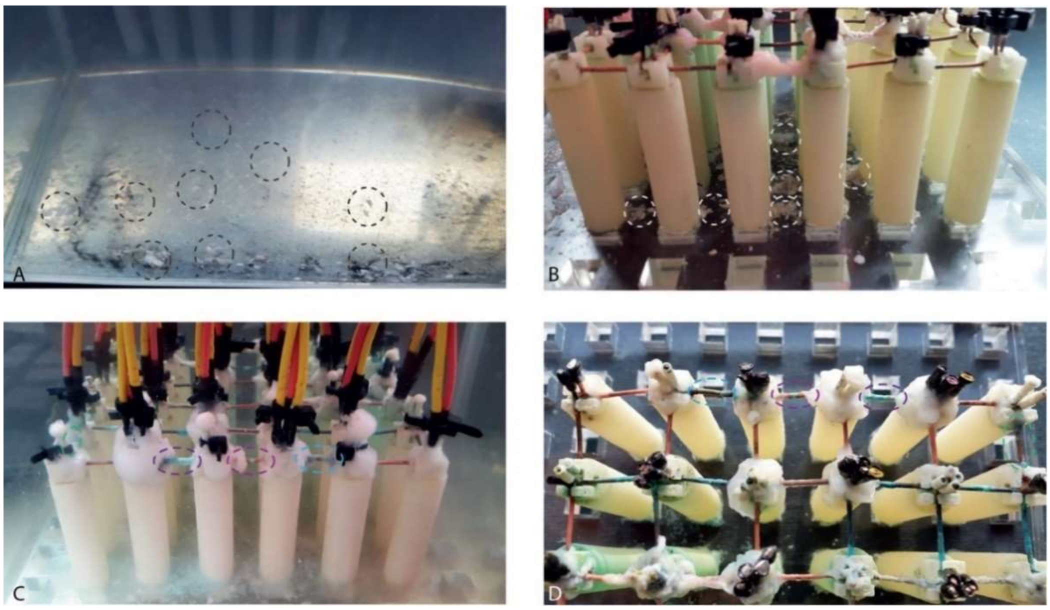


Figure 50: Material decay. A & B) material growth would decay away from the elements of the cathode as it grew. C & D) material decay became more apparent as the voltages increased.

7.6.4 Material probe 04: Conclusions

The 2D grid cathode material probe has shown that growing structures through aggregation achieves two major benefits: 1) the structures can be grown within a 2D matrix scaffold, which can change shape and material properties globally or locally due to the two separate growth phases; and 2) the fabrication process is scalable as the material deposited on the scaffolds is based on the self-assembly of molecules that make up the material aggregated.

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

7.6.5 Cathode typology

Significantly, the results obtained establish that it is possible to grow structures and patterns from an abundant base material (seawater). The 2D grid cathode typology can 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, which shows 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 as the orientation of the cathode elements are all in the same plane. Significantly, inducing turbulence within the material system at early stages indicates that 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 Material probe 04: Development & Discussion

The material probe is analogue in regards to how the heart shape pattern was generated as well as how the stimulus was controlled to grow the shape. This introduces the challenge of being able to control the parameters of the stimuli with more accuracy and raises the question to be explored in the following material probes: *How can modulating parameters of stimuli be automated and associated with data or design tools?* 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 induced via hardware, which can be controlled by a digital design tool. For this reason, the following material probes will incorporate Arduino microcontrollers with data or design tools to induce and ultimately monitor stimuli and their 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 its 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 material probes aim to show a 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; and 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 self-assembly when using material units without pre-designing their properties.

The 2D grid Material Probe, 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 material's adaptive abilities and the development of the system to be 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 Material probe 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 processes, which utilise inert materials, or impose form upon materials, removing the material's 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 design's processes (sketches, models, digital models) and final physical objects are emphasised. The relationships between the two allow time to be accounted for so change can occur, enabling feedback between design and physical structure (Ayres, 2012b). The two material probes within this section attempt to extend the role of *persistent modelling.* They do so by employing stimulus to connect digital parametric design tools with self-assembly to grow desired volumes.

The reconnection between the 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 material properties (e.g. composition, surface texture, highlighted in material Probes 01 - 03) and the structure's 2D/3D *global shape* (e.g. location of material, volume, rate and aesthetics, highlighted in material probe 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 material's 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 resolution of molecules; consequently, structures are highly granular, i.e. they are generated from a bottom-up process, which leads to emergent results that could be highly desirable.

The material probes discussed in this section are material probe 05: *Grown by Data* and material probe 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 duration are automated. The main question explored through these material probes is: *How can digital parametric design tools be used to guide self-assembly processes of material units that do not have pre-designed properties?* Exploring this question and examining the results from material probes 05 and 06 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'.*

7.8.1 Generic material probe properties

Figure 51 documents the set-up for material probe 05 where the cathode wires and carbon anode are submerged in 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 material probe 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) was used to agitate the solution. The pump was set to its lowest speed setting in an attempt to reduce the amount of turbulence-induced at early stages so initial material growth was not inhibited or destroyed.

Figure 52 documents the fabrication process for both material probes 05 and 06. The jig which physically separates 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 signifies 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 material probe. Additionally, 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 53.

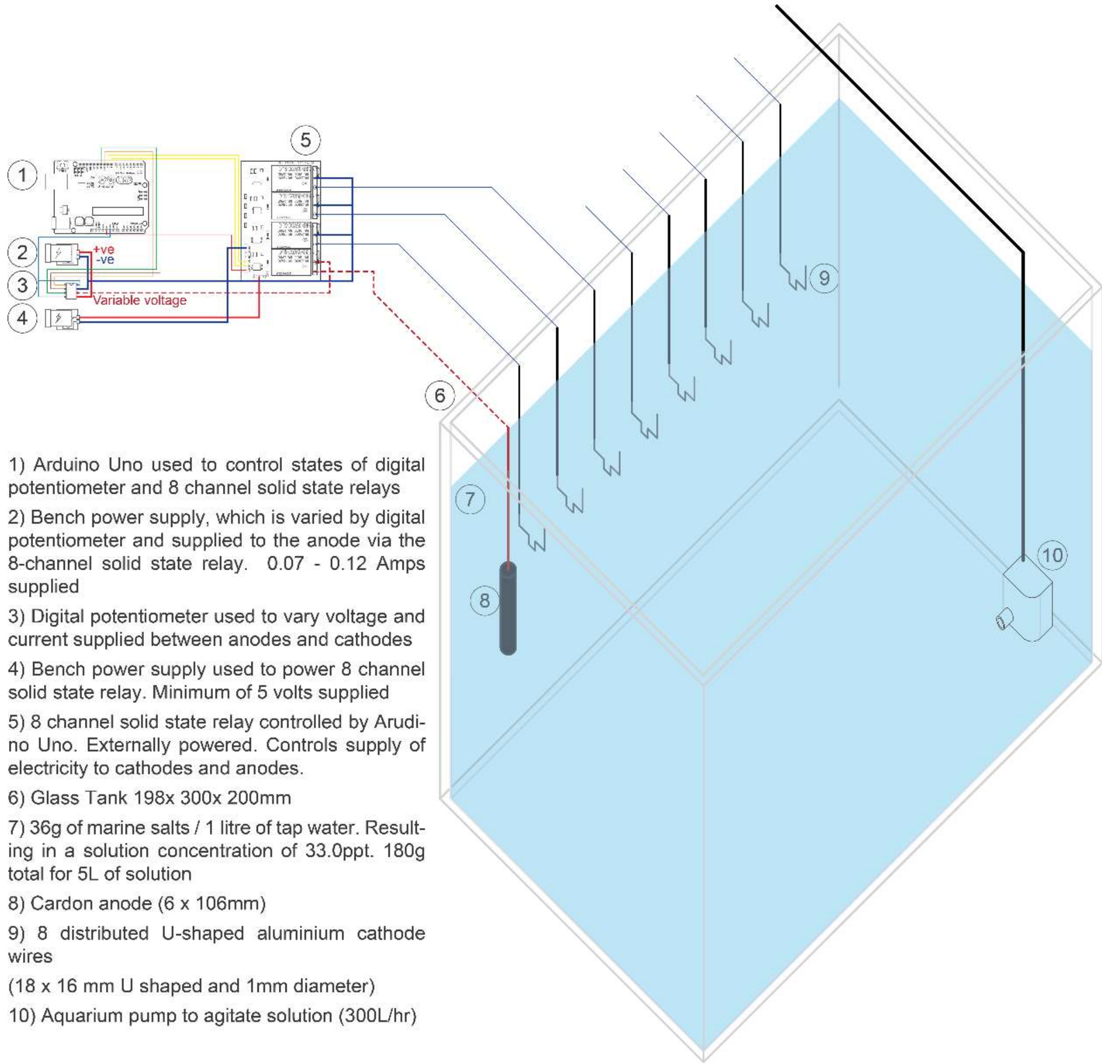


Figure 51: Material probe 05 set-up of eight individual wire cathodes wires. The material probe automates the growth process using Arduino to control hardware that induces the stimulus upon the system. The Arduino controls the systems stimulus/hardware components based on the solar systems planetary data.

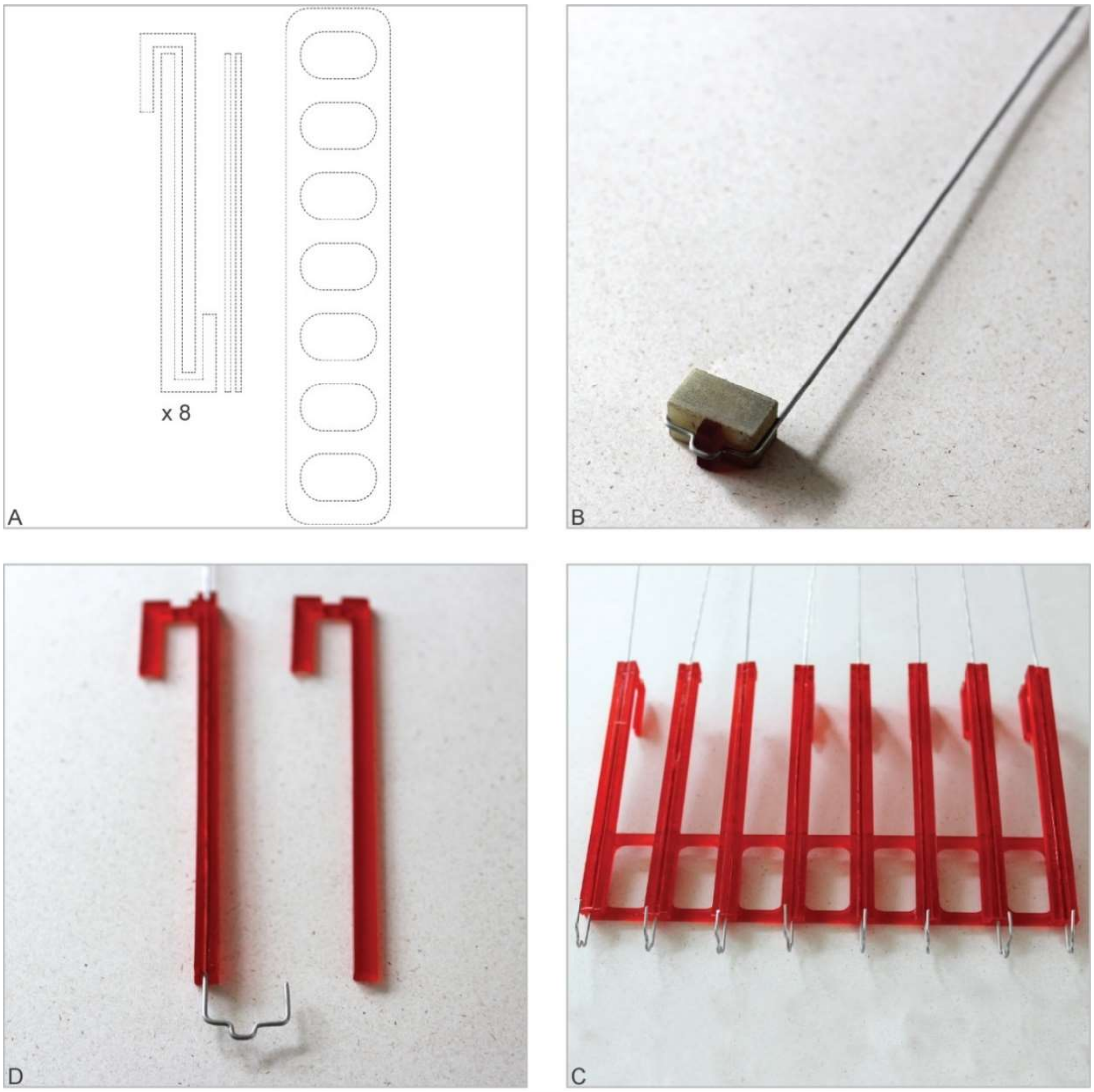


Figure 52: Laser cutting cathode jigs for material probe 05 and 06. ***A****) Components designed in illustrator and laser cut.* ***B****) Aluminium wires rolled on sandpaper to roughen up their surface as well as straighten the wire. Roughened end then shaped around a jig by hand to ensure all 8 cathode wires are the same dimensions.* ***C****) The individual cathode wires are then insulated using electrical heat shrink tubing up to 15mm of the cathode wire shape to prevent growth on those areas. Cathode is then placed in the jig, which is then glued together.* ***D****) Jig components holding the cathode are then spaced equidistantly apart from one another. Aluminium wire total dimensions 8 x 250mm x 1mm diameter.*

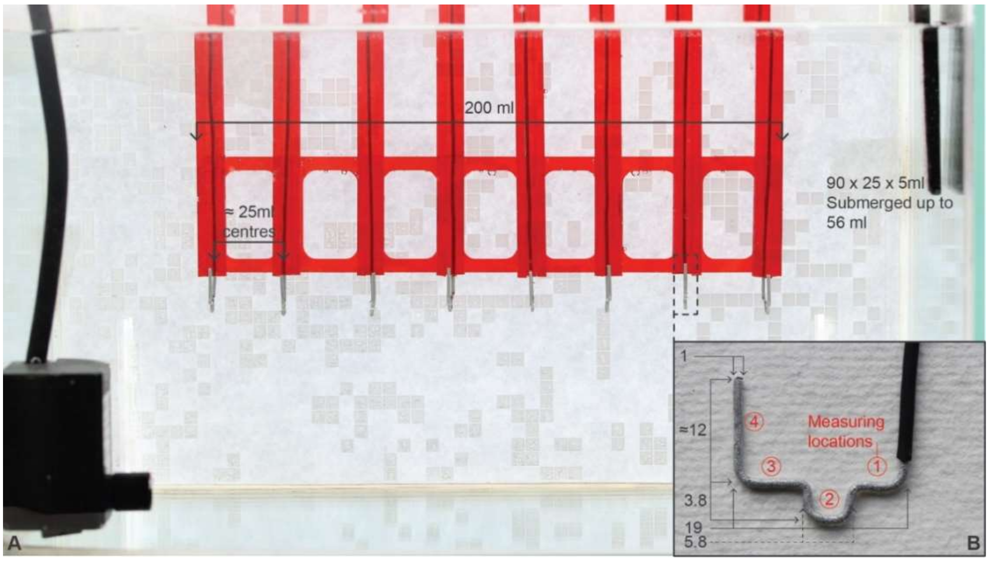


Figure 53: Material probe 05 and 06 set-up. A) 8 U-shaped aluminium cathode wires suspended within 5 litres of seawater solution. The cathode wires are equally spaced by containing them within a laser cut jig. B) Surface texture and modified U-shaped cathode wire to focus material growth. Locations of growth measurements also noted.

To explore the question of automating the growth process, both material probes 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 material probes' 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 of material (see Figures 54 and 57). To control if voltage is supplied to the individual cathode wires a 5V 8 channel relay module[5] is used, 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

[5] 8 channel 5 volt solid state relay module for Arduino from miniinthebox.com

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 material probe, the Arduino is programmed or interacted with differently, which dictates the duration of voltage supply and its magnitude. For material probe 05: *Grown by Data* the Arduino is *'hardcoded'* with values to govern voltage. For material probe 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 material probes will demonstrate the data or design tools can inform material self-assembly and for part of the system's interrelationships.

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

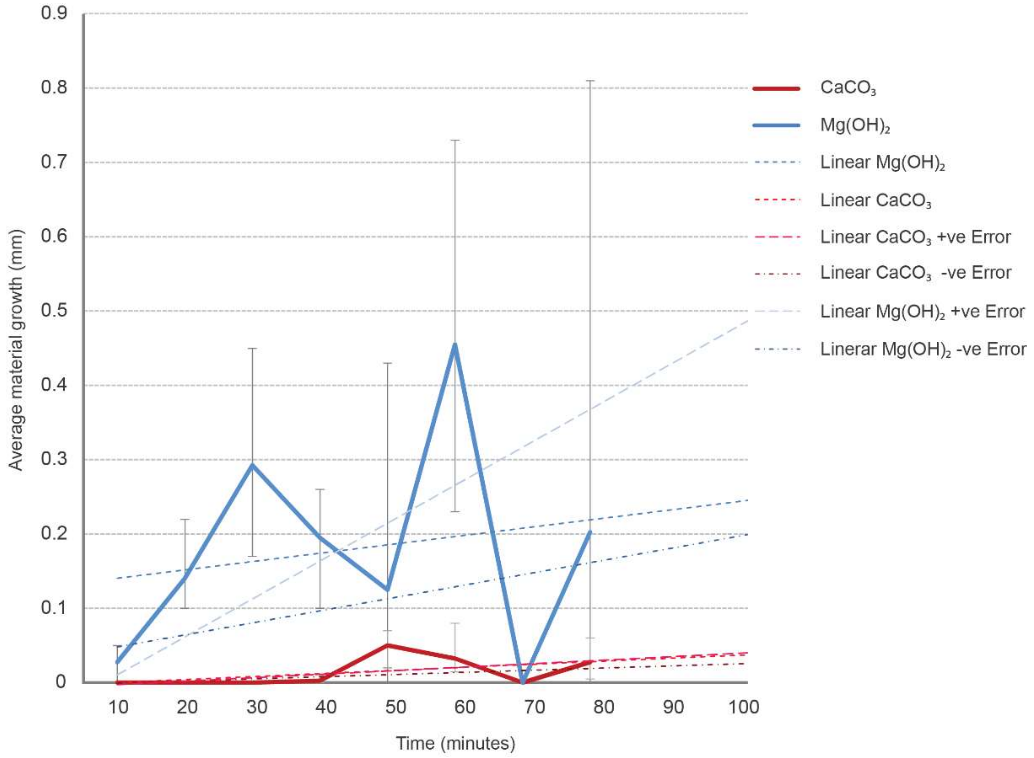


Figure 54: Preliminary results for growth volumes over 80 minutes. The data is used to predict growth durations in both material probes 05 and 06.

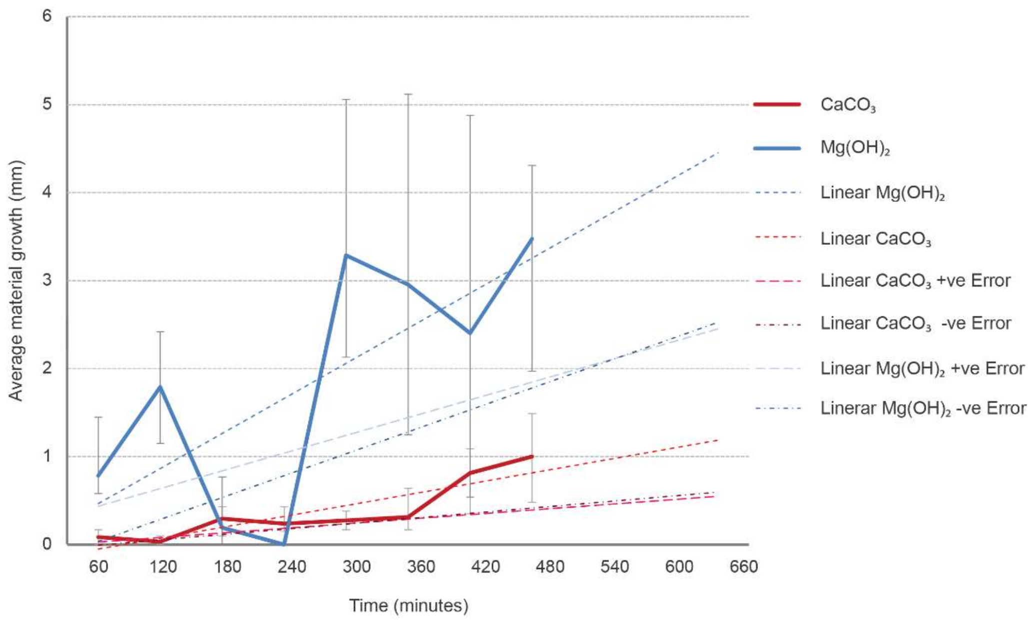


Figure 55: Preliminary results for growth volumes over 8 hours. The data is used to predict growth durations in both material probes 05 and 06.

7.9 Material probe 05: Properties and Data Values

In order to test if self-assembly can be automated when using material units that have not been pre-designed, material probe 05 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 56). For example, the planets Mercury to Mars are rocky, so the material to be grown will be the harder calcium carbonate (lower voltages). 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 magnesium hydroxide (higher voltages). The 4 cathodes representing these planets will be supplied with 0.12 amps. The current is controlled by the digital potentiometers. Again the duration for which each cathode wire is supplied with voltage is determined by preliminary results. Figure 56 projects the required durations to grow the desire volumes to represent each planet. These data values are hardcoded and loaded onto the Arduino microcontroller.

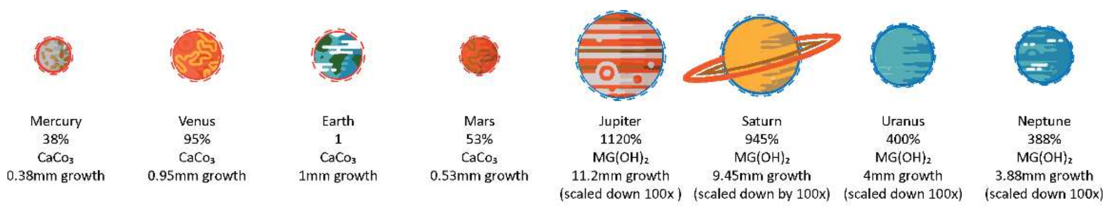


Figure 56: Data based on the size of each planet in the solar system relative to Earth and their composition.

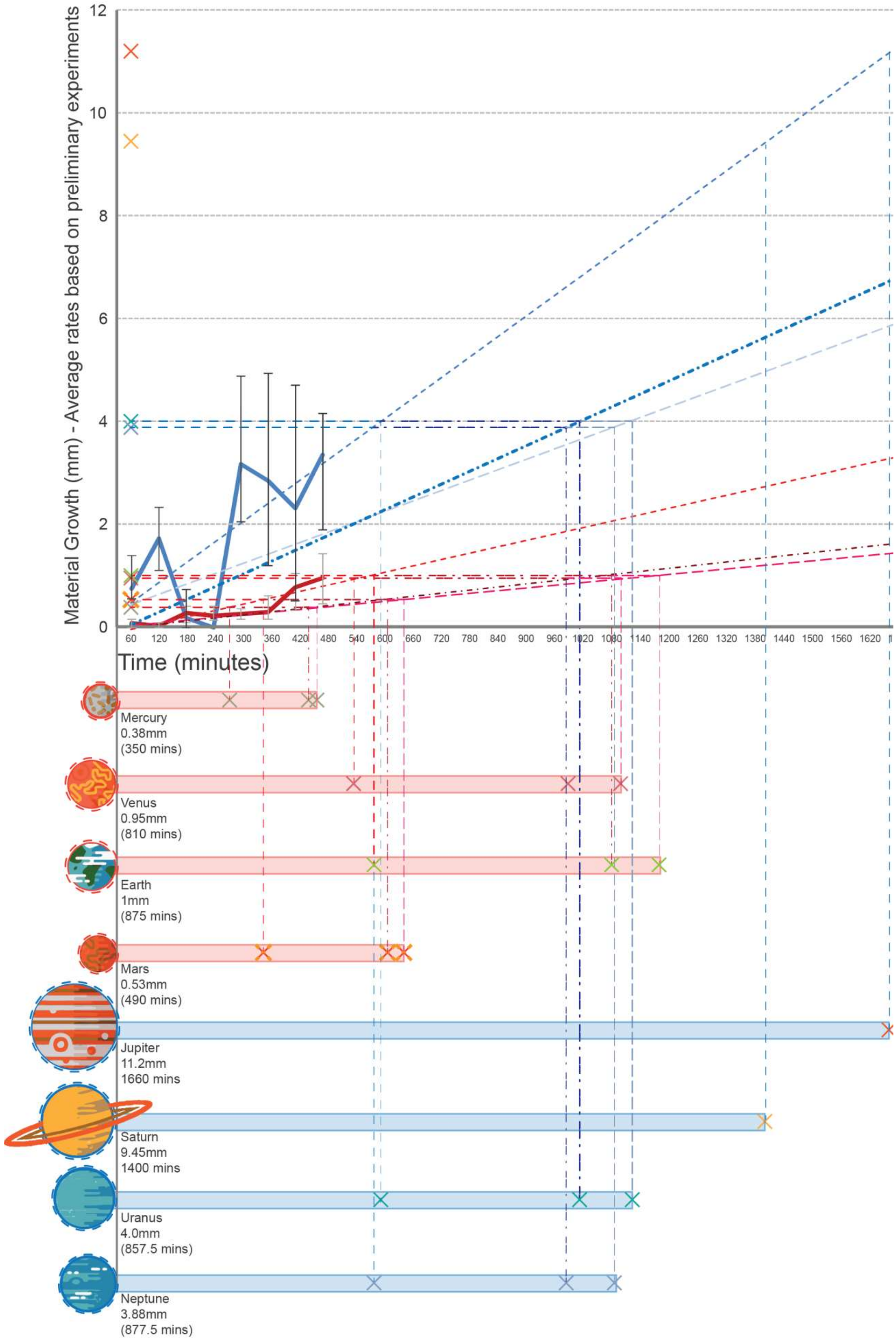


Figure 57: Predicting planet growth times based on the linear projections of preliminary tests.

7.9.1 Material probe 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 58 illustrates multiple points;

- *First,* the volume of material grown can be governed by the amount of time the relay is switched on. The volume of material grown increases over time except for wire 6, which represents Saturn.
- *Second,* an increased rate in material volume growth occurs, 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.
- *Third,* 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 deplete over time and need to be maintained; 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 indicated 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 59 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 voltages. Significantly these varied surface textures are manufactured by the materials themselves, which indicates 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.

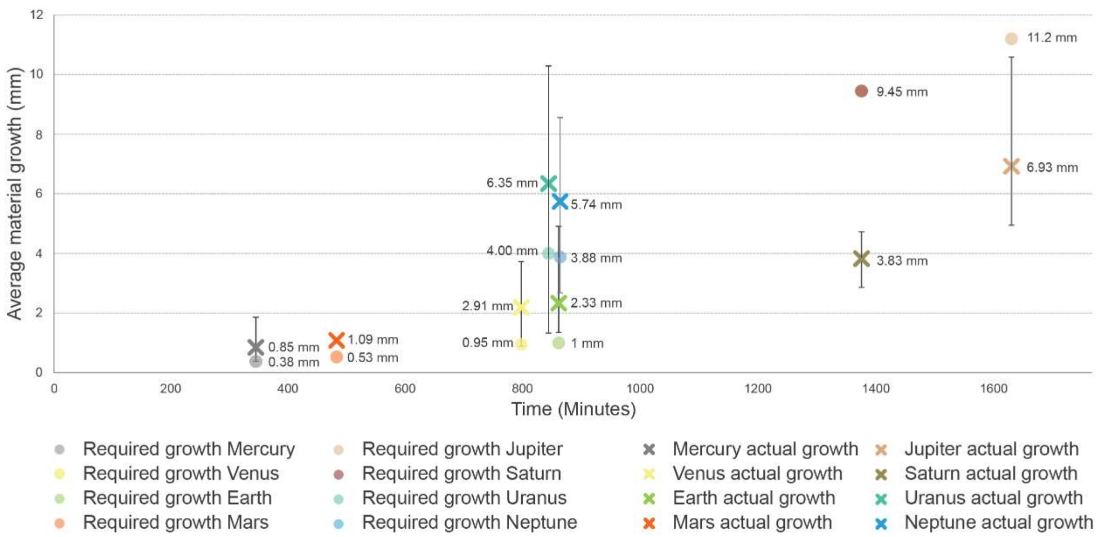


Figure 58: Growth volume graph from material probe 05: grown by data. The results show the required planet volumes compared to the actual growth results. Digital Vernier are used to measure the material volumes grown.

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

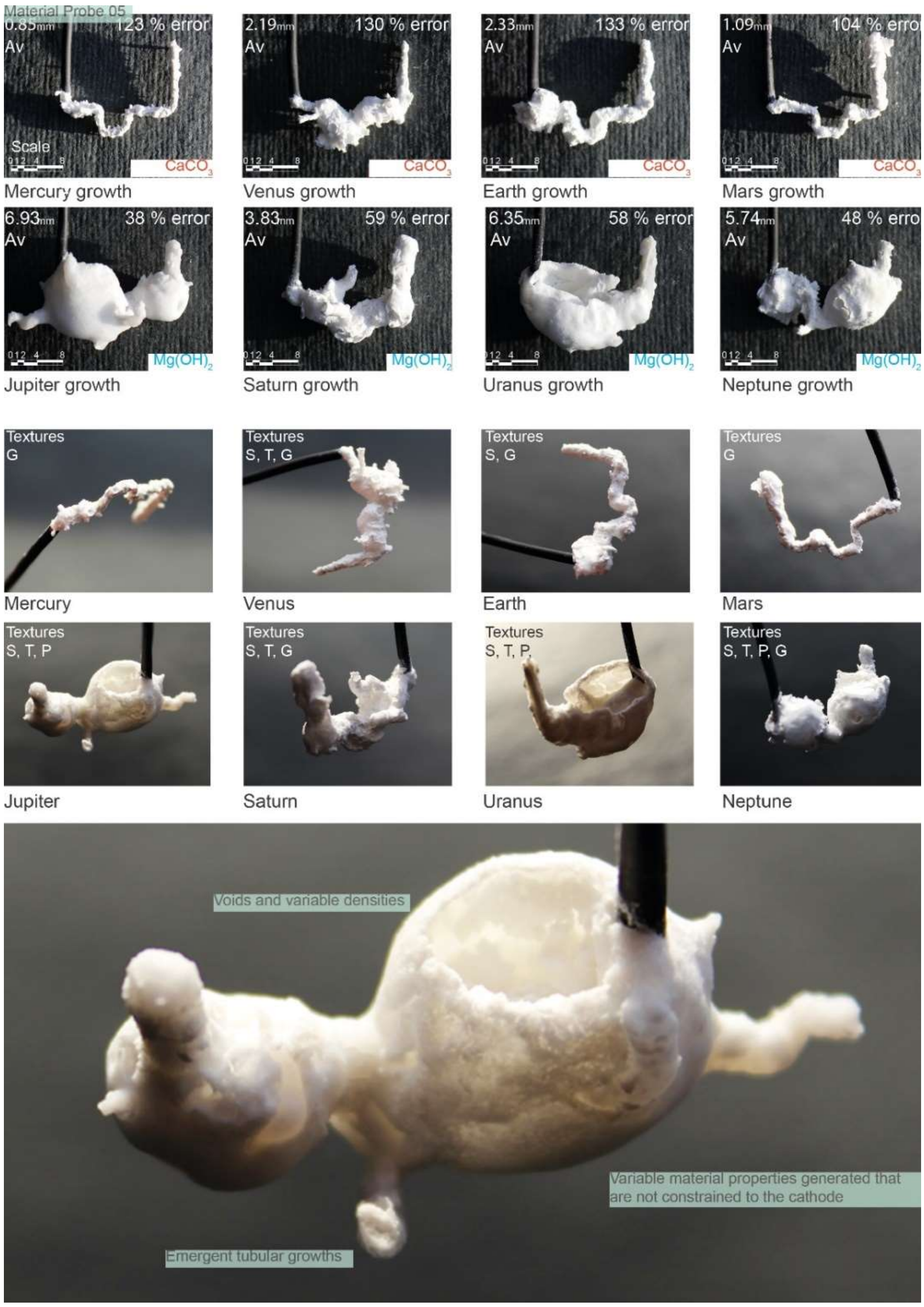


Figure 59: Emergent material properties generated. The first two rows of photographs highlight the various growth volumes achieved, which generally all increased with longer durations. The final two rows highlight the diverse range of emergent surface textures being generated. Interesting, the Jupiter - Neptune cathodes have more porous structures in comparison to the Mercury - Mars cathodes. The images demonstrate data can be used to guide properties' material self-assembly.

7.9.2 Material probe 06: properties and data values

A second material probe 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 self-assembly predominantly via modulating parameters of stimuli associated with parameters of digital parametric design tools would extend the abilities of *persistent modelling* (Ayres, 2012b). Figure 60 displays the set-up for material probe 06, while Figure 61 denotes how the digital design representation corresponds to the physical representation. The material probe 06 looks to extend material probe 05 by three main objectives;

- *First,* if discourse and relationships between digital parametric design, fabrication and material self-assembly can be established through induced stimuli.
- *Second,* 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 a 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 test and the results recorded from material probe 05.
- *Third,* 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.

The set-up for material probe 06 remained the same regarding the solution and hardware components used in material probe 05. 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 circle’s diameter and can be continually altered by a slider. The diameter informs the duration the relay is switched on; 2) the type of material to be grown is determined using the buttons, which governs the digital potentiometer's resistance value.

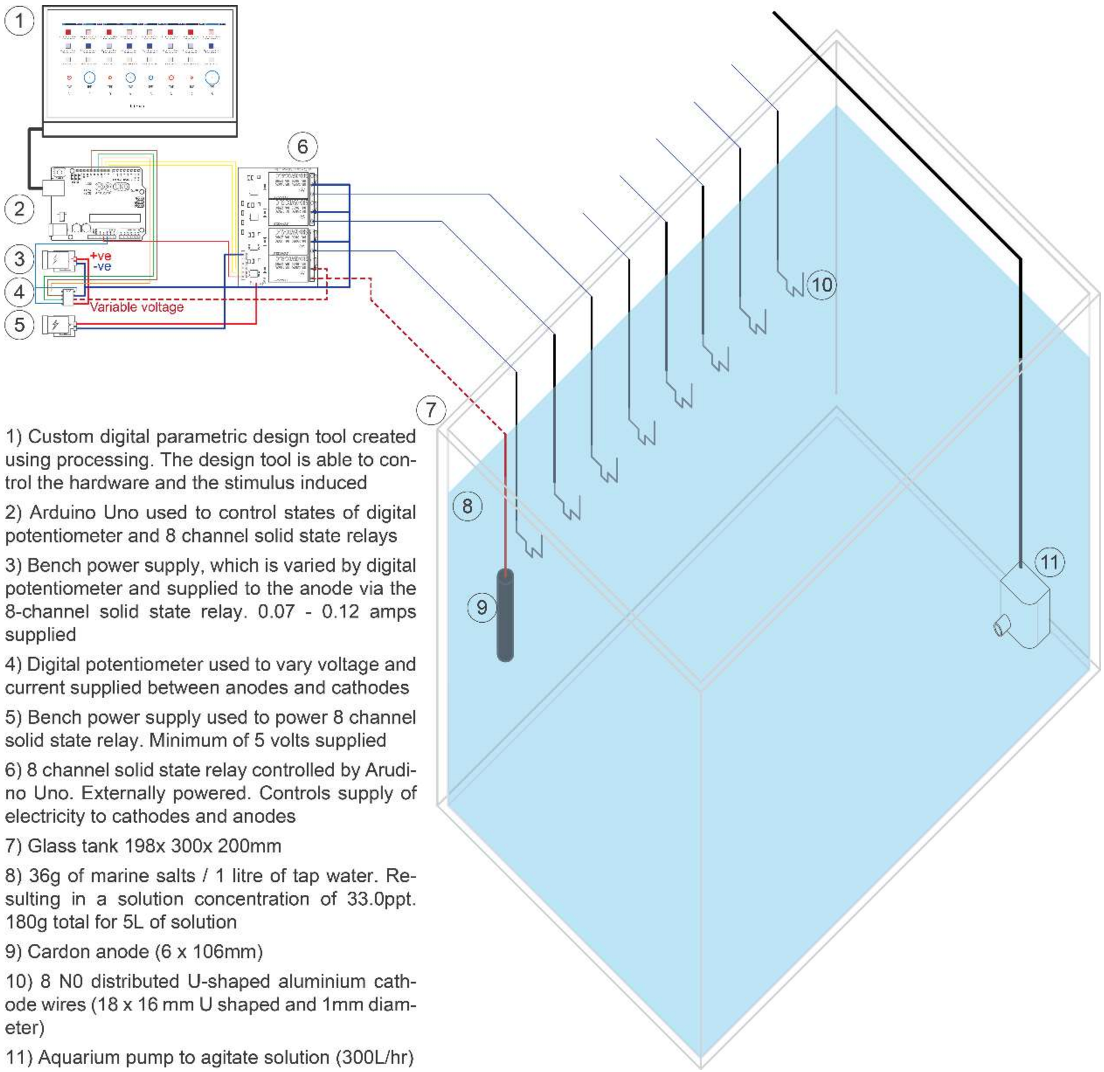


Figure 60: Material probe 06 set-up of eight individual aluminium cathodes wires. The material probe automates the growth process using Arduino to control hardware that induces the stimulus upon the system. The stimuli are controlled by hardware and the stimulus parameters are based on associations made with a digital parametric design tool that was created using processing.

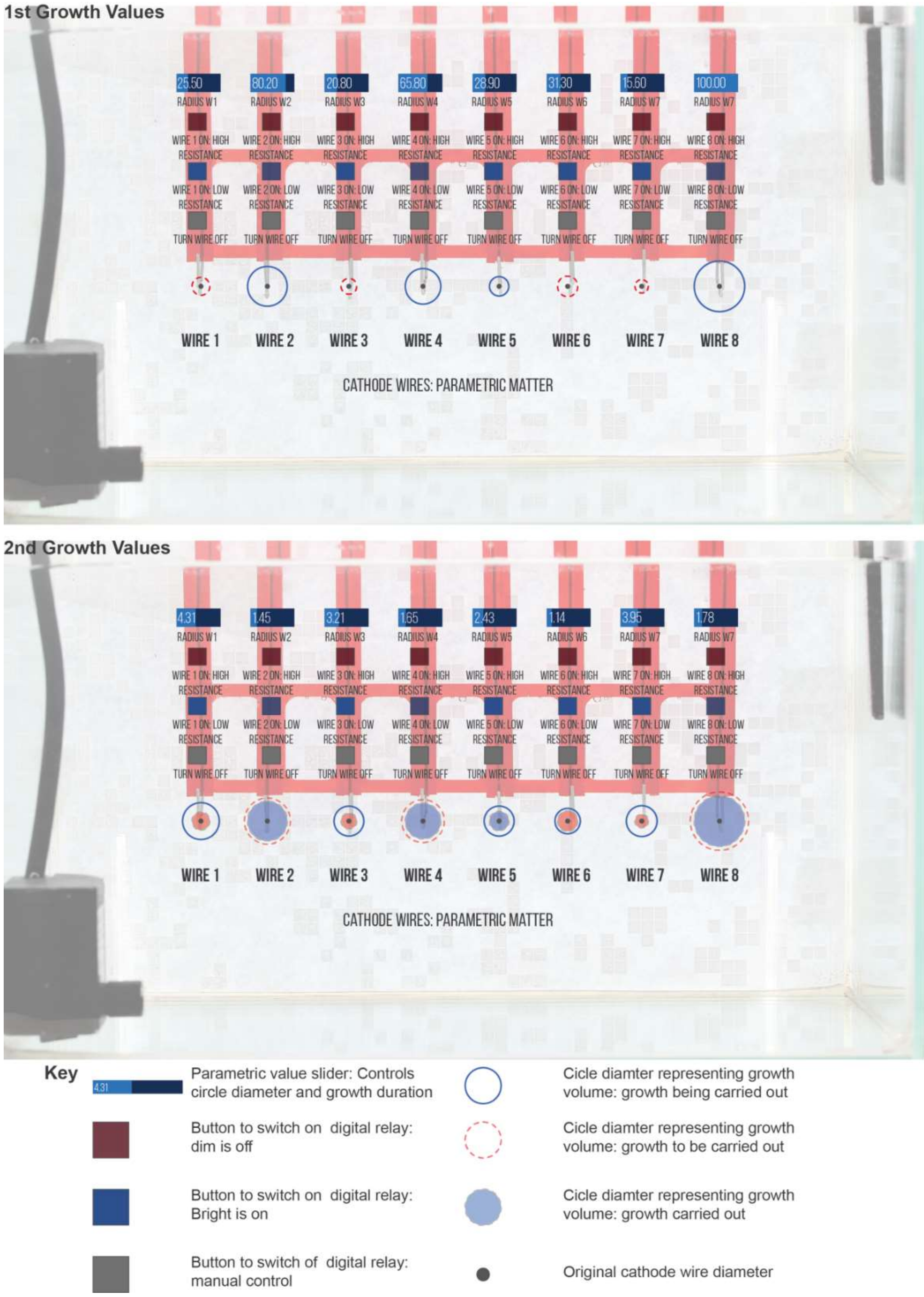


Figure 61: Digital parametric design interface used to govern material growth overlaid on the cathode jig set-up. Circle diameters represent the desired volume to be grown. The red coloured circles represent calcium carbonate with the blue colour representing magnesium hydroxide.

7.9.3 Material probe 06: material volumes & growth rate results

Material probe 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, unintended 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 62 and Table 6 document the discrepancies between desired material growth and actual material growth for both instances of this material probe.

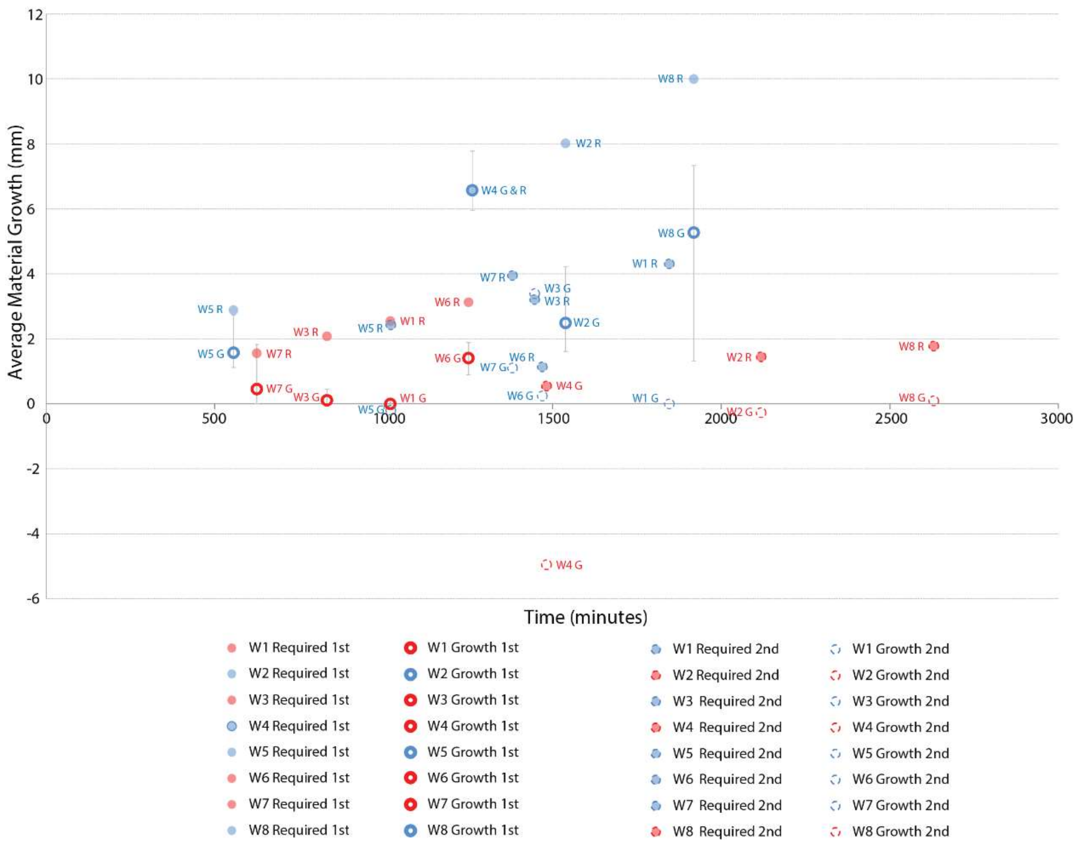


Figure 62: Graph of material growth volumes governed by a parametric design tool. Digital Vernier measured material volumes.

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

- Figure 62 reveals the reduced growth rates of calcium carbonate during the first growth period. The reduced growth rate was a result of growing the magnesium hydroxide first. This shows that material resources within the solution were depleted resulting in a slower calcium carbonate growth rate.
- Figures 62 - 66 also reveal the ability to instil the shape-changing capacities present with digital design into physical material because of the altered material volumes grown.
- Figure 62 and Table 6 illustrate that 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 magnesium hydroxide. Material decay occurred on the wires that had grown magnesium hydroxide 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 magnesium hydroxide. 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 determining 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 that materials can be tuned and controlled by a parametric tool but without removing material the changes become less apparent and slower. 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 as a result time- based average growth rates are not accurate.
- Table 6 and Figures 65 and 66 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 material's 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**
1st						
Growth	1019.16	2.55	0.00	0.00	255.0	Na
1	1538.67	8.02	2.50	0.0016	31.11	S,G
2	831.32	2.08	0.11	0.0001	94.59	G
3	1262.40	6.58	6.57	0.0052	0.11	S,T,P
4	554.46	2.89	1.58	0.0028	45.42	S,G
5	1250.97	3.13	1.40	0.0011	55.19	S,P
6	623.49	1.56	0.46	0.0007	70.67	S,G
7	1218.54	10.00	5.67	0.0030	43.35	S,T,P,
8						G
2nd	826.89	4.31	0	0	431.0	
Growth	579.52	1.45	-0.27	-0.0005	-81.4	Na
1	615.85	3.21	3.39	0.0055	5.6	G,T
2	659.46	1.65	-4.95	-0.0225	-300	G,T
3	466.21	2.43	-0.19	-0.0004	-92.2	G,P
4	218.71	1.14	0.24	0.0011	79.0	S
5	757.82	3.95	1.11	0.0015	71.9	G
6	711.42	1.78	0.09	0.0001	95.0	S,P
7						S,T,P
8						

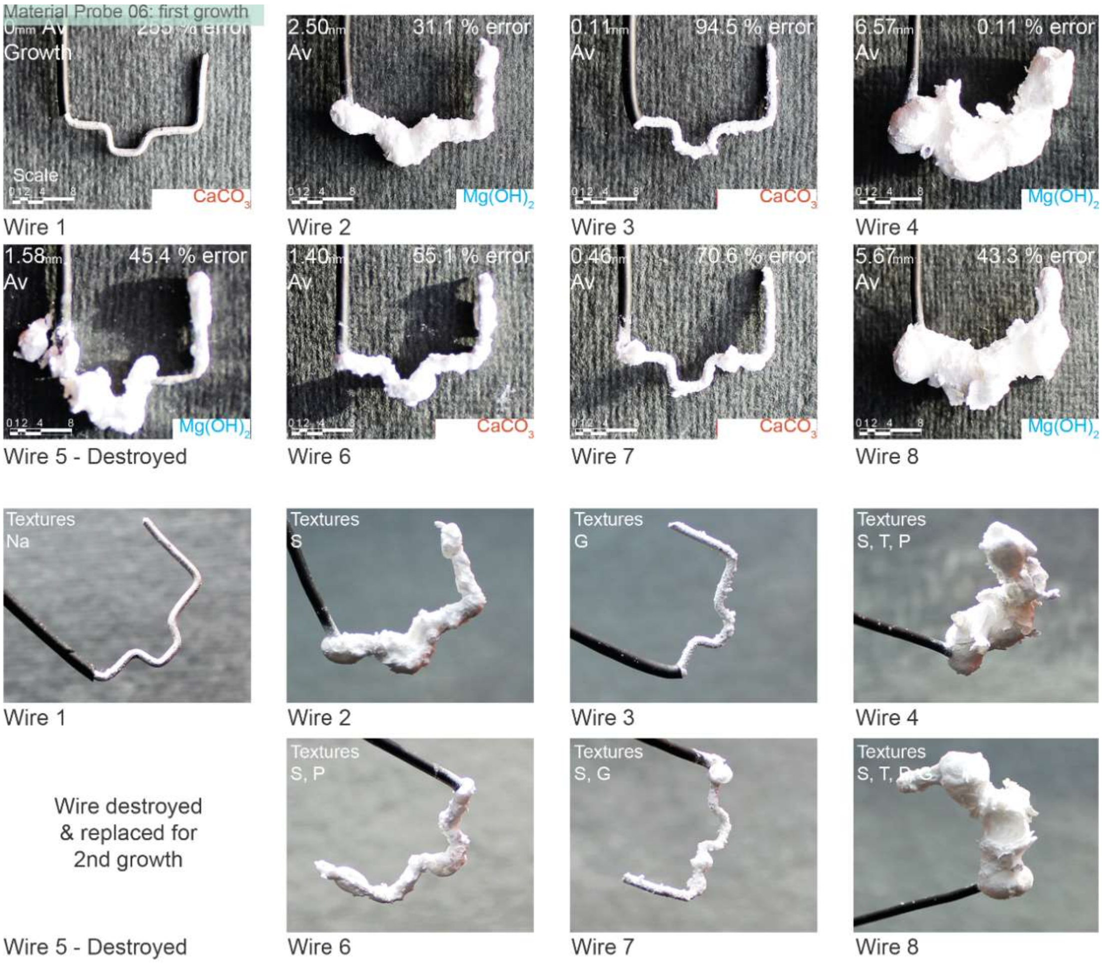


Figure 63: Emergent material growth results from material probe 06. The first two rows compare growth volumes. The last two rows show the varied and emergent textures generated.

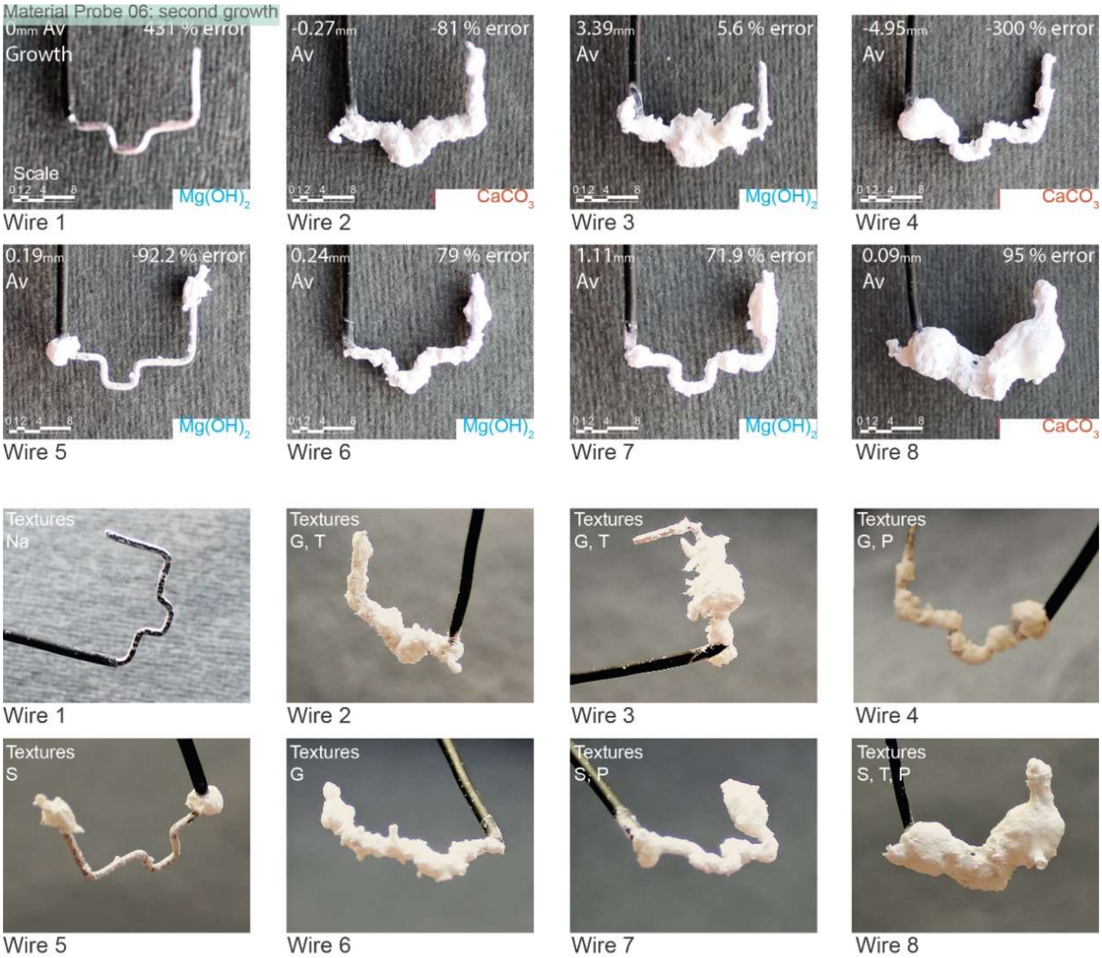


Figure 64: Growth results of material probe 06 after second growth. The first two rows compare growth volumes after second-growth instance. The last two rows show the varied and emergent textures, which have been altered and tuned compared to the first.

7.10 Material probe 05 & 06: Conclusions

Material probes 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 results of each material probe reveal a major benefit of growing materials by inducing environmental stimulus, which is, that material computational processes are produced and engaged with during the fabrication process as well as throughout the structure's 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 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 building's walls being able to increase its material volume, mass and structural capacities, which could increase the building's 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 the energy demands required by the materials to self-assemble and adapt are low and can be generated using renewable means in-situ i.e. within the building itself, e.g. solar power

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 change 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, 1) defining interrelationships between design, fabrication and material properties based on mapping material parameters between induced stimulus, resultant environmental conditions and relevant design properties; 2) 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, and 3) 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

To develop more accurate growth volumes and textures, future work will require interrelationships to be defined and discovered within design and fabrication processes that utilise material self-assembly, or material units that do not have their geometries and interfaces defined. Interrelationships need to be defined between induced stimulus, resultant environmental conditions and material properties. For example, material probes 05 and 06 have highlighted that the solution's salinity and material resources required to grow materials reduce over time within the closed system. As a result, solution salinity must be maintained to sustain material growth. Additionally, if the solution's salinity reduces so does the electrical conductivity of the solution. Thus, 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 sensors directly around the cathode, due to material growth encasing each sensor wire and insulating them against an electrical signal sent to 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.

All of the material probes (01 – 06) carried out up to this point have not explored what mechanisms or phenomena exist within the mineral accretion process to develop and determine how feedback can be achieved between relationships and parameters of design representations, stimuli, resultant conditions and material properties generated. A previous experiment carried out by Hilbertz et al. (1977) showed that as material growth increases in volume, it acts as a contrasting effect to the stimuli induced i.e. material growth insulates the cathode. As a result, material volumes grown over time can be determined by incorporating a series of sensors around the cathode, which effectively embeds the sensors in the material (Hilbertz et al., 1977).

To understand how interrelationships within the system have developed so far throughout the series of Material Probes, the following two sections will discuss how associations between interrelationships can be determined and further explored within the next material probe iteration.

7.10.2 Development: reliability

Predicting growth rates based on time resulted in unreliable results because there are too many variables that alter within the system, which impacted drastically on 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 to a cathode material would grow and increase in volume. This raises the question to be explored in the flowing material probe*: How can certain material properties be determined in real time and associated with parameters of stimuli and resultant conditions so material growth be guided more accurately?*

It has been illustrated 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). This shows that various sensors could be used to monitor *resultant conditions* during the mineral accretion process. The sensors could monitor changes occurring within the solution (e.g. pH, salinity, temperature) as well as *conditional changes/contrasting effects* that occur locally on the cathode (e.g. electrical current), 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 that their parameters can guide material properties generated more reliably, as well as understand how associations can be made to develop feedback between material properties, stimuli and design parameters. This raises the question: *What sensors are required to monitor the main conditional changes that occur during the mineral accretion process, which significantly affect one another and impact on material volume grown?*

7.10.3 Development: understanding feedback between design tools, stimuli & material properties

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 material probe 07 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 volumes could 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, and 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 material probes 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. Here, structures can be grown and their 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 contains self-assembling materials. The idea of, and parameters informing, tuneable environments will be explored further in the following material probe iteration. Interestingly, *tuneable environments* may also extend the methodology of *persistent modelling* (Ayres, 2012b) as they can interact and maintain relationships with material properties and material self-assembly.

A published paper documents and annotates the development of the cathode typologies among other factors, can be found within the paper: *Designing Parametric Matter*.

7.11 Material probe 07: Developing an Adaptive Design & Fabrication System

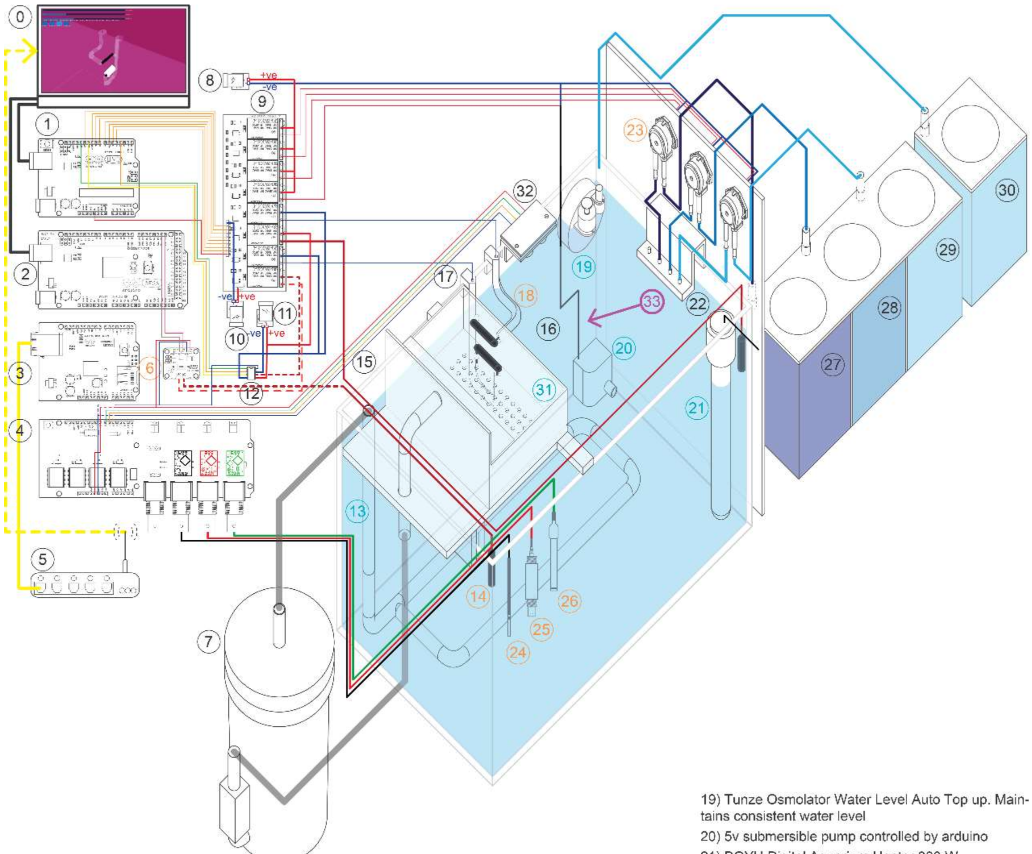
Material probe 07 is the final iteration to uses the mineral accretion process. This material probe aims to understand association and feedback mechanisms between design, fabrication, stimuli and material properties. Essentially, the probe is used to demonstrate how a *closed-loop control system* can be developed when using a material platform that generates interrelationships.

This section is structured as follows: *first*, an overview is given for material probe 07, which displays its set-up properties and fabrication processes used to create the cathode scaffolds. *Second,* the generic properties of the set-up are explained. *Third,* a description of the specific properties of each material probe that form this series. *Fourth,* the methods of analysis are presented together with how they are used to determine if material adaption occurs within the system. *Fifth,* the results are presented. *Sixth,* the conclusions are discussed. *Finally,* development and challenges are discussed.

7.11.1 Material probe 07: overview

Material probe 07 is the final iteration of all the previous mineral accretion material probes. The aim is to highlight new potentials of rethinking 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 combining them with tuneable environments can begin to enable feedback between the system's 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 material probe 07 is displayed in Figure 65. material probe 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. if the electrical sensor’s values decrease as material growth increases, whilst the solution’s resultant conditions are maintained. The database of values generated will reveal if conditional changes can have direct associations with digital design representation and can be used to enable feedback between design parameters, fabrication stimuli, conditional changes and material properties. Significantly, the design representations that are intended to be used to inform stimuli parameters are associative modelling strategies (e.g. parametric modelling), which are based on linear cause-and-effect relationships defined by the designer. This will highlight what types of design tools (e.g. associate modelling or non-linear strategies) are suitable for guiding self-assembling material platforms that create interrelationships. Furthermore, understanding conditional changes between the system's components can be used to further develop an adaptive design and fabrication system that can guide material self-assembly by modulating stimuli without having to pre-design properties of the individual material units that make up that material platform.



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 65: Material probe 07 set-up. Material probe 07 is used to monitor material volumes grown in relation to real-time sensor values, in particular electrical current sensor values. The aim is to generate a database of values that show if conditional changes occur relative to the increase of material growth. These conditional changes can then be used to establish if feedback can be determined between direct/linear associations and interrelationships of material properties and stimuli, which can then be related to digital design tool parameters.

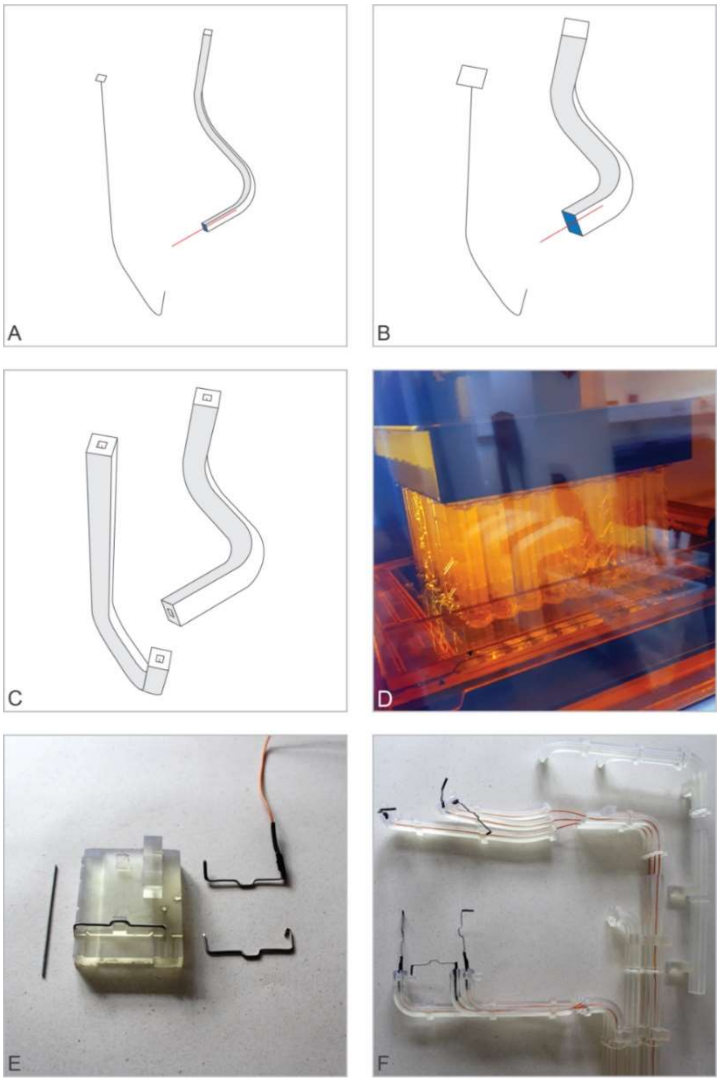


*Figure 66: 3D printing cathodes using single material stereolithography (STL). **A**) 3D model created within sketch-up. Hollow internal paths are created pulling a diamond shape along the desired network of paths using the 'follow me' tool. **B**) The same process is repeated for the external surfaces using a large diamond shape. **C**) The two shapes are then combined. **D**) The digital model is 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 an insulated electrical wire. Carbon cathodes are cut by hand, then wrapped with copper wire, which is then soldered to an insulated electrical wire. **F**) Wires are fed through the 3D printed sections, which are then glued together.*

7.11.2 Material probe 07: properties

This section will outline the role played by each component, stimuli and resultant effect in material probe 07 and how they can be used to build towards an adaptive design and fabrication system in relation to guiding parameters of the mineral accretion process. Significantly, the sensors are incorporated externally to the materials/cathodes, this is done to determine if material platforms that self-assembly can: 1) emit signals, and 2) can be guided without having form imposed upon them.

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). Material probe 07 only deliberately induces voltage/direct electrical current as the stimulus to guide material properties (volume and location) of the mineral accretion process. However, as mentioned previously, various conditional changes occur during the mineral accretion process that affect one another. Various sensors are required to monitor and maintain consistent solution conditions as well as determining differences in electrical current supplied to a cathode and values recorded as material growth volume increases. The sensors incorporated into material probe 07, the reasons for using them, and the parameters of the component (e.g. solution) are:

Parameters for maintaining a consistent solution by monitoring *resultant conditions:* Solution 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 marine salts dissolved into it, which forms the base solution of the material probe. To maintain a consistent solution, electrical conductivity (hereafter EC) and pH will be dosed in during the mineral accretion process chemicals, based on sensor values and defined thresholds. Tap water is used as it is readily available. The resultant effects that occur within the solution during the mineral accretion process that can have a significant effect on electrical current readings recorded between the cathode and anode as material volumes are grown are: 1) solution conductivity, 2), solution pH, 3) solution temperature, and 4) solution volume. The effects of these parameters and how they are monitored are now discussed.

- **Solution conductivity:** The base solution will have to have its electrical conductivity monitored via an electrical conductivity probe.[6] The readings 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 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 surfaces of the cathodes and anodes (Hilbertz, 1979). Significantly, if the base solution's composition (among other conditions) is not maintained, the solution's conductivity reduces, producing anomalous and unreliable results from the electrical current sensor, which are used to determine material growth volumes. Additionally, solution evaporation and temperature also significantly impact the base solution conductivity.
- **Solution pH:** Solution pH also impacts on the type of material growth, since anything greater than a level of 9.0 (Hilbertz et al., 1977) or 9.5 results in magnesium hydroxide growth predominating (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

[6] Conductivity Probe K1.0 by Atlas Scientific.

on the cathodes and anodes. The surface areas of the various cathode types compared to the carbon anodes are noted in Table 7. However, to maintain a consistent solution pH level, a pH probe[7] will be used to monitor these levels. The pH values recorded will be used to 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.

- **Temperature**: solution temperature impacts on the solution's conductivity (Hilbertz et al., 1977) with lower temperatures and lower pH levels promoting calcium carbonate growth (Hilbertz, 1979). Solution temperature will be monitored via a temperature probe[8] and maintained at a consistent temperature of (22.5-26°C) via an aquarium heating element.[9]
- **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 will be maintained using an aquarium auto top-off pump[10] and an ultrasonic sensor,[11] which will monitor the solution's volumes and is used to switch on and off a dosing pump.[12] Reverse osmosis water (hereafter RO) will be added into the base solution in the tank to maintain a specific volume. RO water is dosed in to maintain a solution volume as its electrical conductivity value is minor

[7] Industrial pH electrode by Haoshi bought from DF Robot
[8] PT1000 Temperature Probe by atlasscientific.com
[9] 200 watt aquarium fish tank heater from allpondsolutions.co.uk
[10] Tunze osmolator 3155 auto top off system from aquariteuk.co.uk
[11] Studio 101020010, Ultrasonic Ranger for Grove System from RSuk.co.uk
[12] DC 6V Water Pump Peristatic Dosing head pump from UKBanggood.com

comported to tap water so it won't affect the solution's electrical conductivity values significantly when added.

The electrical conductivity, pH and temperature probe are connected via Whitebox's tentacle shield [13] with the relevant isolated circuit boards [14] to prevent electrical interference. The circuits are set to i2c mode and data recorded at separate intervals so they do not interfere with one another. The sensor data is recorded using a second Arduino that does not receive information from a digital design tool. It is programmed to send information at set values via an ethernet shield. [15] The reason for having two separate Arduinos is so that communication between them is more robust; previous tests highlighted issues with sending and receiving data when using only one Arduino. The circuit diagram for the various probes and pump is featured in Figure 65.

Associating localised conditional changes/contrasting effects: relationships between electrical current and material volumes. Hilbertz established that electrical current consumption decreases over time as the material increases in volume (Hilbertz, 1979). Monitoring this conditional change/contrasting effect in combination with the solution's resultant conditions can be done via an electrical current sensor, [16] 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 and reduced electrical current readings can be used to 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.

[13] Whitebox's tentacle shield for Arduino from atlasscientific.com
[14] EZO™ Conductivity Circuit, EZO™ Ph Circuit and EZO™ RTD Temperature Circuit boards from atlasscientific.com
[15] Arduino ethernet shield 2 from Arduino.cc
[16] Adafruit INA260 High or Low side voltage, current power sensor from pimoroni.com

Time-lapse photography, preliminary results will record material volume growth using time-lapse photography to establish what material volumes correspond to electrical current sensor values as well as pH, temperature and salinity values of the solution.

Cathode deterioration, examining the cathodes from material probes 05 & 06 after the growth was completed, the cathode wires deteriorated, becoming fragile and prone to breaking. This could impact the reliability of the electrical current readings used to determine if a desired growth volume has been achieved. Additionally, it also limits the duration and amount of material that can be grown on certain material types. The cathode acts as a foundation and symbiotic type material, which is needed to support material growth that can tune and adapt its properties. To address this, material probe 07 will use two types of cathodes of different material types: 1) aluminium wires used in the previous probes (01 – 06), and 2) carbon cathodes[17] that have been manually cut to size. The different material types will help in understanding the effects of material type to prevent deterioration and hopefully enable sustained material growth.

Motion capture: if electrical current sensor readings do not prove to be successful, an alternative to electrical current sensor readings to determine growth volumes could be live motion capture data. Live motion capture data is not preferred initially, since only material volumes can be detected and no other material properties generated. For example, how can the same volume of magnesium hydroxide or calcium carbonate growth be determined, a property that may be discernible via electrical current sensor readings? Additionally, motion capture may become redundant when using more complex 3D cathodes as it could become difficult to obtain a clear view of lots of cathode wires within the 3D space. However, the combination of

[17] Carbon electrodes from hope-education.co.uk

motion capture with electrical current sensor readings could improve the reliability of desired material growth properties.

Ayres establishes the ability of design tools to induce stimulus upon physical materials, and monitoring the 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. 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 material probes 05 and 06. These probes 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, thus enabling control over the location of material growth and automation.

Volume of material growth: the amount of time voltage 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, in the case of developing a *closed-loop control system* sensor readings, associated with desirable material properties grown. material probe 07 will be used to generate a database of sensor readings to determine if they can correspond to volumes of material grown, which can then be used to stop material growth when an average sensor reading has been recorded.

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 vice versa. Incorporating this piece of hardware would enable material build-up on a cathode to be completely removed from it, which would further enhance the shape-changing abilities of the cathode in regards to where the material is grown and also removed. However, this would require the cathode to be made from a non-perishable material like carbon in order 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 observations from material probes so far, the first instance of material probe 07 will supply 4.00 volts between the cathodes and anodes using a bench power supply unit. A preliminary test demonstrates that 4.00 volts initially result 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. These voltages are fixed and they will not be varied by a digital potentiometer, as used in Material Probes 05 and 06. Additionally, maintaining these voltages is to grow one material type, predominantly calcium carbonate based on previous material analysis of the Material Probes. This is again to generate more consistent and less complicated sensor readings so associations may be determined more easily. Finally, the intention is to supply voltage between the cathodes and anodes for 12 hrs. However, the voltages and duration will be reviewed after each material probe that make up material probe 07, especially if: 1) no significant sensor values are recorded; and 2) if no significant material growth is produced.

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, positioned vertically in-line, one above the other, to examine the impacts of material growth occurring on the 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 cathodes needs to be spatially organised. In material probe 07 two cathodes are separated and this means 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 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 fixed distance away from cathodes (≈355mm). The distance between anodes and cathode(s) impacts on the material type grown, where magnesium hydroxide predominates at locations where the cathode is closest to the anode (Hilbertz, 1979). Material probe 07 will use two different cathode materials with differing properties. The cathode material types are carbon and aluminium. Carbon is used since the aluminium wires appeared to deteriorate and disintegrate in material probes 05 and 06. The cathodes' material properties, dimensions and surface are highlighted in Figure 67 and Table 7.

Cathode wire connections: Numerous cathode wires connecting to the power supply should be spaced evenly to achieve more uniform growth (Hilbertz, 1976). However, the cathodes are individually separated and relatively small in comparison to the size of cathode structures used by Hilbertz. The single wire connection to each cathode has typically produced uniform growth in previous material probes 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 material probes 04, 05 and 06.

Solution agitation: In order to maintain a homogenous solution when chemicals are dosed into the solution as well as counteracting the effects of gravity, which causes the solutions ions to sink, a 3-6V submersible pump[18] 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, and for 2 minutes, after a 30 minute interval, if no chemicals have been added within that time. An aquarium filter pump[19] will also agitate the solution. 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 as was witnessed in all the previous material probes. 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 that the material that has been grown, which is composed of magnesium hydroxide and calcium carbonate, changes composition, where the percentage composition of magnesium hydroxide is reduced and replaced by an increase in calcium carbonate, without inducing voltage (Hilbertz, 1992). This material composition state change will not be accounted for within the material probe 07.

Hardware and Communication: The sensors and electrical components used within the material probe are documented in Figure 65. Two Arduinos are used in the material probe. The first Arduino is used to control the actuators (relays for voltage, dosing pumps and agitation pump). This first Arduino will 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

[18] Micro mini submersible water pump dc 3-6v from ebay.co.uk
[19] EF-150 Aquarium external filter pump 400litre/hour from allpondsolutions.co.uk

voltage/electrical current). 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 sensors used to monitor conditions, which establish feedback between, and have a significant effect on, 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 (except the temperature sensor), which could result in unreliable results and system actions. To maximise the benefits of the sensors' 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 before carrying out each material probe that generated results. 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. 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 dose in 2ml of a solution. The solution is then agitated for 2 minutes via a pump and then the solution's EC values are taken again after 5 minutes to determine if the solution is within an acceptable threshold range. **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 material probes are outlined 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 68).

7.11.3 Material probe 07: specific properties

There are two properties to material probe 07: *first,* the intention is to run a series of material probes for a total of 12 hours, but this will be reviewed if the volume of material 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 10th 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. *Second,* two material probes will determine if carbon cathodes can sustain material growth and produce reliable sensor readings without deteriorating, since aluminium cathode deterioration was witnessed in probes 05 and 06.

Cathode materials, shape and texture: material probe 07 uses three different types of cathodes and their properties are documented in Figure 67 and Table 7. The shape, material and surface textures of the cathodes used will determine three factors: 1) What effects does 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) Do the material type and properties (e.g. geometry, texture, materiality) have an impact on being able to initiate growth and support it for long durations?

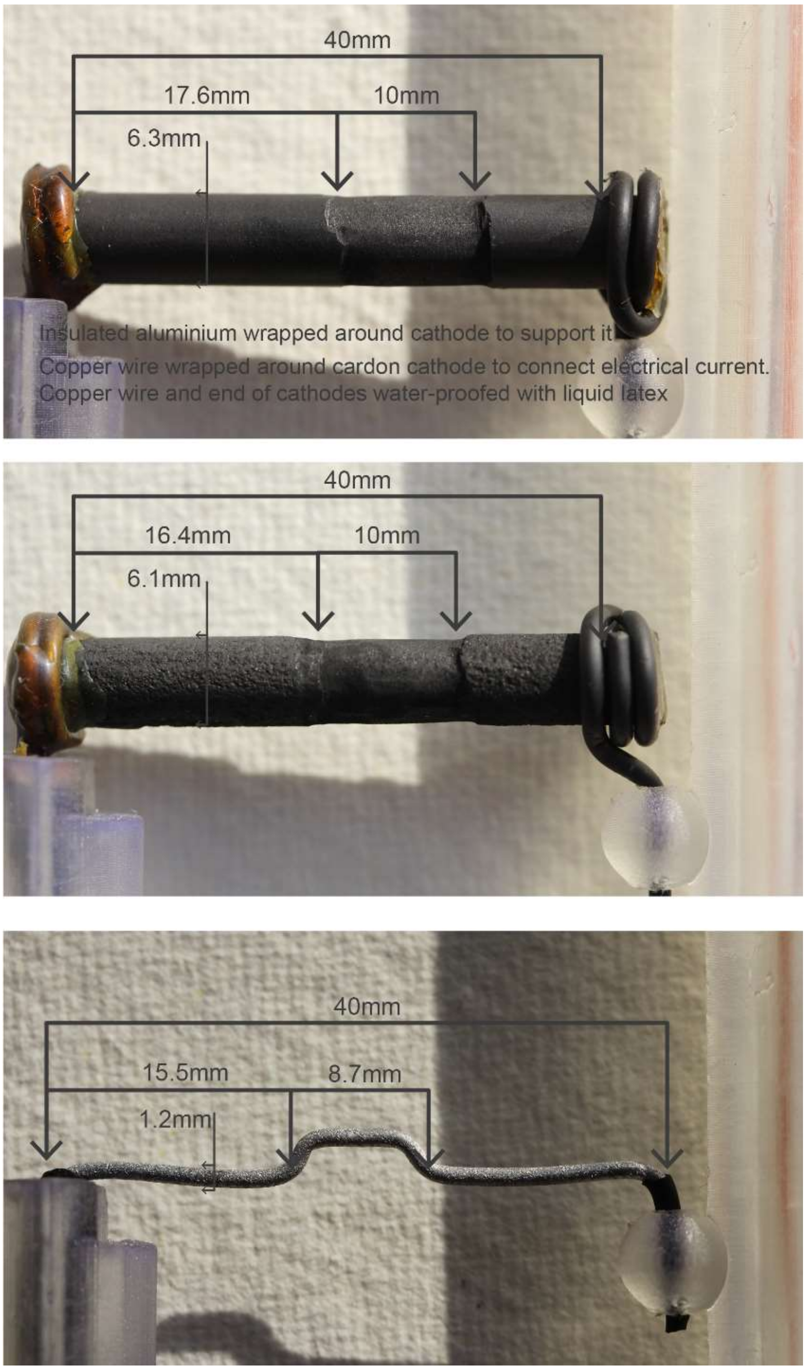


Figure 67: The three types of cathodes used in material probe 07 explore the impacts of surface textures and material type on material growth and current sensor readings. The material types are: top - smooth carbon; middle - rough carbon; bottom - rough aluminium. Additionally, the carbon cathodes have their ends waterproofed and insulated 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: Material probe 07 base solution properties. Values taken before each material probe.

Material probe	Bench power supply values	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

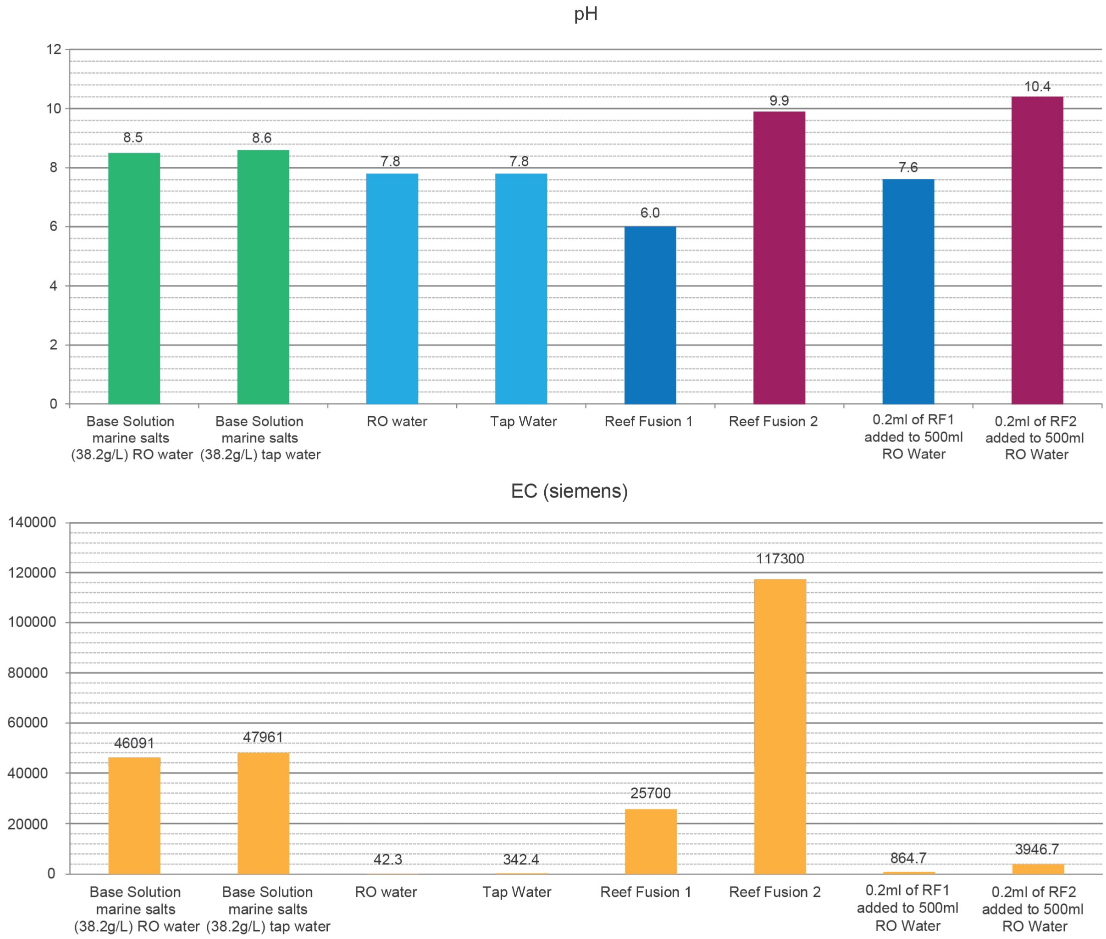


Figure 68: Graph of the various chemical and base solutions' pH and EC values. These values will inform threshold values and actions of the system. Base solutions' values created with 500ml of RO water or tap water with measurements taken at temperatures between 24.5 and 26.0 °C.

7.12 Material probe 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 depicted in Figure 69. 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, switch on dosing pump 2 to dose 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 dosing pump actions do not 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 does not inform any of the system actions and the filter pump will be controlled manually, and switched on and off at random intervals and for random durations.

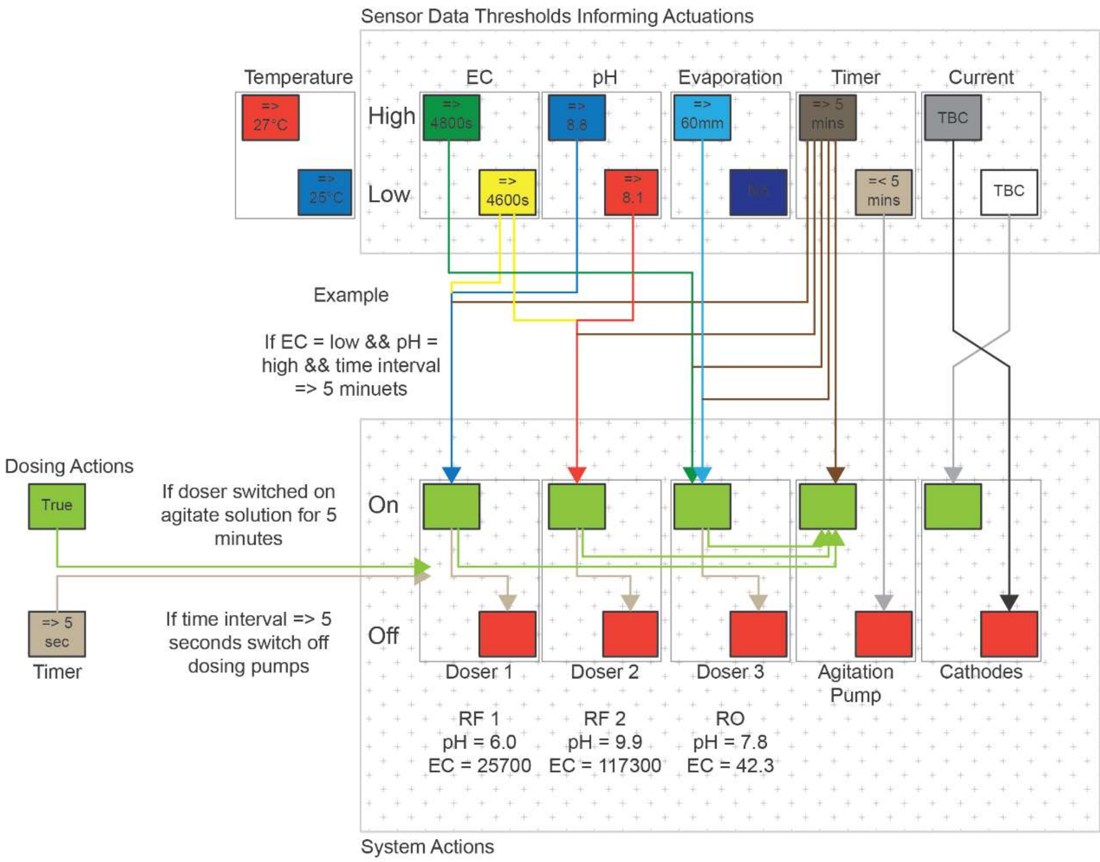


Figure 69: Overview diagram of the system logics for how defined threshold values inform what actions are carried out. Additionally, in order to prevent a large number of actions being carried out constantly, single actions can only be carried out every 5 minutes.

7.13 Material probe 07: Analysis

The analysis and results generated from material probe 07 will be based on combining 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. To achieve reliable photographic analysis for growth volume data, the camera positions will not be moved.

7.14 Material probe 07: 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. This 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 self-assembly without the need for using pre-designed units of matter; and 2) utilising material platforms that have inherent interrelationships. Additionally, these results reveal 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 Material probes 07 results: database of material volume, growth rates & corresponding sensor values

First, 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. *Second*, the key principles of the result from each are discussed. *Finally*, overall conclusions are discussed that illustrate various design principles and issues when developing an adaptive design and fabrication system that is based on stimulus, interrelations, material self-assembly at highly granular resolutions, and sensors that are incorporated externally to the material units.

Table 9: Material probe 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

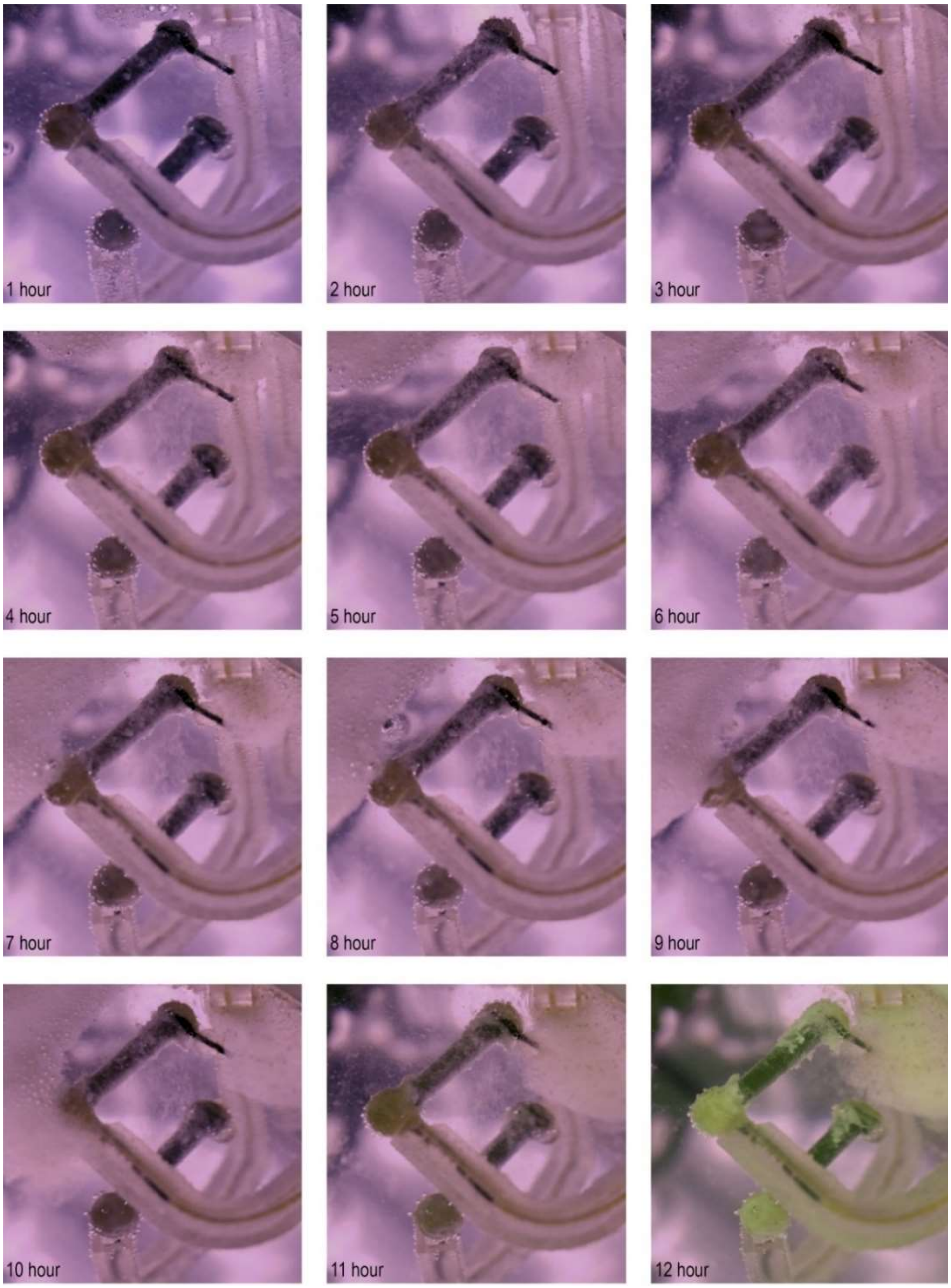


Figure 70: Series of images showing the limited material growth that occurred within material probe 07A (smooth cathode) over a 120-minute duration. The last image reveals small amounts of material growth predominantly occurring at the ends of the cathode but also along the cathode's length. This demonstrates that a smooth surface texture does not impact growth. Link to time-lapse video: https://vimeo.com/user12085005/review/380364588/5d86943f8c

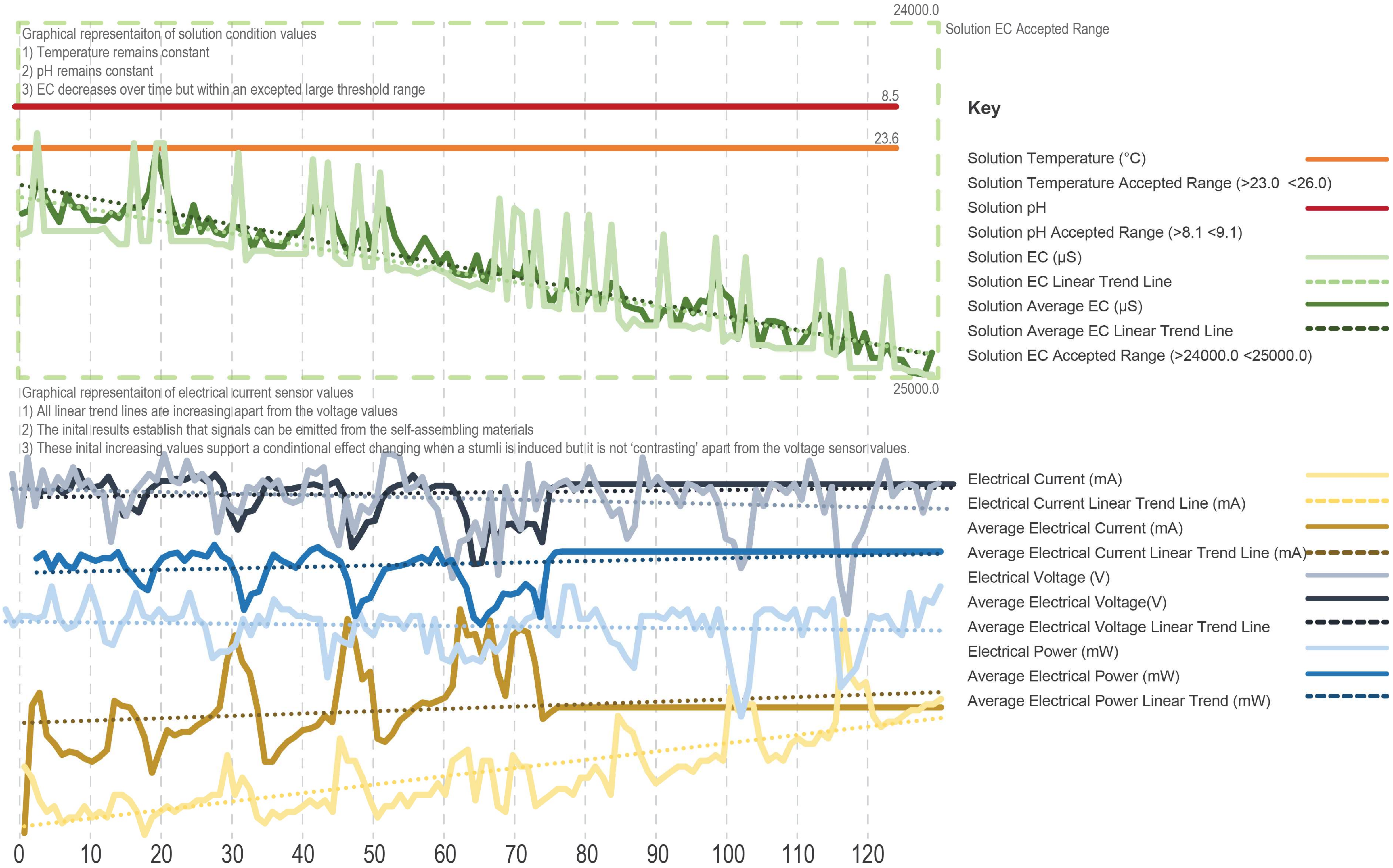


Figure 71: Graph combining real-time sensor data values for probe 07A (smooth cathode). Material volume growth is not included as no significant amount was grown over 120 minutes. The sensor values also terminated after 2 hours due to a communication fault that occurred unexpectedly. However, these initial results indicate that voltage values decrease over time whilst current and power sensor values increase, whilst the solution's resultant conditions (EC, pH and Temperature) remain within the range of accepted threshold values.

Table 10: Material probe 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

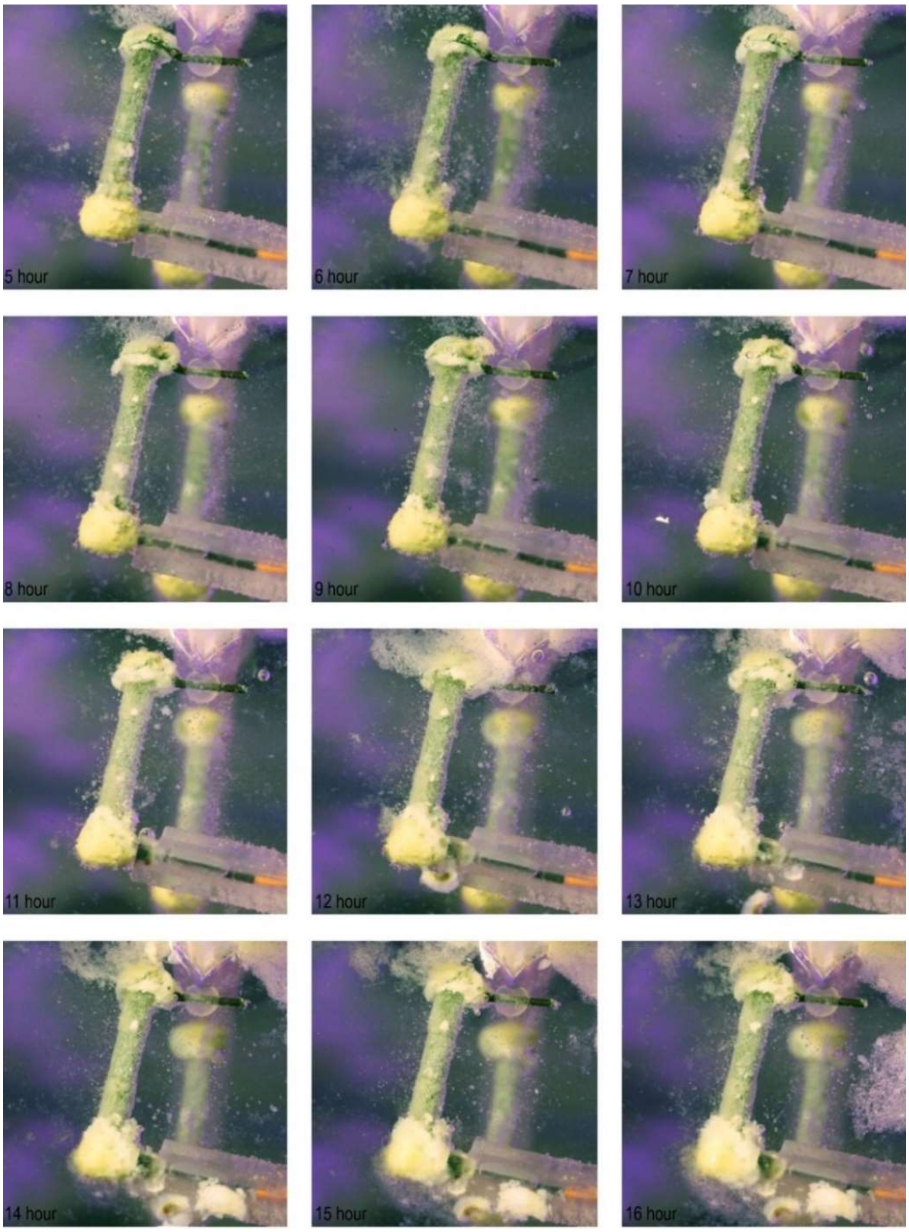


Figure 72: Series of images showing the material growth that occurred within material probe 07B (rough carbon cathode) over a 16-hour duration. The series of images reveal that over 16 hours, minimal material growth occurs. The growth that does occur focuses at the ends of the cathode where the electrical wires are connected. This demonstrates that the cathode's material acts as a foundation and had a significant impact on facilitating and then supporting material growth. Link to time-lapse video: https://vimeo.com/user12085005/review/380372447/9f83e6d0bb

Figure 73: Graph combining real-time sensor data values for probe 07B (rough carbon cathode). Again, insufficient material volumes were grown to determine associations. The electrical current sensor values show initially large fluctuations, but then the average becomes steady after 3 hours. The solution's conditions remain somewhat constant apart from the solution's EC which appear to increase almost linearly over time. The linear increase of solution's EC matches the steady linear increase in the voltage sensor values. Only one dosing pump action was recorded within the system even though threshold conditions of the solution's EC was exceeded, highlighting issues of system action reliability to maintain conditions.

Table 11: Material probe 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

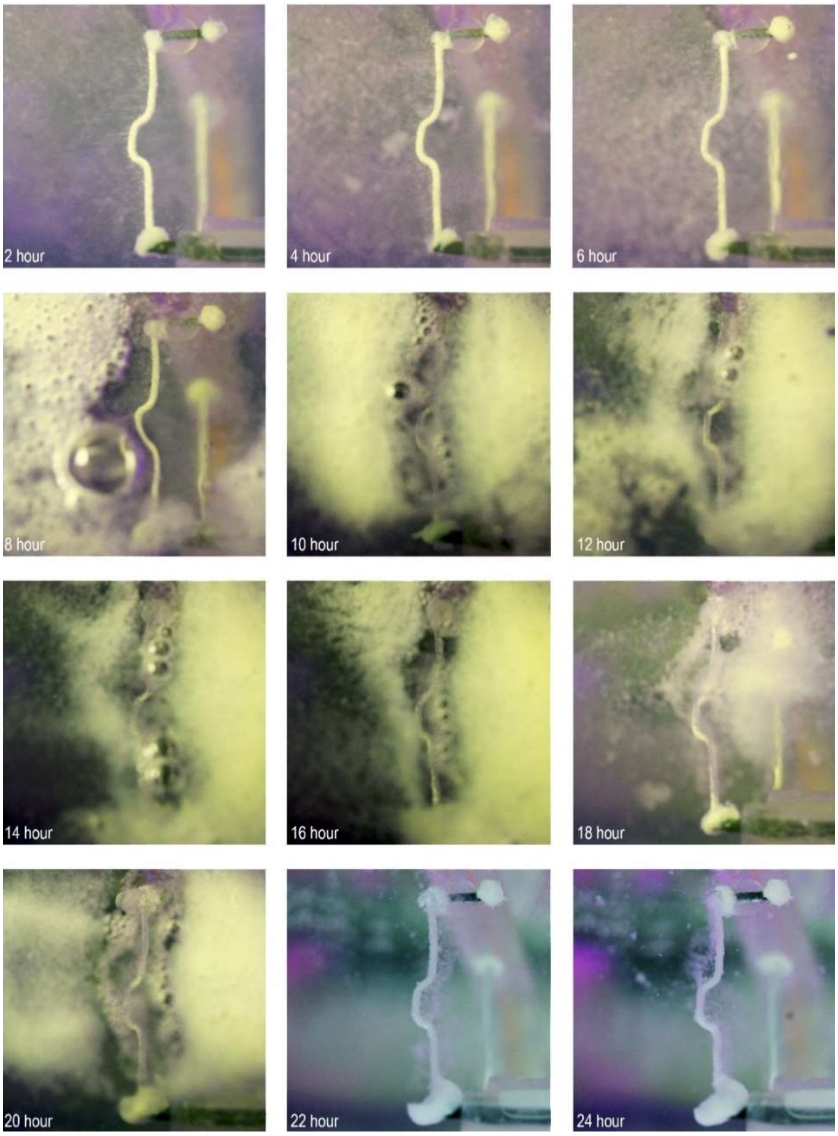


Figure 74: Again, over a 24-hour duration, insufficient material growth has been created to determine associations between senor readings and material properties generated. This demonstrates the significant role of the material assembly rate in being able to determine associations, and informs possible applications of the material's potential adaptive abilities. The lack of material growth over all three material probes establishes that the design and fabrication process must centre around ensuring favourable conditions to grow materials, which means that only inducing stimulus/energy doesn't strictly generate material self-assembly. Link to time-lapse video: https://vimeo.com/user12085005/review/380528892/37b9e051f6

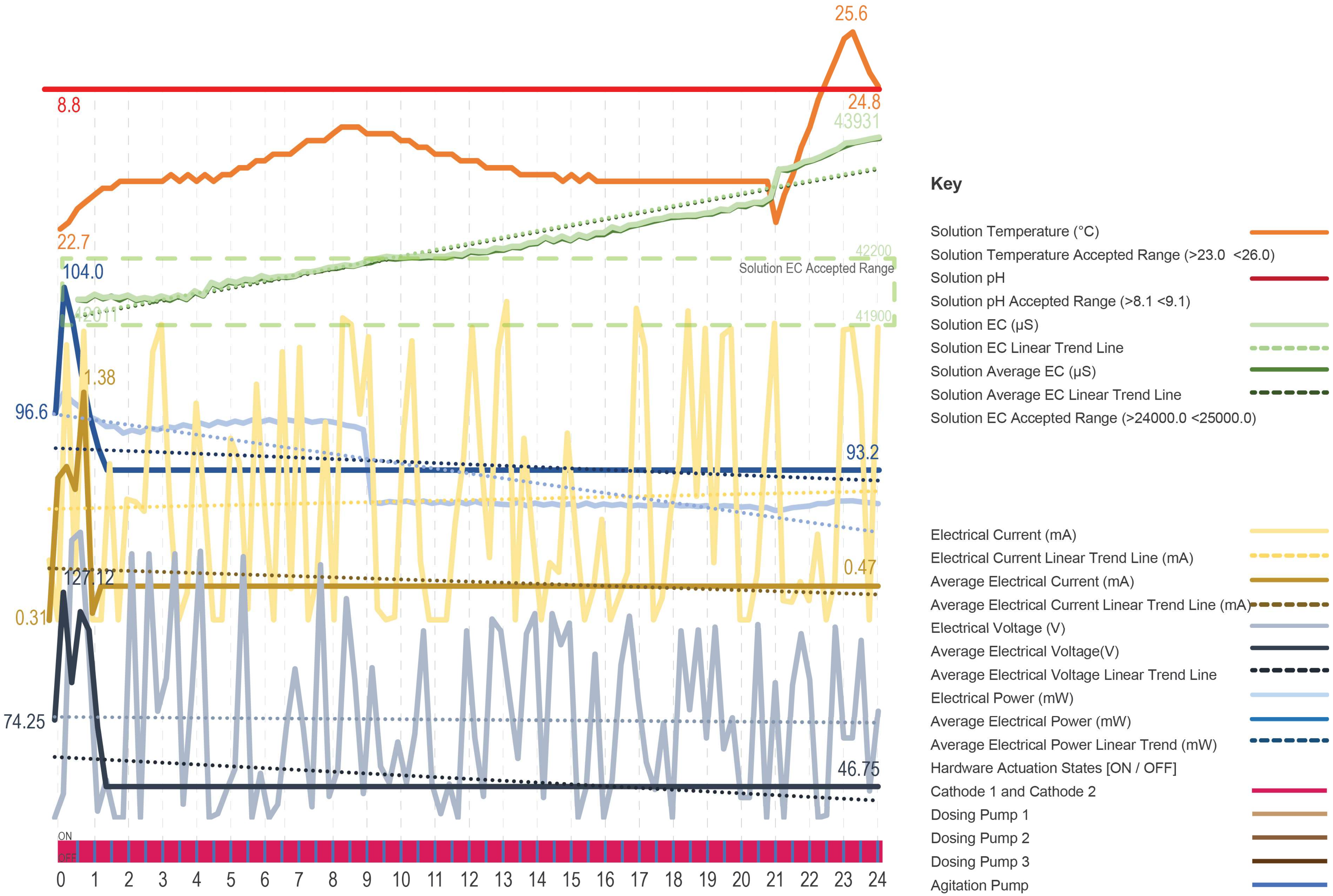


Figure 75: Graphical data representing real-time sensor data values for probe 07C (aluminium cathode). The data demonstrates that all electrical sensor values reduce as solution electrical conductivity increases, which is outside the accepted range. The reducing electrical sensor values further highlights the impact the foundation/substrate material has on informing interrelationships within the system; these values are likely due to the aluminium cathode deteriorating as minimal material was grown upon the cathode.

Material Probe 07A (smooth cathode): Cathode 1 growth

Material Probe 07B (rough cathode): Cathode 1 growth

Material Probe 07C (aluminium cathode): Cathode 1 growth

Material Probe 07A (smooth cathode): Cathode 2 growth

Material Probe 07B (rough cathode): Cathode 2 growth

Material Probe 07C (aluminium cathode): Cathode 2 growth

Figure 76: Macro photographs highlighting the small amount of material grown and varied material properties generated. The images establish several factors: 1) the cathode materials act as a foundational material and have a significant impact on material growth, sustaining material growth and producing variable properties. 2) Carbon cathodes (left and middle row) are poor 'foundational' materials for supporting material growth irrespective of surface texture when compared to the volumes grown upon aluminium cathodes, as material probes 05 and 06 demonstrated at similar durations. 4) The carbon cathodes with insulating material at the ends 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 material probe 06 at much shorter durations.

The results of material probe 07 are discussed individually in regards to the key factors and issues of each cathode type and sensor values generated. These 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 resemble a closed-loop control system when incorporating material self-assembly at granular resolutions and complex interrelationships.

Material probe 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 shown in Figure 70.
- The error in hardware communication resulted in a small sample size (see Table 9) but indicates that hardware communication must be robust to maintain sensor values throughout the fabrication process to monitor conditional changes.
- Based on the small sample size, resultant conditions of the solution's 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 71), meaning that only agitation actions occurred.
- Figure 71 shows the electrical current sensor values where only voltage values decrease over time, indicating that only voltage could potentially be associated as a *contrasting condition* to the stimulus.
- Figure 71 shows average voltage, electrical current, average current, power and average power values all increase over time, which was not expected, but the increasing linear trend could still be associated to parameters of a design as they vary over time. These increasing sensor values could be termed *parallel conditions* if associated with increasing material growth volumes.

Material probe 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 shown in Figure 72.
- Table 10 and Figure 73 illustrate average power values decreasing over time 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 73 depicts both voltage and average voltage values increasing as the solution's electrical conductivity gradually increases over time, which did not remain within defined threshold ranges. This indicates that the system requires significant calibration for future work.
- These electrical current sensor values do not have any correlation with material probe 07A, and begin to highlight multiple complex interrelationships.

Material probe 07C (aluminium cathode wire): Data results

- Again, insufficient material growth was generated during the material probe, which reveals the unpredictable nature of the process. Critically, the lack of growth on a cathode type that has previously enabled comparatively large volumes of material to be grown in previous material probes highlights that inducing a stimulus/energy does not solely dictate material self-assembly based on material units that do not have their geometries and interfaces designed. Instead, favourable conditions must be ensured, which are based on interrelationships.
- Table 11 and Figure 74 demonstrate diminishing electrical current sensor readings for all the values of current, voltage and power even as the solution's electrical conductivity increases outside the accepted range. This shows the impact the cathodes' material has on interrelationships, and conditional changes within the system as, comparatively, the carbon cathodes electrical values all increased.

- The solution's 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 indicates 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 shows that any component within the system that can induce a stimulus must be accounted for and can be related to each other, which becomes increasingly complex, and reveals 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. To address this, the surface must be cleaned of this resultant effect, which was achieved by placing filter pump tubing at this location.

7.15 Material probe 07: Conclusions

Analysing the results generated from material probe 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 material probe 07A and 07B with probes 05 and 06, which grew material over similar durations. This shows that the cathodes materiality act as a foundational/substrate material within this system, which has a significant impact on material self-assembly.
- **Variable substrate materials**: The carbon cathodes had their ends insulated with silicone but material growth at these locations is focused and generates various material properties, from petal-like to almost

multiple barnacle-like formations (see Figure 76). The combination of the conductive cathode and insulating silicone reveals the possibility of creating cathodes with variable material properties, which could provide further control over growing desired material properties at specific locations.

- **Favourable conditions**: must be created to support and initiate material self-assembly, which is highlighted due to the lack of material growth over all three material probes. This establishes that tuneable environments must be used to create favourable conditions and not just used to simply induce stimulus to grow materials as no significant material growth occurred. 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, p4); in particular *energy and entropy*, to guide material self-assembly at highly granular resolutions 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 affect the solution's 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 sensors directly around the cathode to determine growth volumes produced (Hilbertz et al., 1977) and potentially indicates that to

accurately determine properties of material self-assembly that have not had their material units designed, sensors may have to be directly incorporated into the material's units 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, material probe 07 highlighted the multiple interrelationships that exist within the system between stimulus, material properties, local conditional changes and global resultant conditions. This means it would be extremely difficult to determine and capture all the complex relationships and create 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 processes that can be based on non-linear associations (Richards and Amos, 2016) would be more appropriate as they can be used to discover complex interrelationships.

7.16 Material probe 07: Future Work

There are three main areas of future work that can be extended based on the material probes up to this point. *First,* incorporating digital design tools to finally create an adaptive design and fabrication system; *second,* exploring 3D/volumetric growth; and *third,* how to begin to move away from the predefined scaffold's structures, which forms the basis for the following material probes 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 material probe 07 and govern parameters of stimulus by determining if direct association can be made from the results of material probe 07 (Figure 77). 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 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 material probe 07. It was discarded due to no direct associations becoming apparent within material probe 07, resulting in: 1) no growth volumes were created; and 2) the electrical current sensor data varied significantly. Comparatively, persistent modelling and the material system used by Ayres enables a direct association, where 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 indicate 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 at highly granular resolutions and have inherent interrelationships.

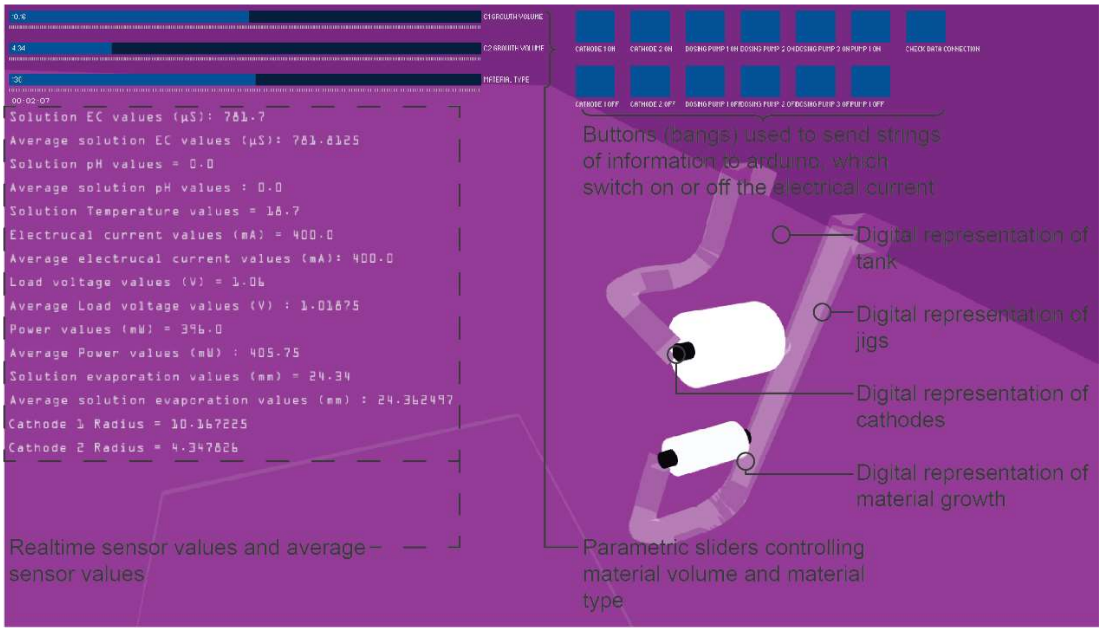


Figure 77: Interface of the proposed digital parametric design tool to be used to govern the parameters of material growth. The parametric design tool was discarded due to the direct associations required, which are not apparent in the results generated in material probe 07.

To address these problems, three main strategies could be employed within future work: 1) incorporate machine learning processes as a way to map and determine associations between the system's parameters. However, for machine learning to be useful, desirable material properties in certain applications must be determined in initial instances. 2) Incorporate material-based computation design tools (Oxman, 2010a; Richards and Amos, 2016), 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 material probes. 3) Utilise digital design strategies and tools that do not require predefined relationships or direct associations between parameters i.e. the relationships can be non-linear, enabling the system to generate their own associations and interrelations (Richards and Amos, 2016). Consequently, the multiple environmental conditions and effects could be engaged with and controlled with more freedom but more accuracy in terms of how they guide material properties during the mineral accretion process.

7.16.2 3D Growth

The majority of the material probes carried out within this research using the mineral accretion process have been carried out predominantly within 2D, especially for the material probes using physically separated cathode wires. Because of this, controlling variable material properties within a 3D volume has not been defined or explored. Figure 78 documents a preliminary material probe that demonstrates that variable material properties can be controlled within a 3D scaffold.

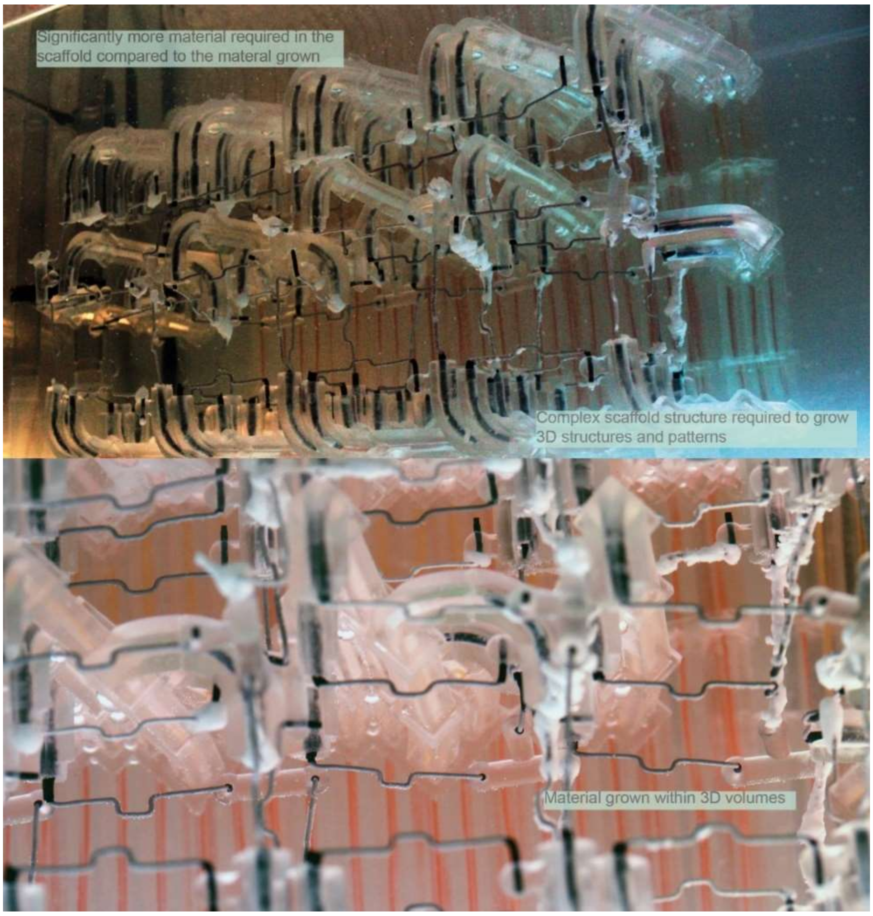


Figure 78: A preliminary material probe establishes volumetric material growth is possible with locally variable properties. The cathode scaffold is made up of 96 aluminium wires.

7.16.3 Mineral accretion material probes unit of matter

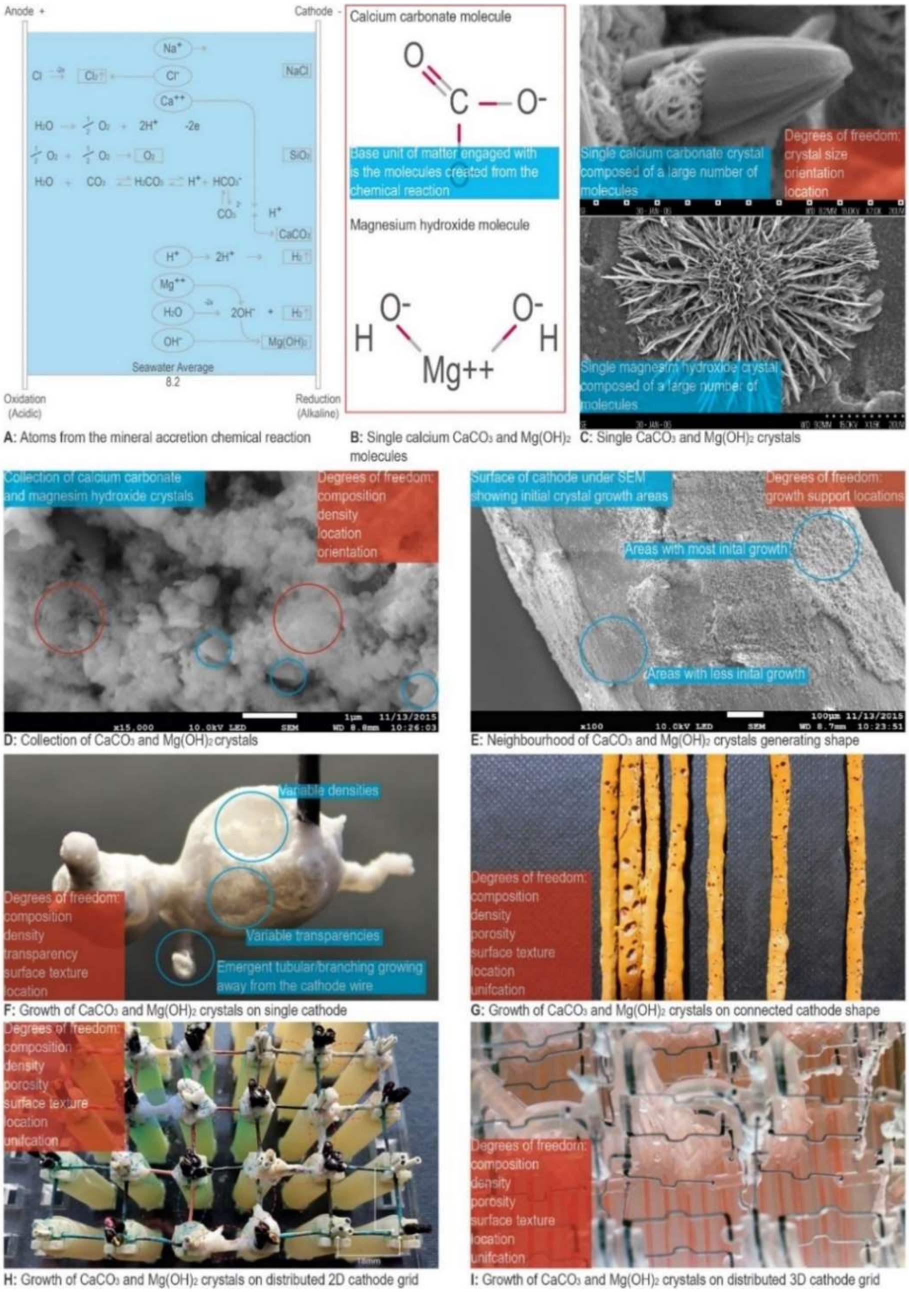


Figure 79: Units of matter across the development of the mineral accretion probes. The process is based on molecules as the unit of matter and generates various material textures, compositions, densities and forms that can be tuned and adapted at granular levels. However, the unit of matter also becomes informed by the resolution of scaffold structures. Image C source: Goreau, T. Year: 2012.

Within the series of mineral accretion material probes, the units of matter directed to self-assemble are the molecules of magnesium hydroxide and/or calcium carbonate. Engaging with material units at this resolution has generated various granular material properties (textures, compositions, forms) that can be tuned and adapted but also have higher degrees of freedom when compared to strategies that impose form and properties upon the units of matter that self-assemble. However, the extremely high resolution potentially afforded by the material units in the mineral accretion material probes are dictated by the overall resolution of the cathode scaffold as this acts as the infrastructure needed to induce and guide the self-assembly of the molecules to generate crystal formations regarding certain properties (location, volume, composition, type). Hence, the cathode scaffolds can be seen as a secondary unit of matter within the material probes. The problem with the cathode scaffolds is that they have form imposed upon them and this results in them having fixed properties. Although this secondary material unit of the cathode scaffolds can be turned ‘on’ or ‘off, and the resolution of the scaffold can vary to the extent of the number of cathodes wires within the scaffold structure. Furthermore, the material volumes that grow upon the scaffolds are not strictly limited to the dimensions or geometries of the individual cathode wires, especially as the material volumes grown become larger as many forms begin to grow away from the cathode wires as seen in the tubular forms in Figure 79 F. The impact the scaffolds have on the resolution and ultimately the extent the material can adapt and tune their properties is the area to be discussed next.

7.16.4 Development: self-assembly without scaffolds

Two major limitations within the series of mineral accretion material probes are the fact the material growth and the global adaption of the shape are restricted to the cathode scaffold’s dimensions and resolution as well as significant growth material growth occurring over very long durations; for example, the pixelated heart shape grown in material probe 04 and the long durations taken to grow small volumes of material. However, the mineral accretion material probes have established that *tuneable environments* can be used to guide self-assembling material properties without having to directly predefine properties of the individual material unit. 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 series of material probes in the following chapter. Importantly, the flowing material probes 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 material probes explore how patterns can be manipulated over shorter periods using *tuneable environments*, in both two and three dimensions, without the need for restrictive scaffolds.

7.17 Chapter Summary

Key areas from each mineral accretion material probe 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.
- It is possible to grow 3D forms and patterns within a 3D physically distributed cathode network, which could lead to structures that can adapt their internal material properties, which would mimic the heterogeneous qualities found in biological bone structures.

Open-Loop Control System

- Stimuli enable discourse between digital design tools, fabrication, granular material 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 results is not reliable as the process is not linear. Feedback is needed.
- Interrelationships and resultant material effects/properties must be associated to build towards a closed-loop control system.

Closed-Loop Control System

- Favourable conditions must be created and maintained to initiate and sustain granular material self-assembly, which extends the role energy plays within the required design parameters to achieve self-assembly defined by Tibbits (2016).
- When utilising material platforms that self-assemble at molecular resolutions and inherently have interrelationships between conditions and material properties, direct association become extremely limited as they cannot account for all the complex interrelationships generated. This makes 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 material probes 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 material probes. The three probes 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 is:

Material probe 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'*.

Material probe 09: *Contrasting Interfaces* is a small exploration which explores how 3D acrylic ink diffusion can be delayed via a contrasting support material interface.

Material probe 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 material probe highlights how different support materials generate multiple material properties over a range of times.

The series of material probes within this chapter are used to explore the idea of creating *tuneable environments* to guide material self-assembly without the need for rigid scaffolds or pre-designed material units. Rephrasing this aim into the question: *How can tuneable environments guide material self-assembly at granular resolutions and without needing constraining scaffolds?* Due to this main aim along with the design principles required for establishing feedback within the mineral accretion material probes, these paint and ink material probes are not concerned with establishing feedback between material properties generated, stimuli and design tools. Essentially, all of the material probes and systems developed are *open-loop control systems*. The material platforms (inks and paints) used in the material probes 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 self-assembly may lead towards.

8.1 Generative Paint and Volumetric Ink Diffusion Overview

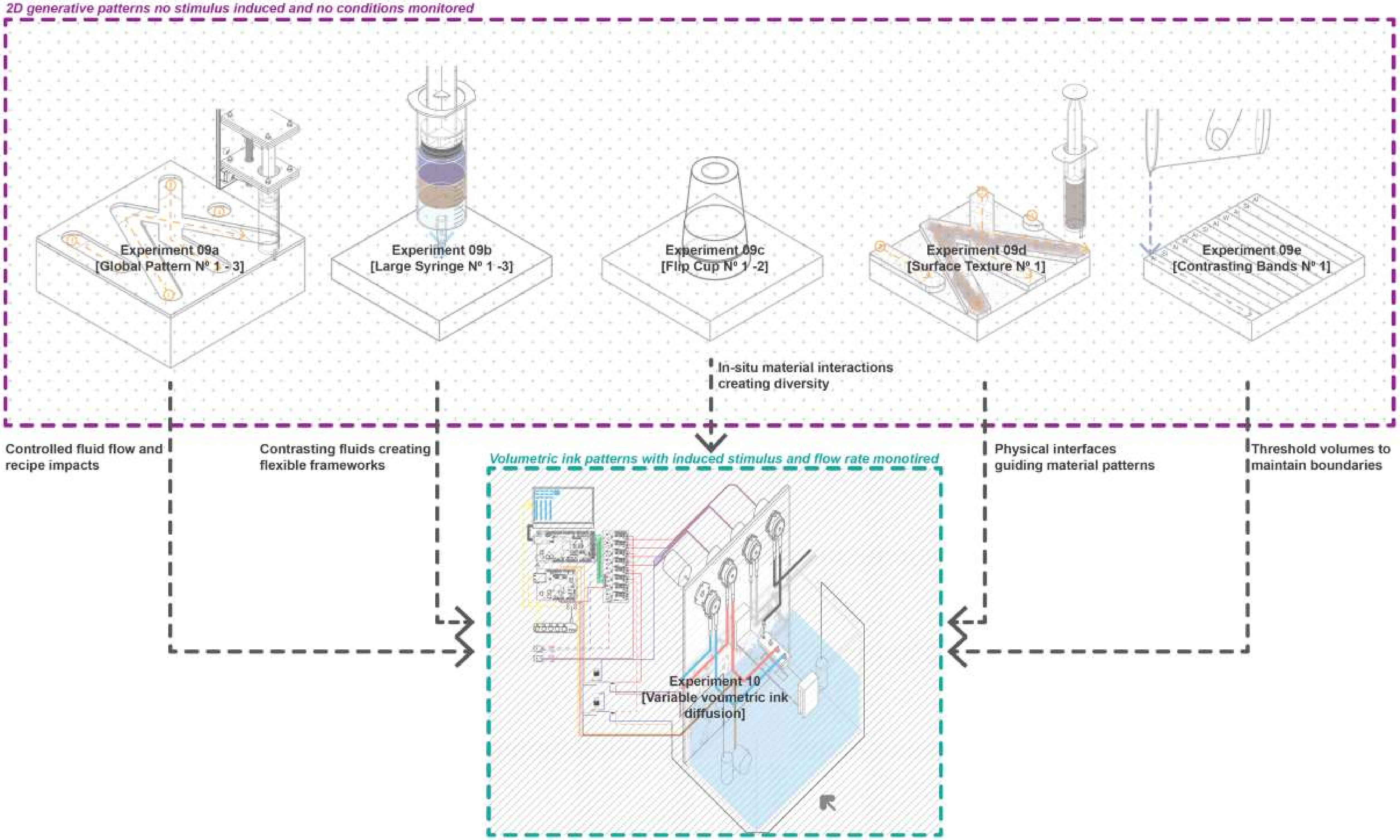


Figure 80: Overview of the multiple 2D generative paint material probes and the 3D ink diffusion material probe.

8.2 Generative Recipes Overview: Moving Away from Scaffolds

The 2D generative paint recipe and 3D ink diffusion material probes are simply explored as a means to understand how to move away from the restrictions of the cathode scaffold structures within the mineral accretion material probes, whilst still examining the role stimulus can play within these material platforms. Neither of these material probes are intended to establish feedback between design, fabrication or material properties.

8.3 Material probe 08: Generative Recipes

The *'Generative Recipes'* material probe proposes to creatively explore granular resolutions of material self-assembly using tuneable environments via generative 2D paint patterns. The paint patterns are generated by varying the recipe's 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, how the paint recipes are deposited also impacts 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 material probes will help to understand how a stimulus (agitation) 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 ingredients to achieve self-assembly, the other two being: *I Materials and Geometry and II - Mechanics and Interactions* (Tibbits, 2016). The following material probes within this chapter attempt to explore energy and entropy's impact on pattern generation, as the predominant approach within an architectural research context has focused on the first two ingredients by defining the material unit's geometries and connection interfaces

(Tibbits, 2014b; Dierichs and Menges, 2015). 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; Correa et al., 2015).

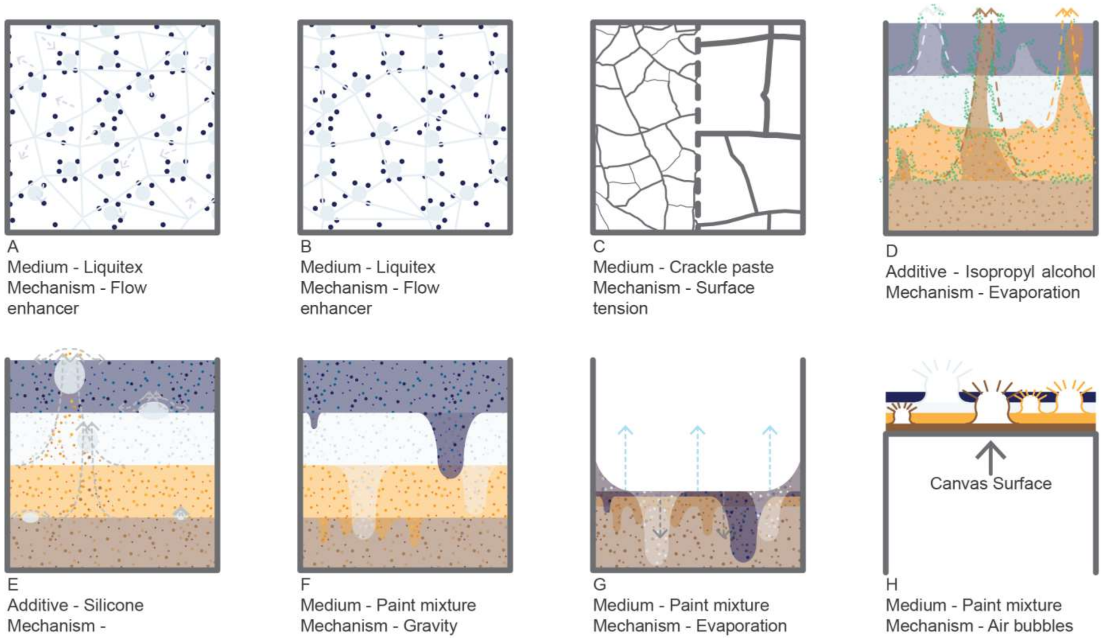


Figure 81: Interaction mechanisms occurring between paints, additives, stimulus (evaporation, gravity, air pockets bursting) and interfaces.

This series of material probes attempts to define conditions and/or parameters which form the major factor for generating a pattern's 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 material probes 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 denotes 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 leveraged by rethinking fabrication processes by engaging with material computational processes and mechanisms.

8.3.1 Material probe 08: properties

The generative paint material probes will be carried out 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 ingredients are as well as the impact of how the paint recipe is deposited on the canvases. Figures 84 - 88 document the various methods in which the paints will be deposited in material probe 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 a 152x152mm deep edge canvas, which will be primed with 2 coats of white gesso to create a smooth surface. The canvas 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 the paintings within the material probes 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; and 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

Material probe 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*

To further ensure the environmental conditions are the primary contributors to generating the effects, several other factors are maintained: A) the recipe's 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) 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 of each painting is generated along with the various interactions and mechanisms explored by the paintings:

Paintings A - C: 9ml volumes were deposited in layers using a mechanical syringe system over a global pattern and explored how global patterns are affected by varying recipe viscosities by increasing additive volumes (see Figure 82).

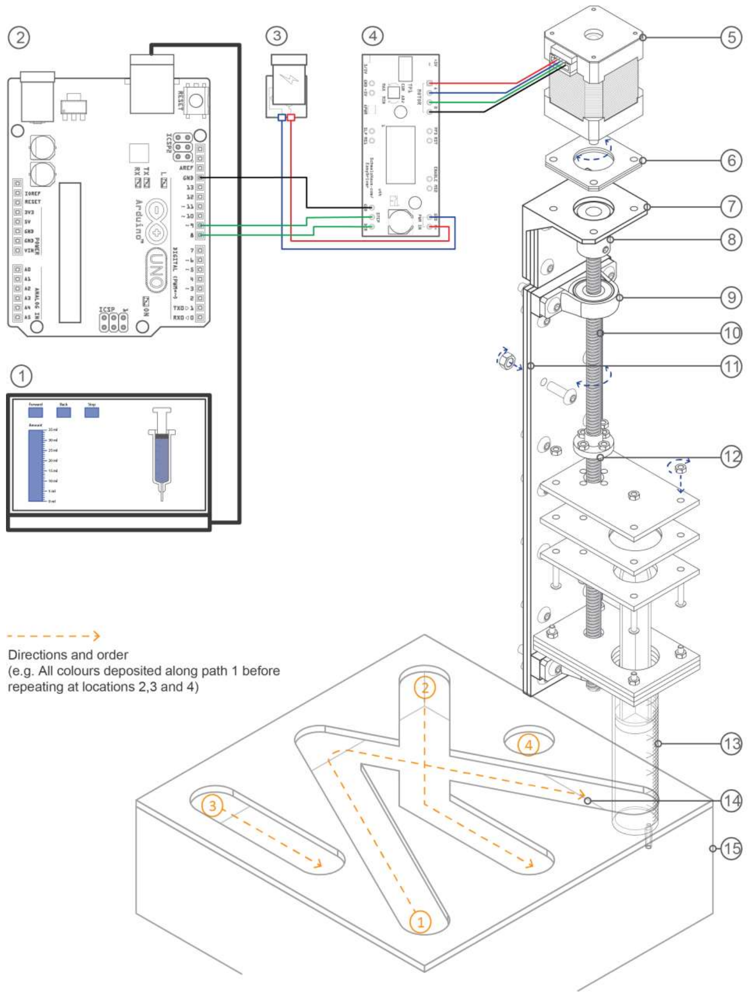
Paintings D - F: the syringe sucks up each volume of paint then deposits all of them at one time at the canvas centre. They explore the importance of where material interactions occur and the robustness of the additives (see Figure 83).

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 show the process, 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 84).

Paintings I: is deposited in the same way as material probes 8A-C but explores how the varied surface textures guide material flows (see Figure 85).

Paintings J: paint is deposited into a cup as in material probe 8G, but then poured along the defined silicone stripes, which were created beforehand. Isopropyl alcohol and water are then deposited in stripes next to the paint to explore how material boundaries interact (see Figure 86).

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 material probes: 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 82 Material probe 8a - global pattern. The material probe deposits the paint mixture across a template pattern using the syringe system. 3 different paint recipes are deposited. The paints are deposited with the least dense paint first and the densest 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 are controlled using a digital interface created using processing. The material probe examine the effects of paint order and ingredients on global patterns.

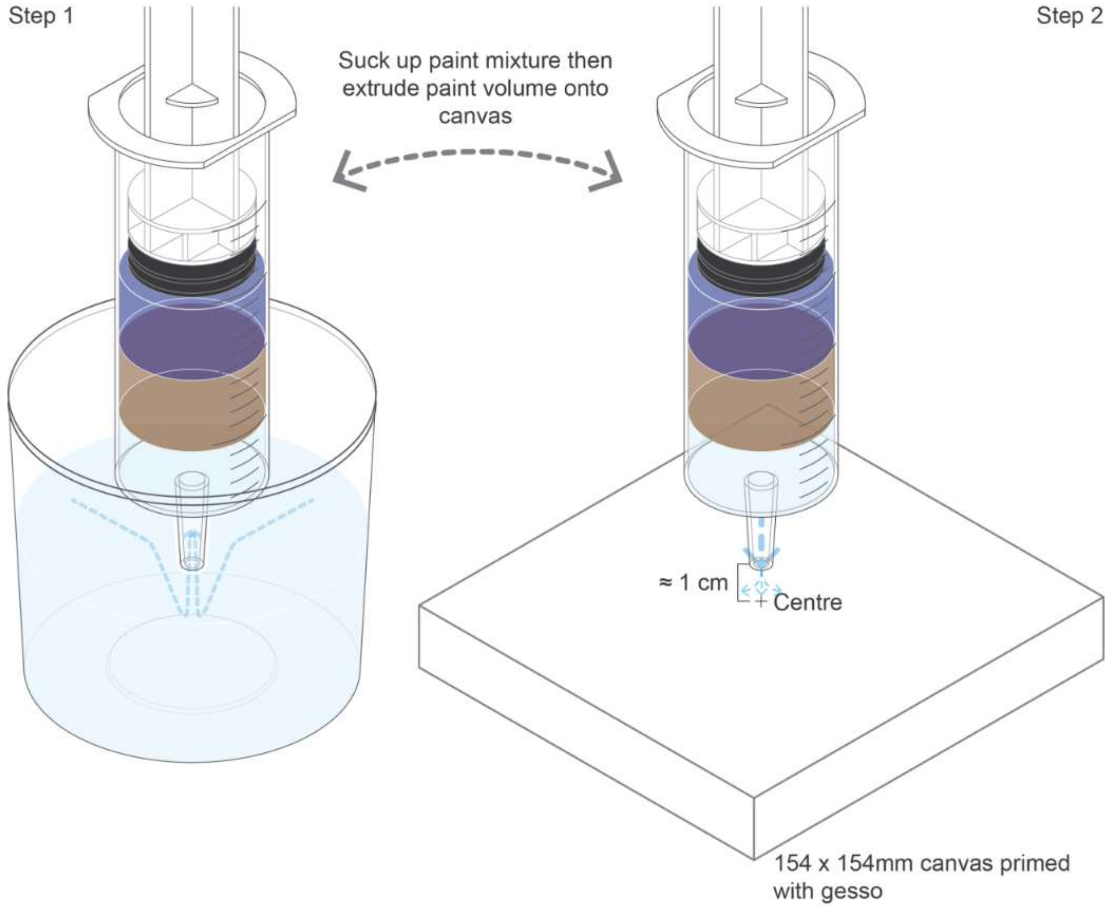


Figure 83: Material probe 8b - large syringe. A large syringe is fitted to the syringe system as it is modular. Similar to material probe 8a paint mixtures, a series of paint colours are sucked into the large syringe with the densest paint colour first this time as that will be the colour to be deposited last. 17ml of the mixture is sucked of the uppermost colour with a total of 85mls plus 5ml silicone at the end. The entire mixture is then deposited all at once from the syringe at the centre of the canvas. The material probe examines the impact of how the paint is deposited.

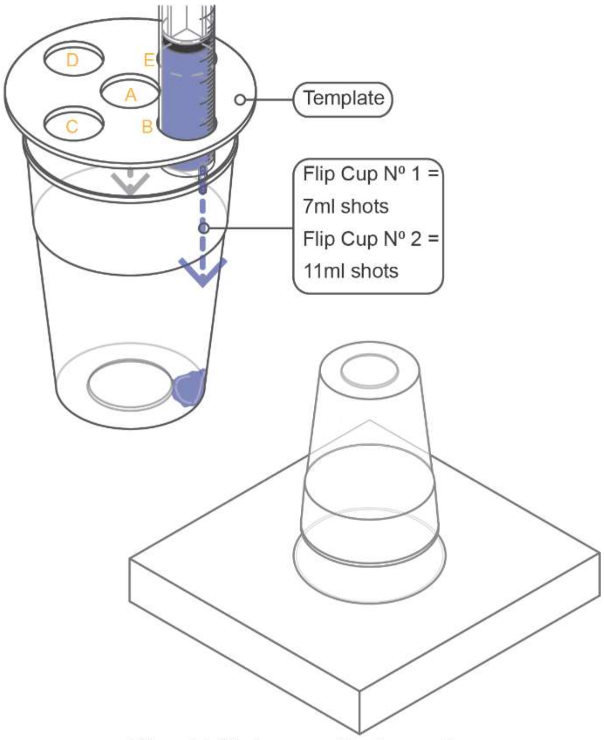
Template location = A B C D
Paint order =1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

A
1 TW + AL + SL
8 BC + AL
B
2 CB + SL
6 TW
11 FB + AL
C
3 FB
7 CB + AL + SL
D
4 BC + AL + SL
9 TW + SL
E
5 FB + SL
10 BC + AL
12 CB + AL

Acrylic ink order for
Flip Cup Nº 1

A
1 TW + AL + SL
6 PG
11 IC
B
2 TY
7 PG
12 BU
C
3 BU
8 IC
13 TY + AL + SL
D
4 TW
9 BU
14 PG
E
5 IC
10 TY + AL + SL
15 TW

Acrylic paint Order
Flip Cup Nº 2



Flip paint-filled cup upside down onto canvas

Paint recipe
Flip Cup Nº 1 = 15ml Floetrol (pouring medium) + 3ml Water + 1ml Acrylic Ink + + 1ml Isopropyl Alcohol + 1ml Silicone
Flip Cup Nº 2 = 30ml Floetrol (pouring medium) + 2ml Water + 2ml Acrylic Paint

Colour Key	IC = Iridescent Copper Light	***Acrylic Ink Colours***	FB = Fluorescent Blue
Acrylic Paint Colours	TY = Transparent Yellow Iron Oxide	TW = Titanium White	***Additives***
TW = Titanium White	BU = Burnt Umber	BC = Birdwing Copper	AL = Isopropyl Alcohol
PG = Paynes Grey		CB = Carbon Black	SI = Silicone

Figure 84: Material probe 8c flip cup. Again various paint mixtures are deposited via a syringe, but this time by hand, into a large plastic pint cup. 11ml of paint is deposited each time in a certain order and locations. 1ml additive is added at the various locations and in the same order. The locations are kept consistent through the use of a jig. The canvas is then placed on top of the cup and then flipped upside down. After 1 minute, the cup is lifted off the canvas to allow the paint mixture to flow across the surface of the canvas. The material probe examines the impact of how the paint is deposited.

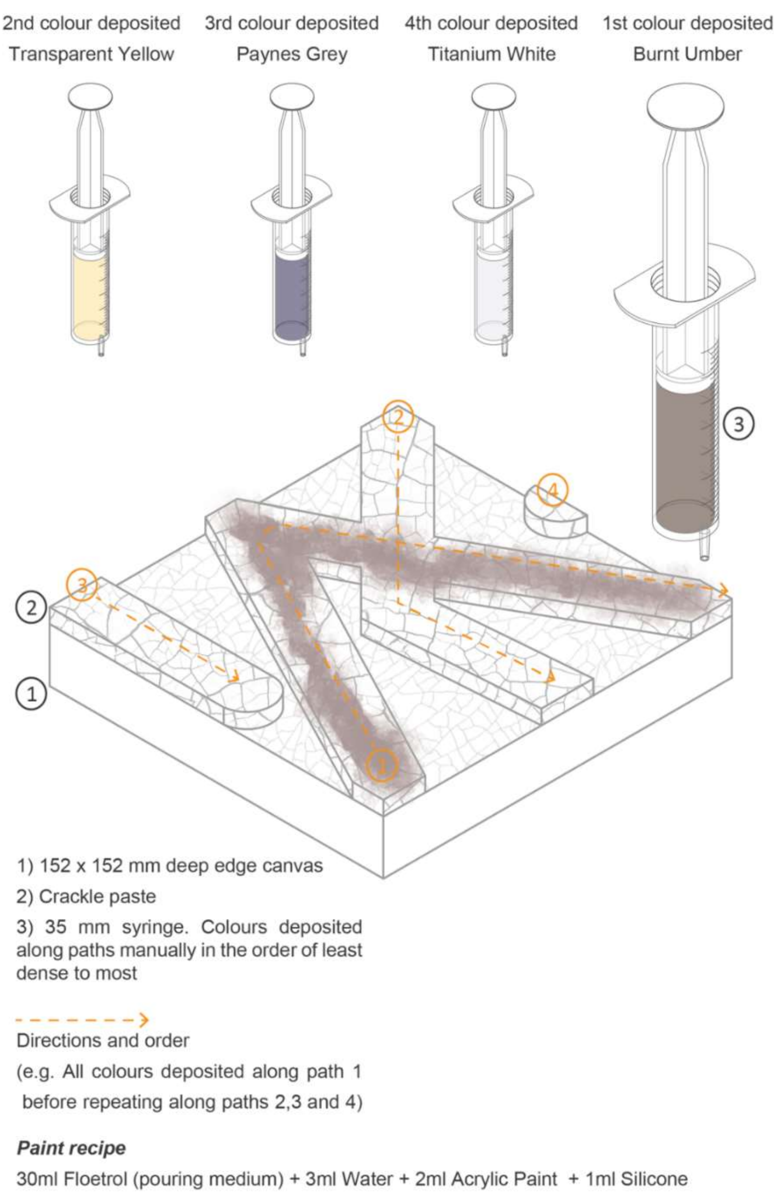


Figure 85: Material probe 8d surface texture. Similar to material probe 8a, paint mixtures are deposited along a global path in order of least to most dense per path order. However, this is done manually. 2 variations of surface texture were created using crackle paste. First, a thin layer is spread 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 material probe 8a. The thicker layer generates fewer cracks but they are much larger and more widely separated. The material probe examines how surface textures and physical interfaces can impact on pattern generation.

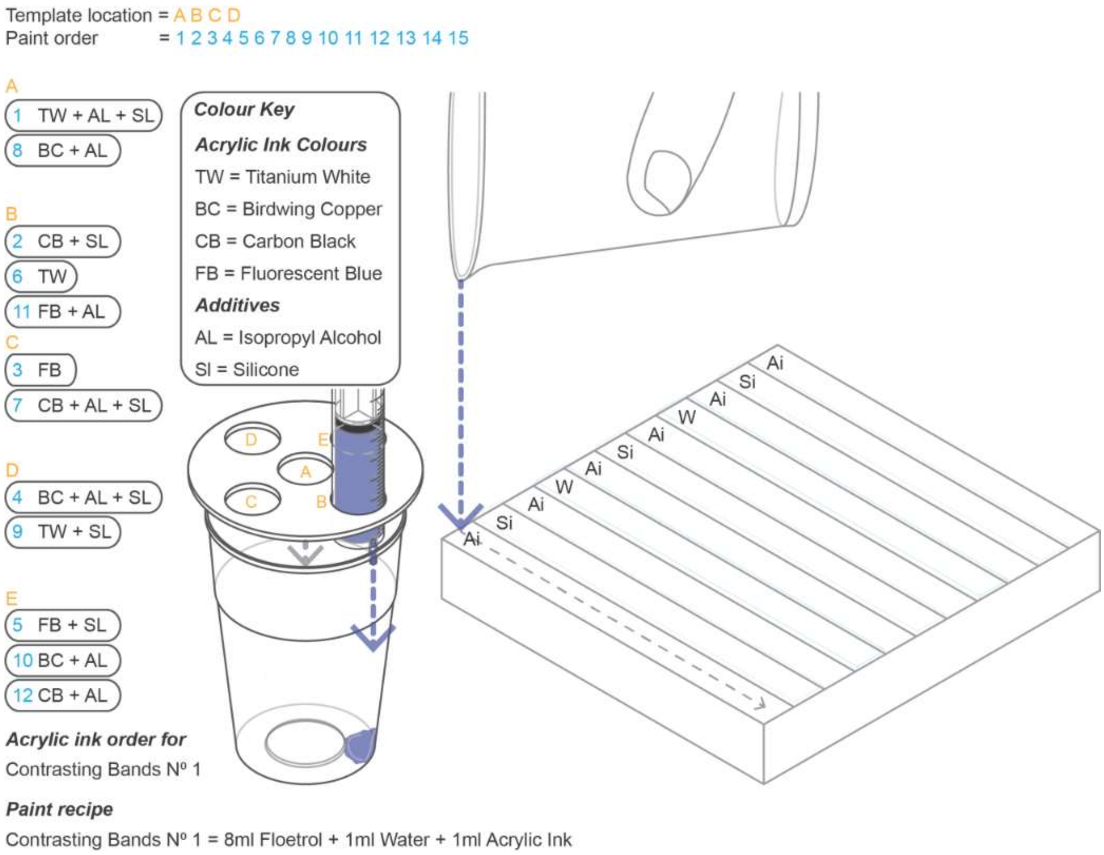


Figure 86: Material probe 8e contrasting bands. The canvas's surface is separated into alternating bands where paint mixture, water, isopropyl alcohol and silicone will be placed. First, before depositing the paint from the cup, 5ml of silicone is spread across its defined bands using a palette knife. This is because it repels the water-based paint and thus, needs to be placed first. Second, the paint mixture is poured from a cup into the bands without silicone. Similar to material probe 8c, paints are deposited into a cup. Third, 5ml of water and then 5ml of isopropyl alcohol are deposited in their defined bands. The material probe examines if defined pattern boundaries can be created and maintained using contrasting mediums before introducing paints, and also the impacts on boundary patterns by introducing disruptive materials (water and isopropyl alcohol).

8.4 Material probe 08: Results

The results are documented as a series of images, which reveal the effects and patterns generated in two dimensions (see Figures 89 - 96). 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 of how the 2D patterns are generated is now presented along with a reflection on how they reveal new ways to guide self-assembly. These 2D material probes have informed material probes 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

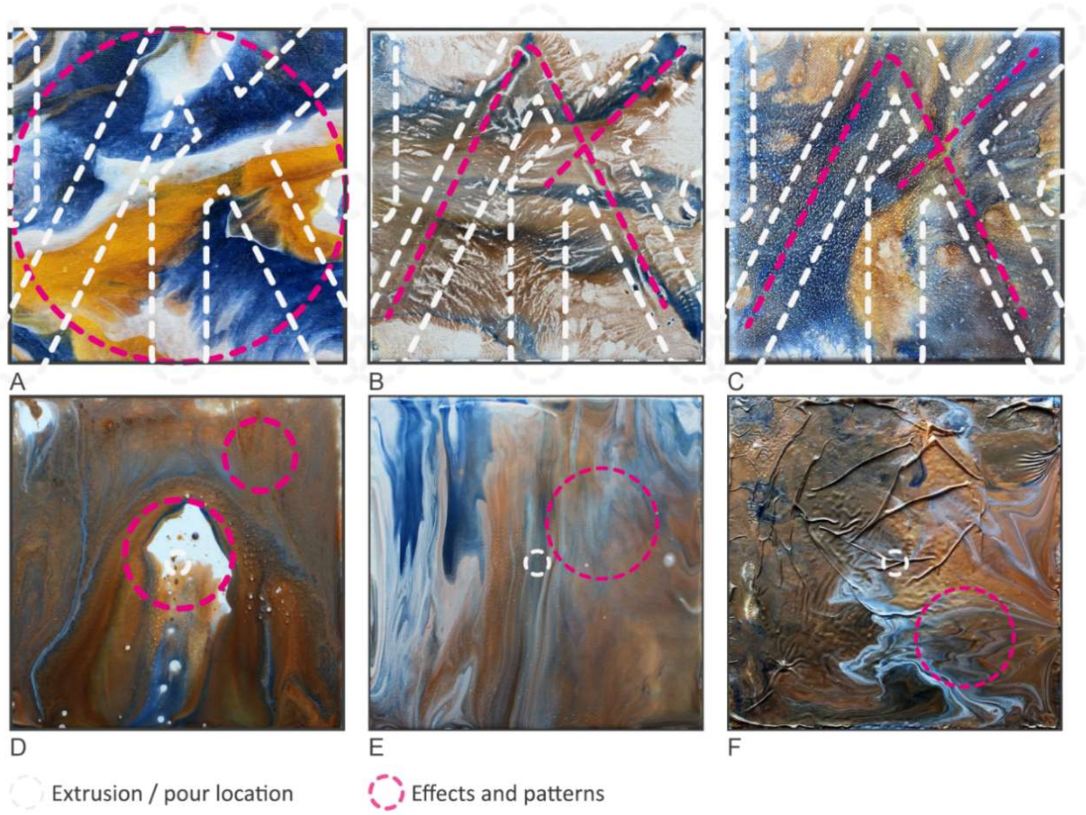


*Figure 87: 2D paint material probes photographs display the diverse range of effects achieved. **A - F**) reveal global patterns.*

Figure 88: 2D paint material probes photographs display the diverse range of effects achieved. ***G - J****) reveal global patterns.*

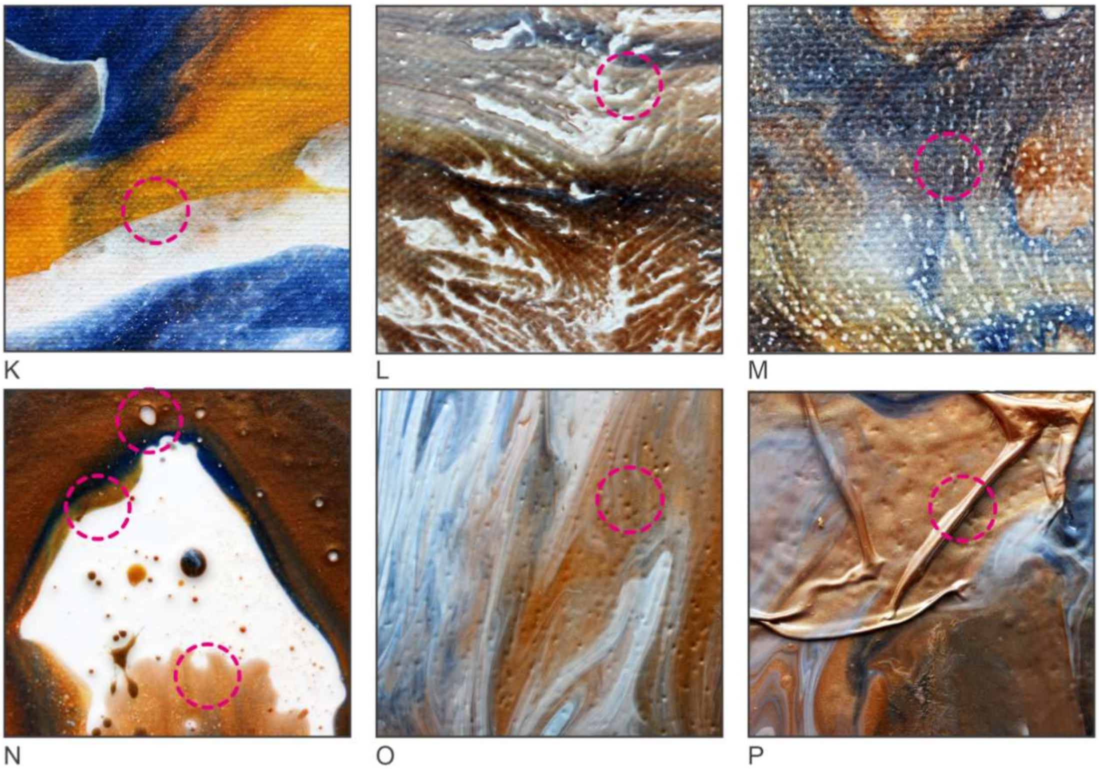


Figure 89: 2D paint material probes photographs display the diverse range of effects achieved. ***K - P****) display the local effects generated.*

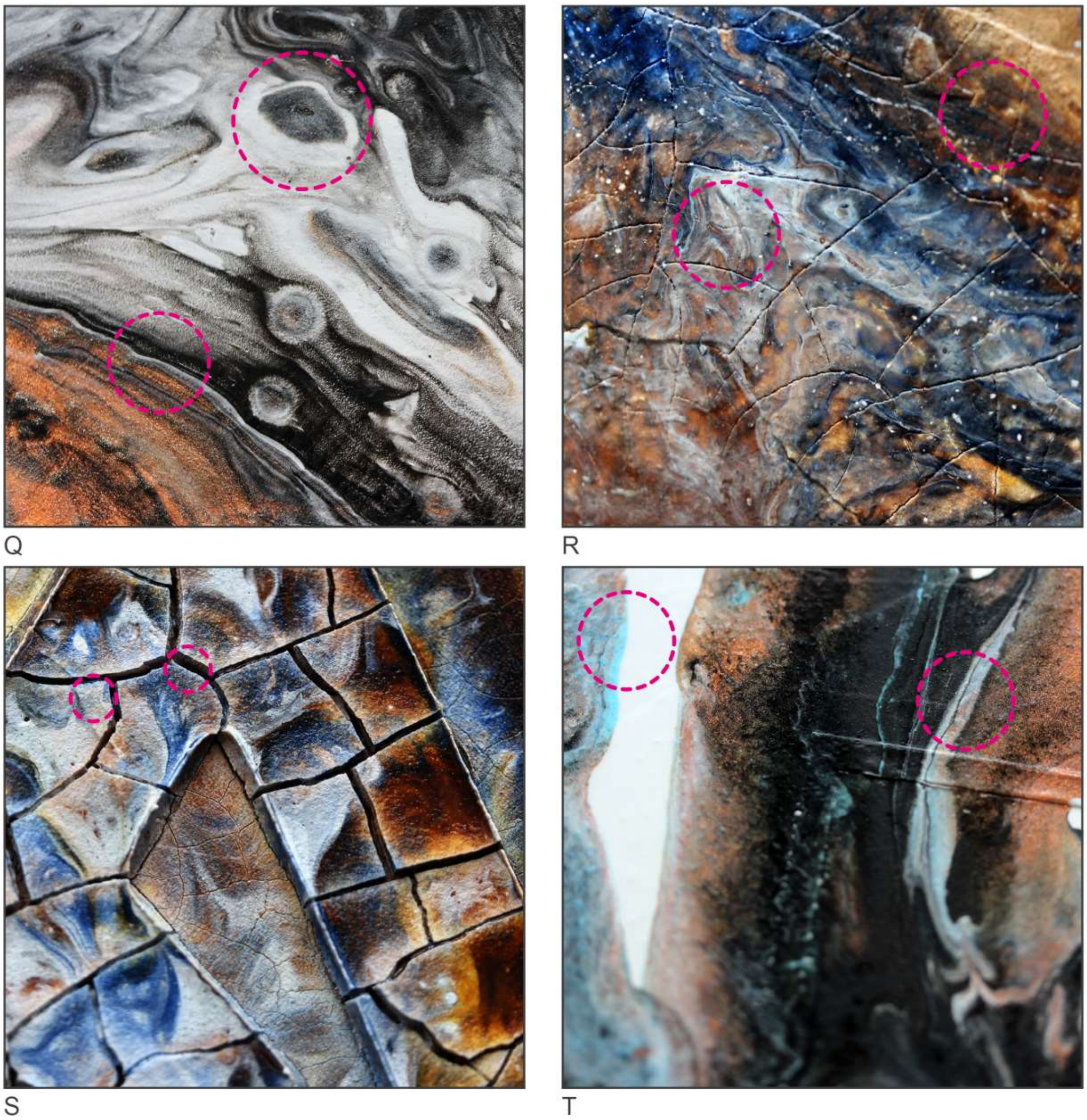


Figure 90: 2D paint material probes photographs display the diverse range of effects achieved. ***Q - T***) display the local effects generated.

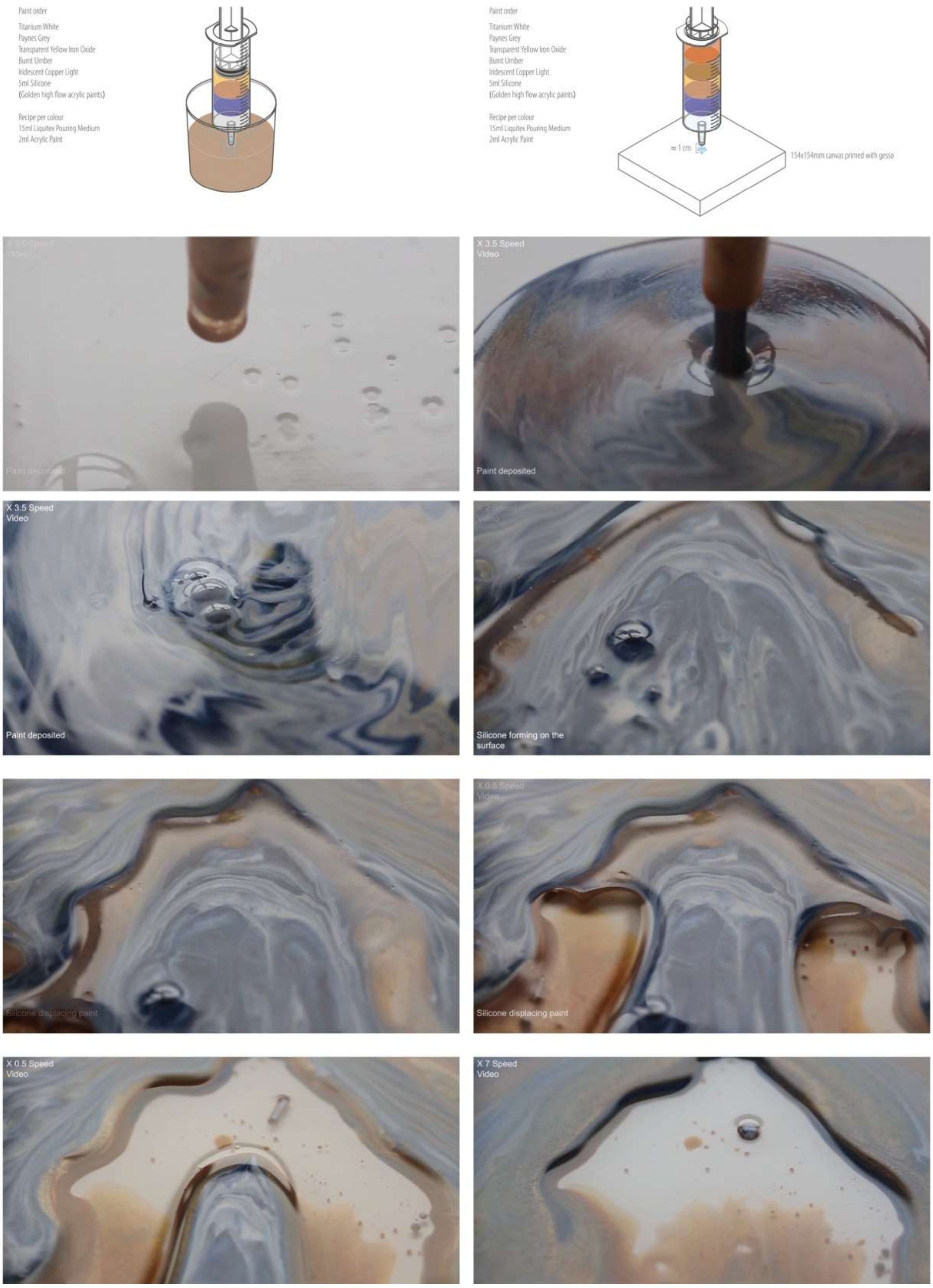


Figure 91: Silicone contrasts and displaces acrylic paint informing: void spaces (i.e. empty spaces), boundaries, layers and streak formations, which highlights how contrasting materials can guide self-assembly. Video link for painting D: https://vimeo.com/270687667

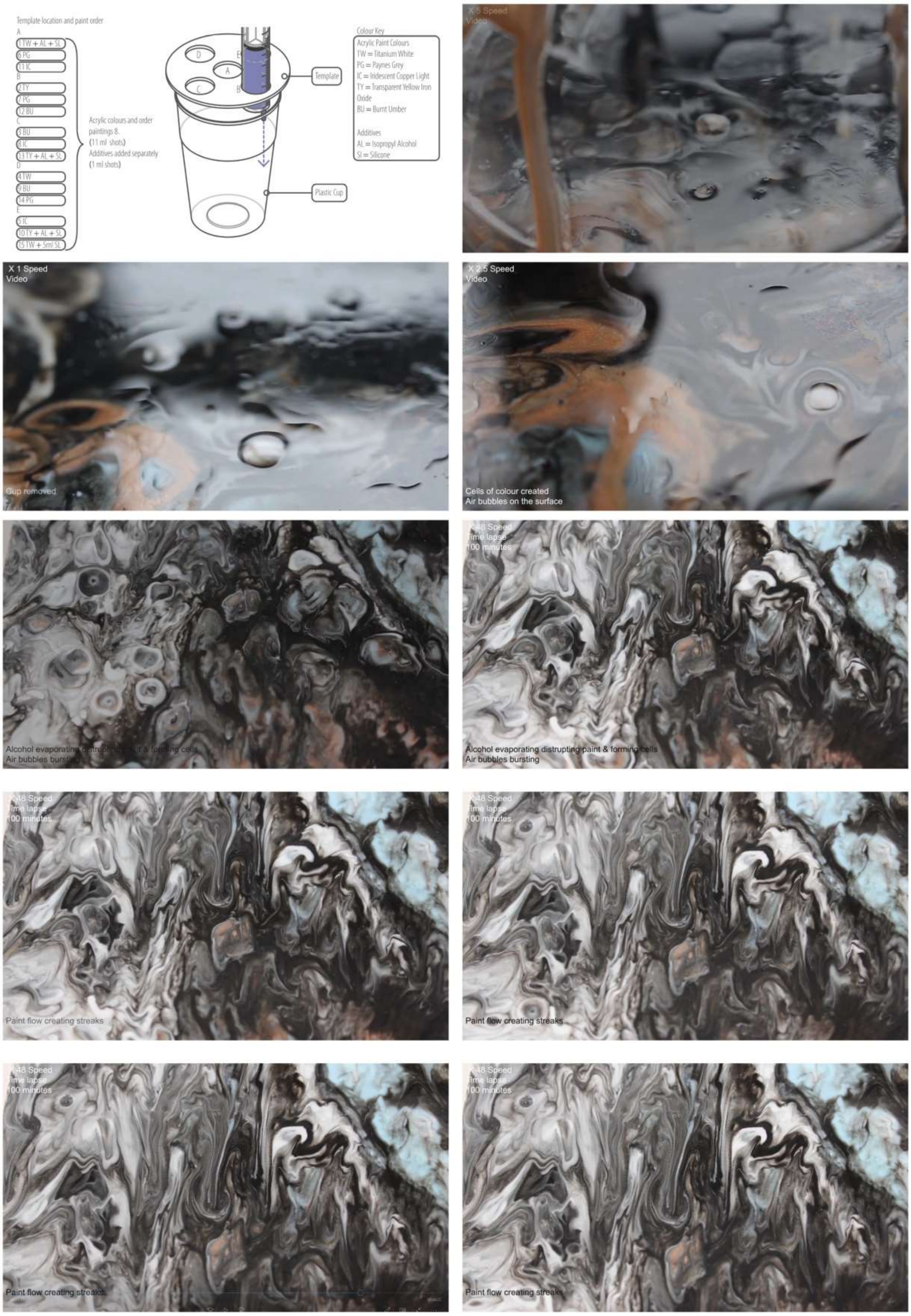


Figure 92: Images reveal interactions taking place in situ produce greater pattern diversity. Video link for painting G: https://vimeo.com/270696373

Figure 93: Series of images revealing how surface texture affects 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 87A). However, defined colour boundaries were created (Figure 89K). Recipes with lower viscosities (Figures 87B and 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 Figures 87B and 91L, compared to Figures 87C and 91M, which depicts 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 and granular properties (e.g. granulation, crazing) could be controlled locally. This could lead to self-assembled structures with gradient-based material properties, which afford increased capacities and reduced material waste (Oxman et al., 2011; Richards et al., 2017).

8.4.2 Pre-initiating interactions

Figures 87D-F and 89N-P illustrate the importance of where material 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, and creating structures with improved material integrity as there are no defined joint lines. Soldevila et al. demonstrate how controlled material transition can be achieved using 3D printing technologies (Soldevila et al., 2015). However, the combination of silicone and paint (Figures 87D, 89N and 91) revealed an exciting possibility for guiding the shape of material self-assembly by using *contrasting materials*. *Contrasting materials* means materials are combined that 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. In this way, contrasting materials could be used as a flexible scaffold to guide material self-assembly in comparison to the rigid scaffolds required in the mineral accretion process.

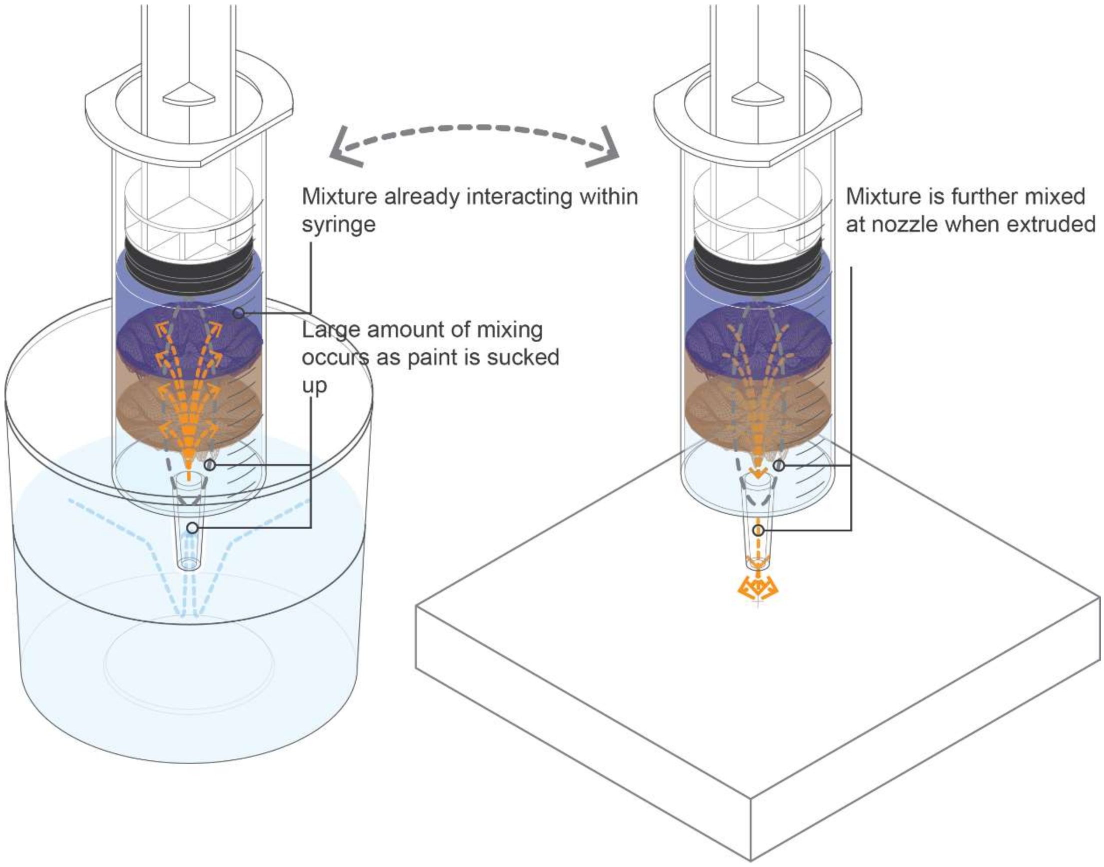


Figure 94: As the paint volumes are sucked up within the syringe the paint flow and then gravity cause the colours to mix. Additionally, further mixing and colour homogenisation occurs as the collection of paints is then squeezed out through the syringe's nozzle and onto the canvas.

8.4.3 In-situ interactions

Figures 88G, 88H, 90Q , 90R and 92 reveal the diverse patterns possible when the interactions are carried out in situ 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 of unmixed fluid materials can create infinitely diverse patterns.

8.4.4 Surface textures

Figures 88I and 90S demonstrated the effect that varied surface textures have on paints deposited in individual layers compared to Figures 87 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 interactions 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 demonstrates how global patterns can be maintained as the *contrasting materials* do not mix. However, a threshold volume of material is required in order to maintain material separation, in this case, the heights of the materials 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 86J. Water and alcohol acted as *disruptive materials* as they initiated material mixing and broke down material boundaries (Figure 88T). *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, self-assembled structures.

8.5 Material probe 08: reflections

The results have revealed several challenges in reproducing patterns and effects:

First, the ability to reproduce homogenous 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 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).

Second, the results also demonstrate 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 enables more robust interactions, this prevented the two material types mixing but the combination of them still affect the patterns generated. By combining 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, which means that material dispersion, diffusion or mixing could happen at various levels and amounts within a 3D volume. The ability to govern diffusion rates and enable 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.

Third, 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, 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 Material probe 08: Conclusions and Development

The results demonstrate the variety of material effects made possible when using undefined self-assembling materials. Guiding material interactions at granular resolutions 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 stimuli. 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 and questions that need to be explored are:

How can patterns generated in 2D be generated in 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.

How can stimuli be induced 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 generated. For example, diffusion and dispersion rates reduce using more viscous support materials.

The next two material probes will explore these challenges. In doing so, the probes reimagine 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 material probes can be found within the paper: *Designing Parametric Matter*.

8.7 Material probe 09: Contrasting Interface

Material probe 09 is a small study, which is to initially understand how 2D generative patterns can become 3D and how varying support material properties (densities) into which inks are deposited 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 Material probe 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 material probe. The different properties of the support materials are the only focus of this probe. There is no stimulus deliberately induced upon the materials once they are all combined/deposited. The significant stimuli that 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 material probe was carried out https://vimeo.com/274898577.

8.7.2 Material probe 09: analysis

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

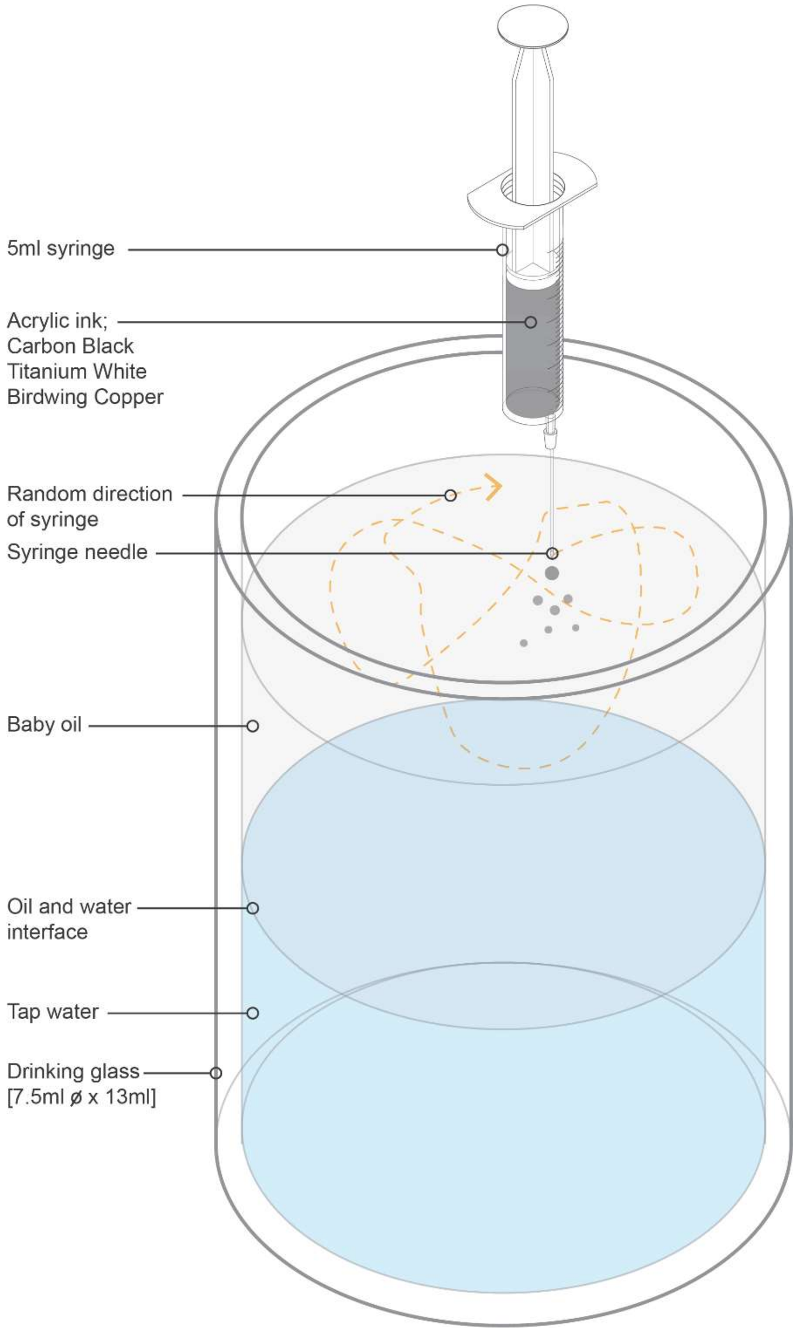


Figure 95: Material probe 09 contrasting interfaces. A glass was filled half with water and half with baby oil, which creates a contrasting boundary interface. Acrylic ink was then manually deposited into the mixture, using a syringe with an attached hypodermic needle. The material probe examines how various liquids impact 3D ink diffusion. Video link highlighting the process: https://vimeo.com/274898577

8.8 Material probe 09: Results

The results from depositing the inks are shown in Figure 95, which is a sequence of images taken from a video. The several factors of interest witnessed (see attached link below Figure 95) will be discussed sequentially:

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/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) Over time, the ink droplets randomly burst at the oil and water interface, which then results in three material properties; *first,* the energy created from the droplets bursting can displace and eject other droplets from the cluster. Therefore, contrasting materials can be used to instil energy into the materials to move units without directly inducing a stimulus from hardware devices. *Second,* 2D ink patterns are generated 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. *Third,* 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, showing that multi-material patterns and forms are generated across timescales.

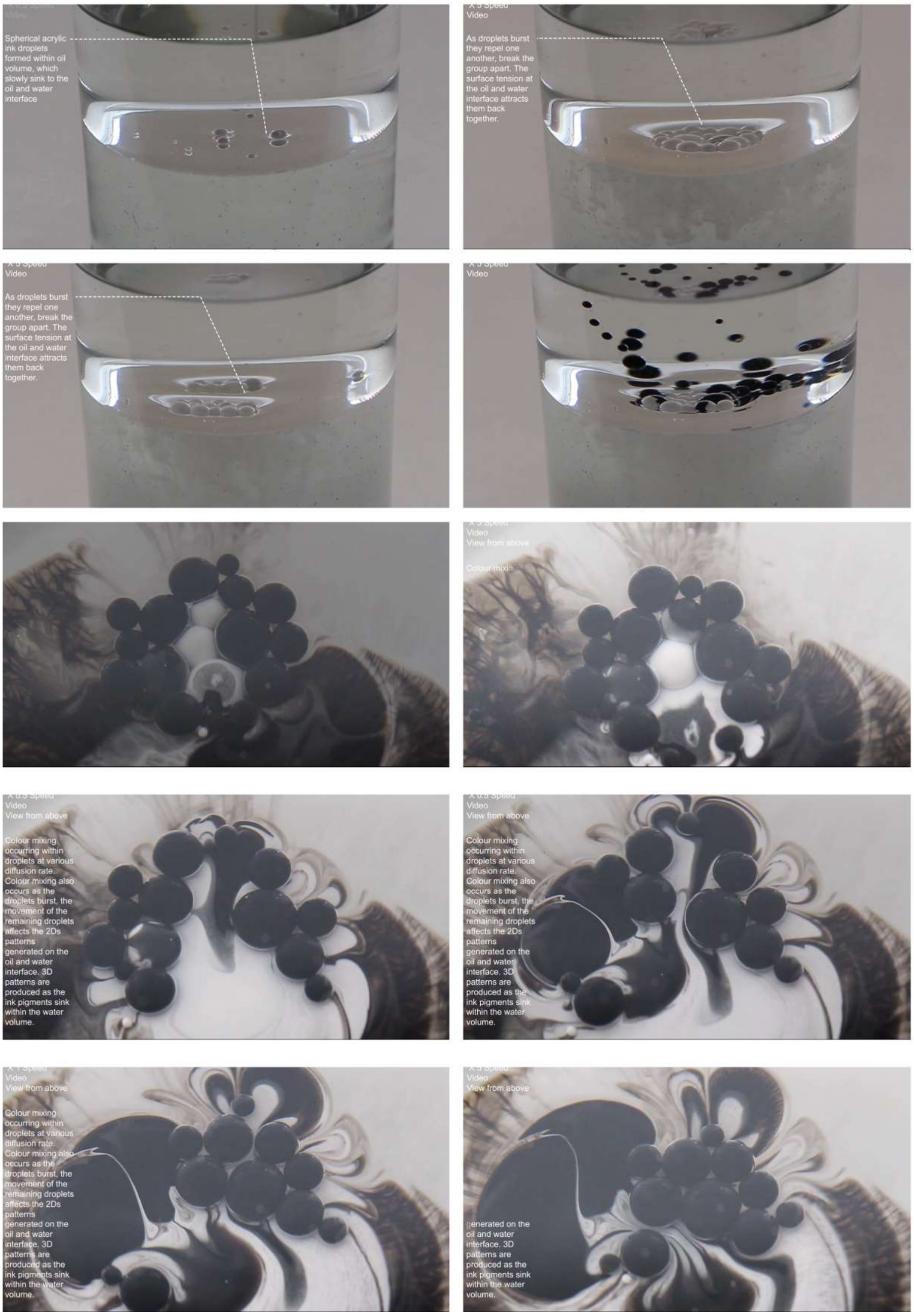


Figure 96: Contrasting interfaces. Reveals ink behaviour within contrasting support volumes; bursting at the oil/water boundary to form ink clouds. Video link for interface induced diffusion: https://vimeo.com/274898577

8.9 Material probe 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, and 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 material probe 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:

First, 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 on 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) because the system is based on diffusion.

Second, the material probe 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 (EWOD) technology is a stimulus 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 material probe are possible since the process is based on material computational processes, such as diffusion. The final material probe explores the question: *How can support material properties and stimuli tune and adapt multi-material properties within 3D volumes?*

8.10 Material probe 10: Diffusing Clouds

Material probe 10 is the final exploration carried out within this thesis. It builds on previous material probes 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 Material probe 10: overview

The ink diffusion material probe is investigated as a means of moving from the 2D paint material probe into 3D volumes. The ink diffusion material probes explore how volumetric ink diffusion properties can be manipulated by varying the viscosity and density of the material/liquid into which they are deposited. The liquid is then agitated via two pumps to evaluate the impacts this stimulus and gravity have 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: 1) water; 2) a sugar syrup at a ratio of 1 part sugar to 2 parts water; and 3) vegetable glycerine. Table 14 highlights the support materials' properties at temperatures between 20 - 25 °C. Water is the least viscous and vegetable glycerine the most viscous.

To evaluate these properties, the same volume of ink must be deposited across all the material probes and at set time intervals. Additionally, the two pumps that agitate the liquids must also be done at set intervals, a set number and set intensities. Four peristaltic dosing pumps are used to ensure the same volumes of ink are deposited. 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 the liquids' viscosities impacts on the amount of energy/stimulus supplied to the self-assembling ink clouds.

8.10.2 Properties

Figure 97 documents the set-up of the material probe. 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 totally dissolved, creating a solution ratio of 1 part sugar to 2 parts water. The syrup was then removed from the heat as soon as all the sugar had dissolved then left to cool to room temperature (≈23°C). Other sugar syrup ratios were produced and tested in preliminary tests but this ratio proved to be the most effective. Table 14 documents the properties of the other support materials used.

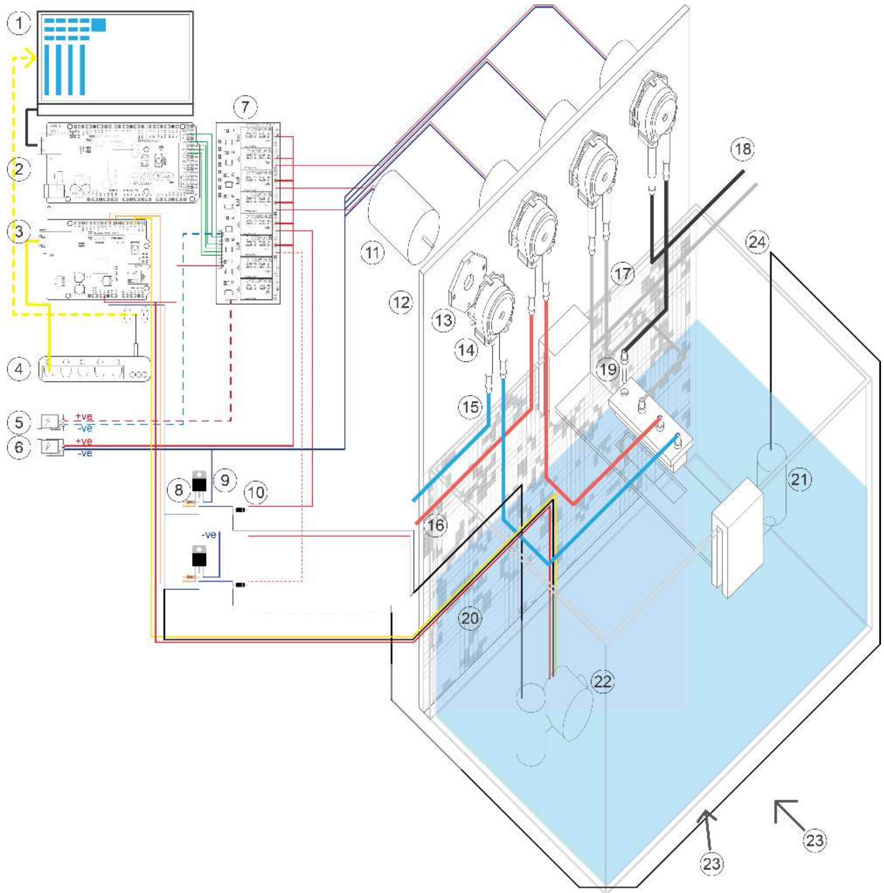
Table 14: Density and viscosity data of support materials

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 pump's speed is slowed in an attempt to make them similar. The timings of the peristaltic dosing pumps and agitation pumps are controlled using Arduino (see Figure 97 for connections). The time durations are defined using a simple user interface created using processing.

8.10.3 Material probe 10: analysis

The material probe results are generated 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 98 illustrates the global effect with the sequence of images for Figure 99 showing 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 the reasons given 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 100).



1) Design tool controlling the hardware developed in processing
2) Arduino Mega
3) Ethernet sheild stacked on top of Arduino Mega
4) Wifi router connected to ethernet shield 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 - 10 connected on prototyping bread board)
11) Peristaltic dosing pump motor
12)
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 held in 3D printed jig
20) 5L support solution, either: water, syrup of vegatble glycerin
21) Agitation pumps
22) Flow meter
23) Camera positions
24) Galss tank 198x 300x 200mm

Figure 97: 4 acrylic ink colours are deposited into 5 litres of liquid (water, sugar syrup or vegetable glycerine) contained within a glass tank. 2ml of each ink colour is 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 that the inks are deposited and the agitation duration, intervals, speed and number of cycles are 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.

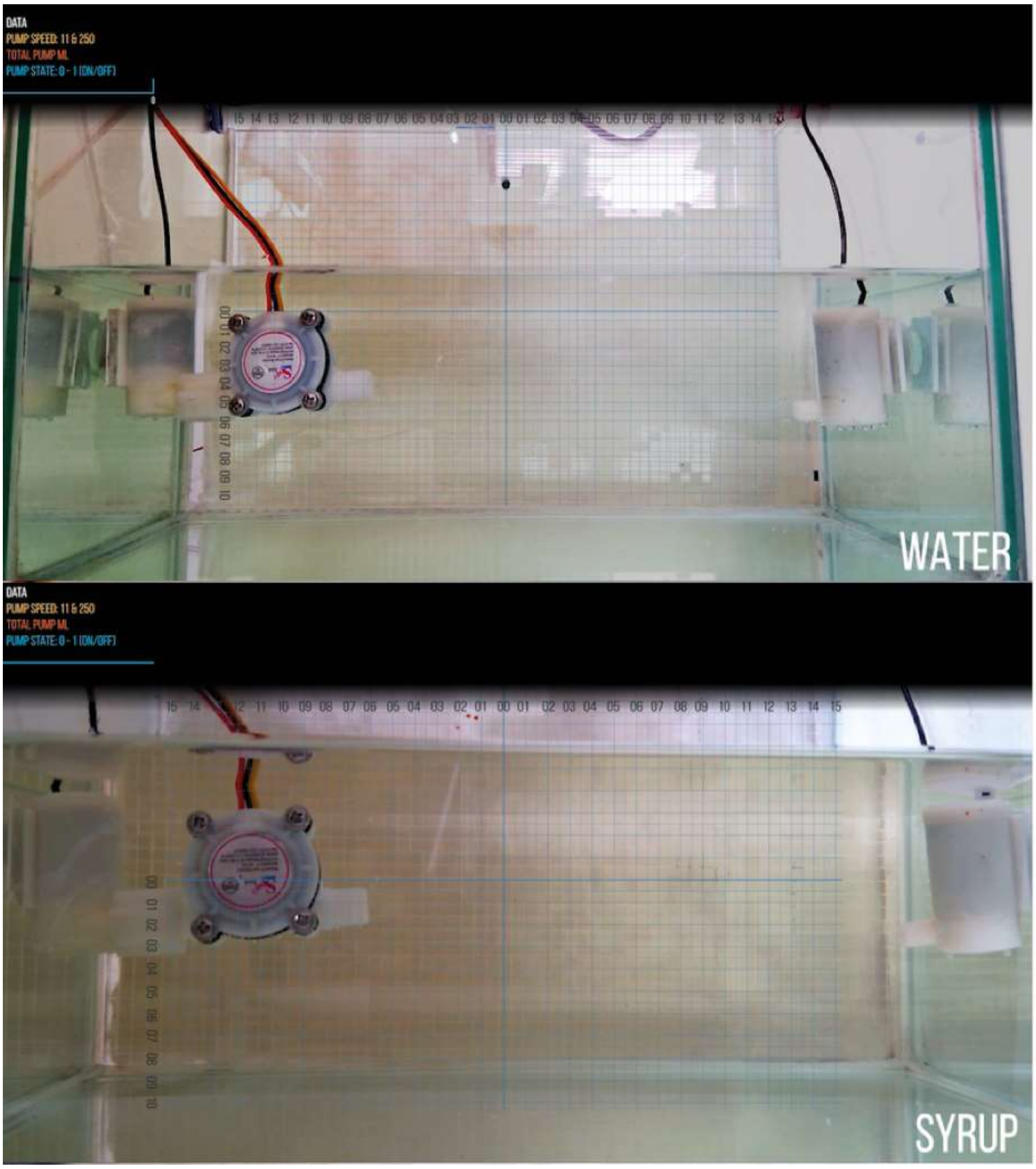
8.10.4 Material probe 10: results

The comparative results between a support material of water and sugar syrup demonstrate several major interesting factors (see Figures 98 - 100);

- ***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 within water. 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 within sugar syrup. This shows that interactions can be slowed down twice as much with a slight change in support material density and viscosity. 0.086 g/cm^3 and 0.37 cp is the difference between water and sugar syrup densities and viscosity values.
- ***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. The 2D patterns, however, are generated by all the other ink colours as they floated back to the surface because the sugar syrup support material is denser than the inks. The pumps and inks created 2D swirled patterns on the syrup's surface, which informs the third point.
- ***Homogenous 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 100).

- ***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 surface patterns were not manipulated either. This indicates that 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 101.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WATER
DATA
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TOTAL PUMP ML
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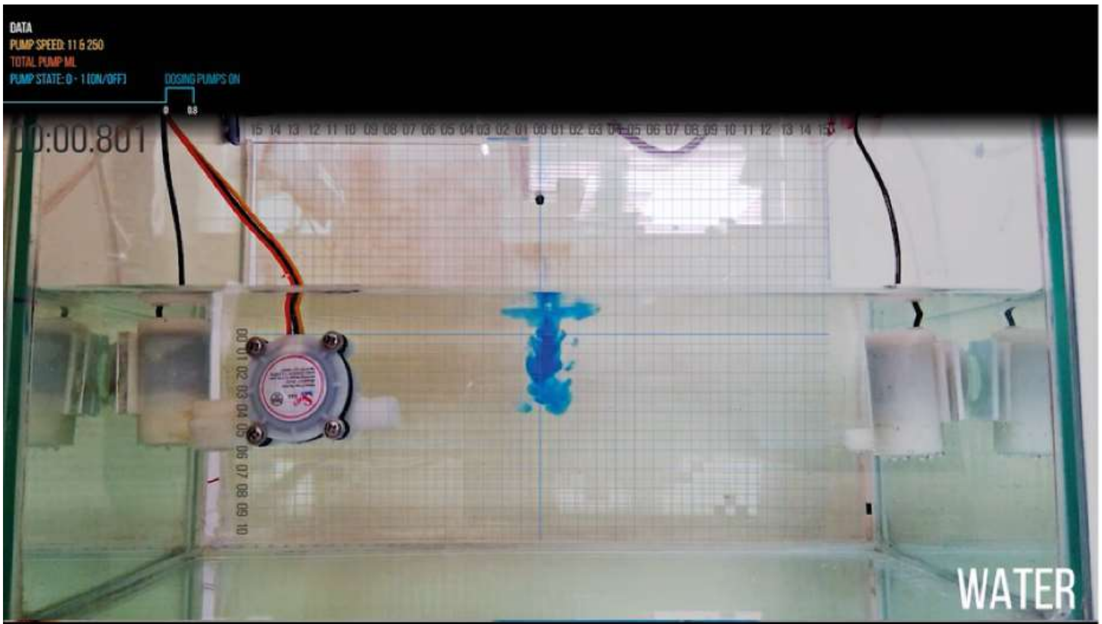
SYRUP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WATER


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TOTAL PUMP ML
PUMP STATE: 0 - 1 [ON/OFF]
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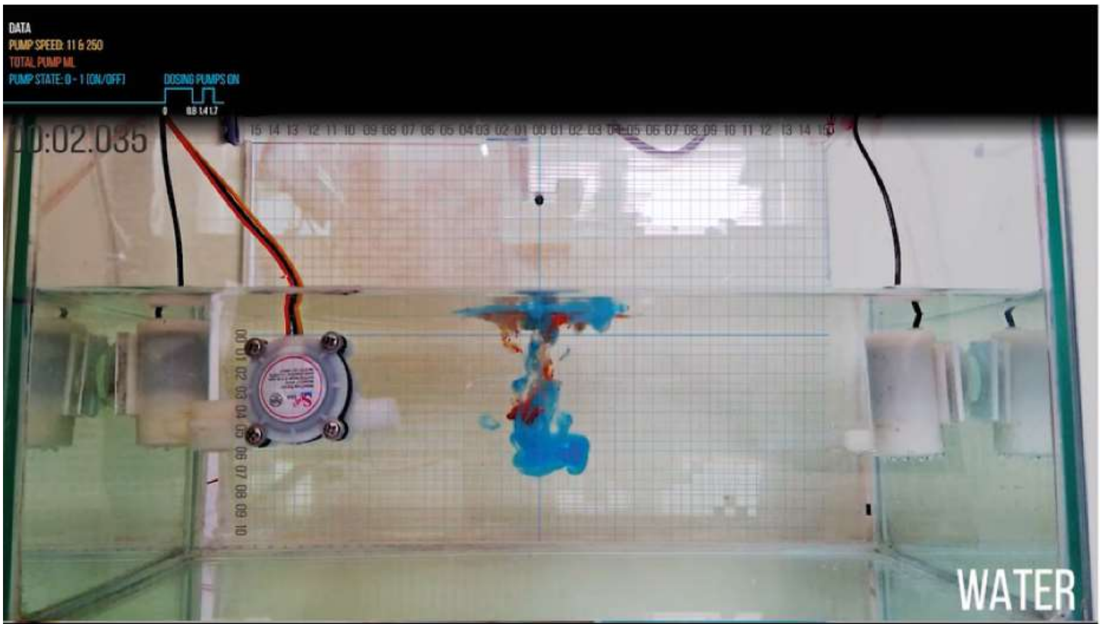
THE BLUE,WHITE AND BLACK INK INKECTED INTO FLOAT BACK TO THE SURFACE BECOMING A PLANAR PATTERN
SYRUP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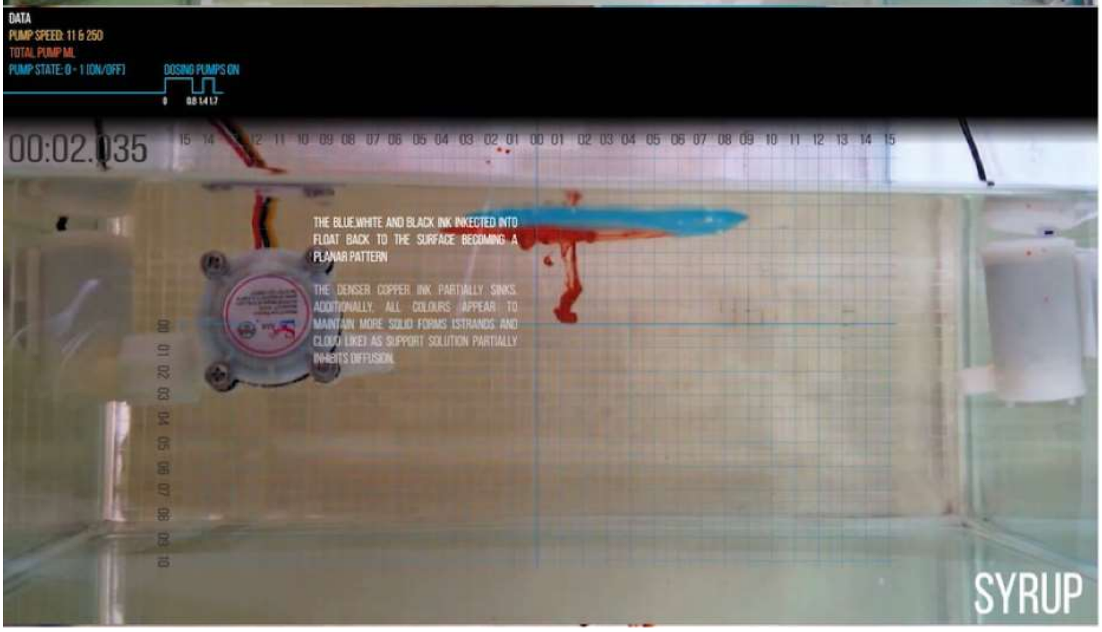
WATER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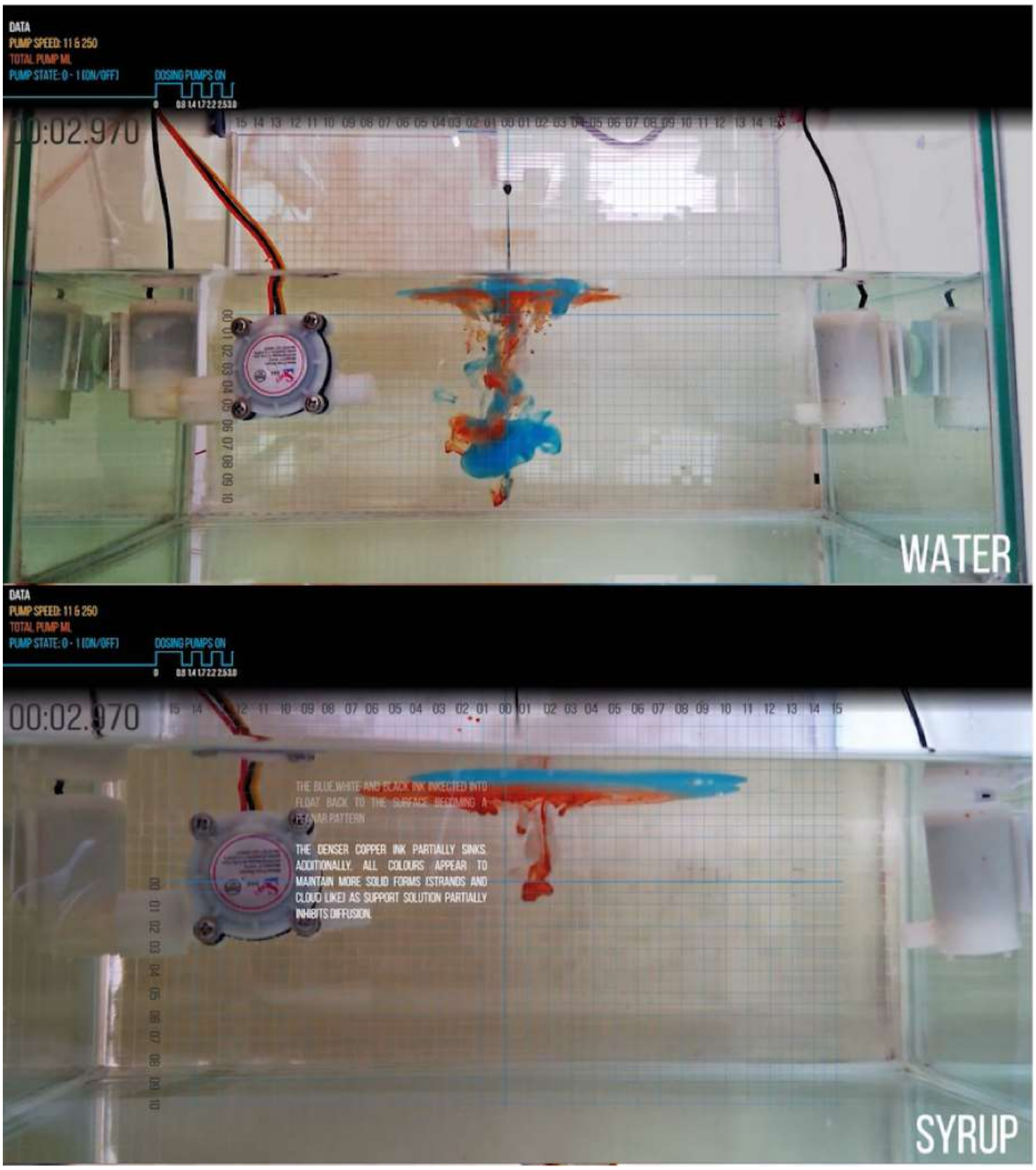
THE BLUE,WHITE AND BLACK INK INKECTED INTO FLOAT BACK TO THE SURFACE BECOMING A PLANAR PATTERN
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP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WATER
DATA
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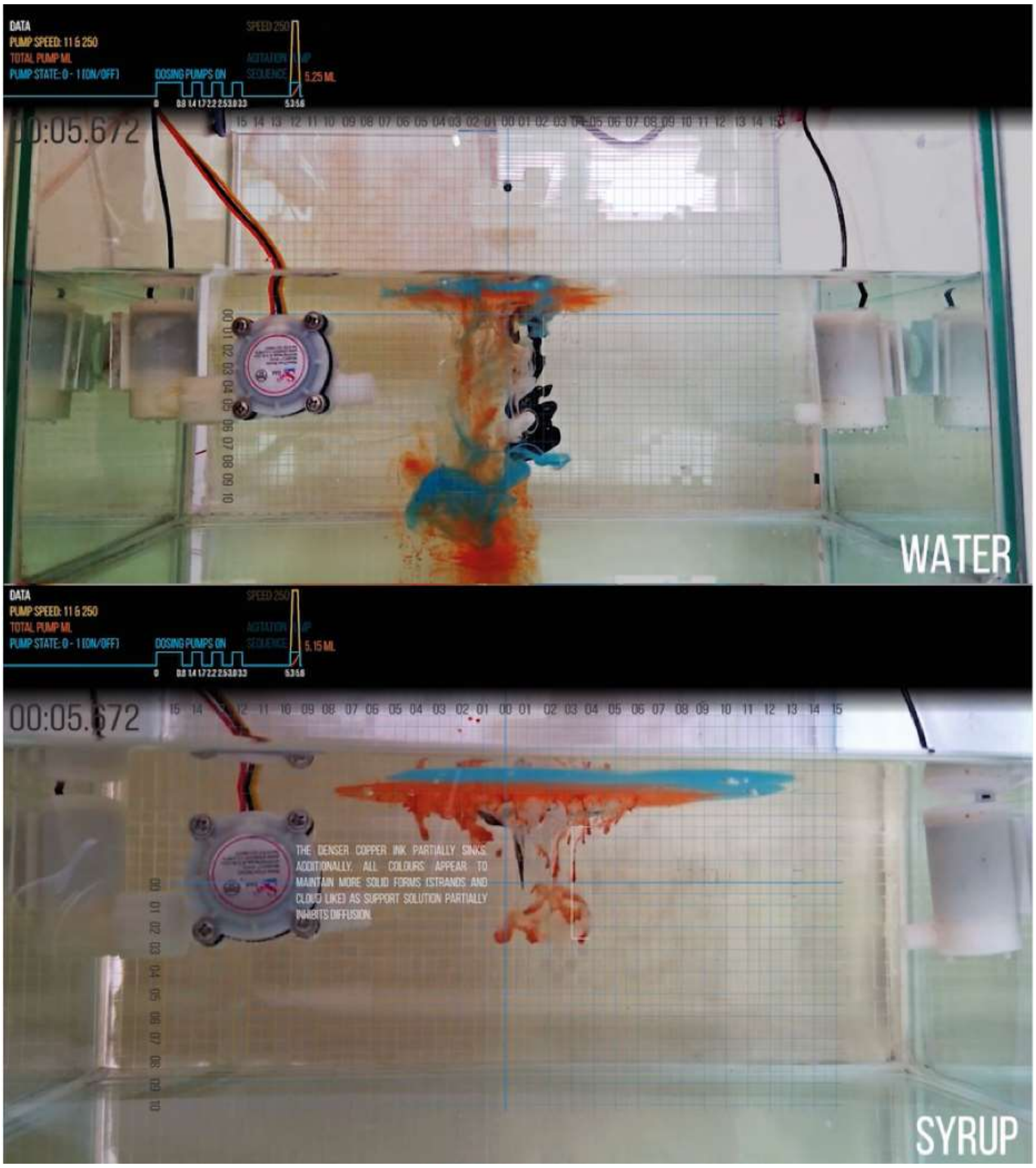
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
0 0.8 1.4 1.7 2.2 2.5 3.0
00:02.970
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP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WATER
DATA
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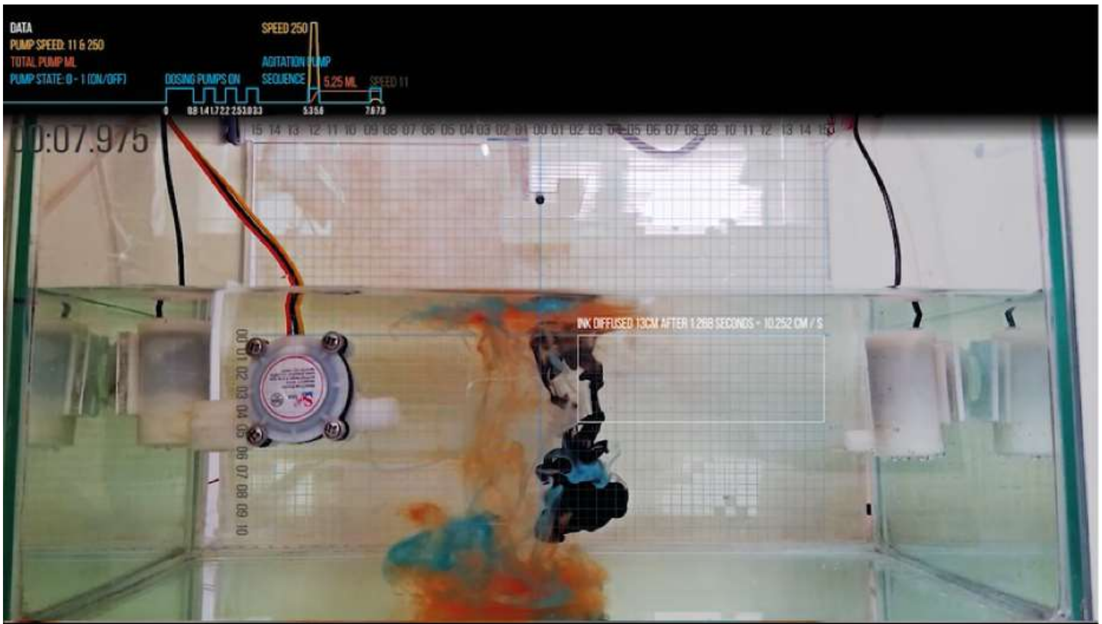
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
5.15 ML
00:05.672
THE DENSER COPPER INK PARTIALLY SINKS. ADDITIONALLY, ALL COLOURS APPEAR TO MAINTAIN MORE SOLID FORMS (STRANDS AND CLOUD LIKE) AS SUPPORT SOLUTION PARTIALLY INHIBITS DIFFUSION.
SYRUP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DOSING PUMPS ON
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AGITATION PUMP
SEQUENCE
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SPEED 11
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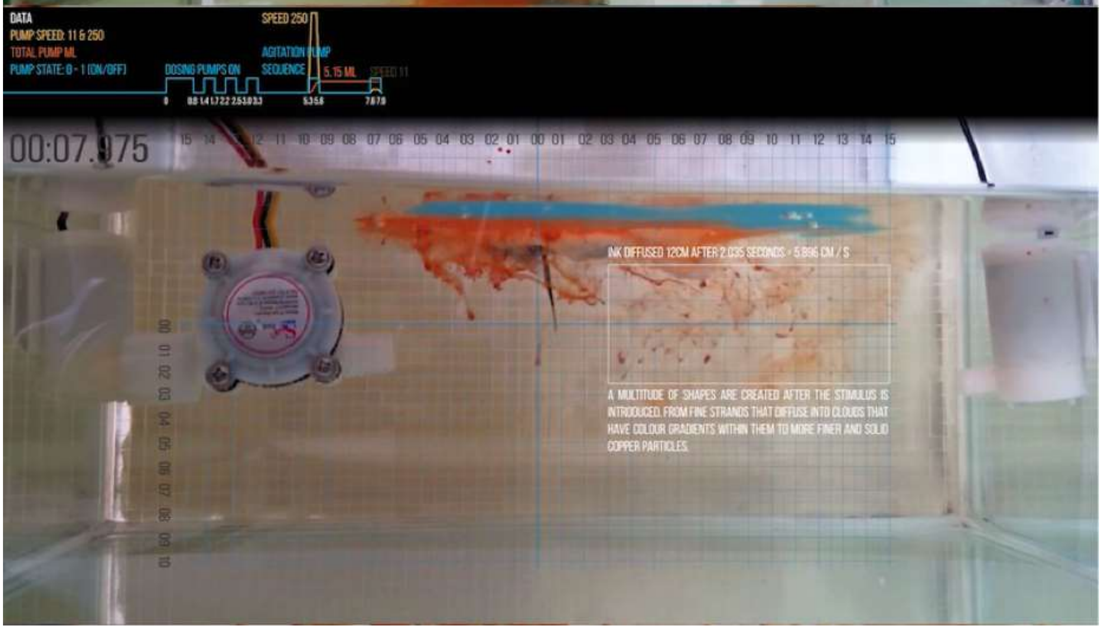
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S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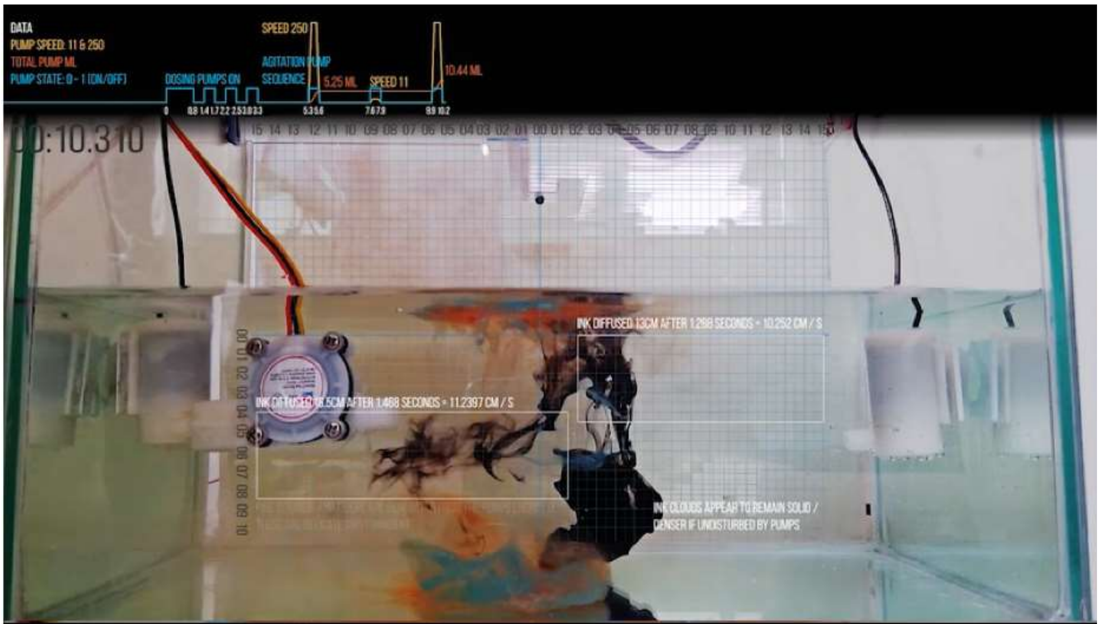
SPEED 250
AGITATION PUMP
SEQUENCE
5.15 ML
SPEED 11
00:07.975
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED. FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.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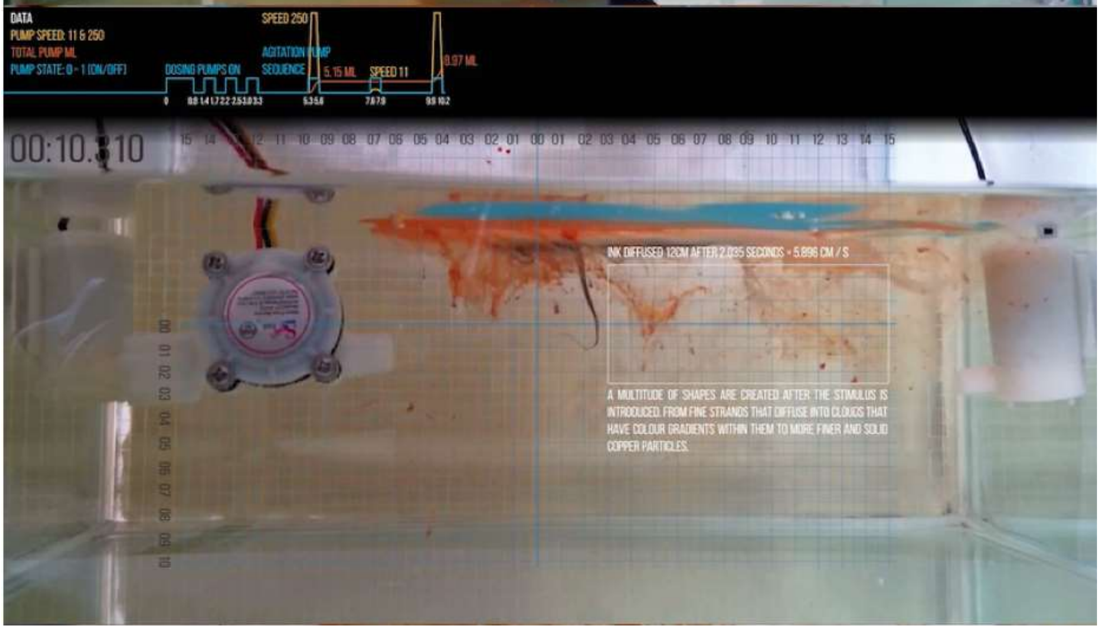
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP SEQUENCE
5.25 ML
SPEED 11
10.44 ML
00:10.310
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
INK DIFFUSED 16.5CM AFTER 1.468 SECONDS = 11.2397 CM / S
INK CLOUDS APPEAR TO REMAIN SOLID / DENSER IF UNDISTURBED BY PUMPS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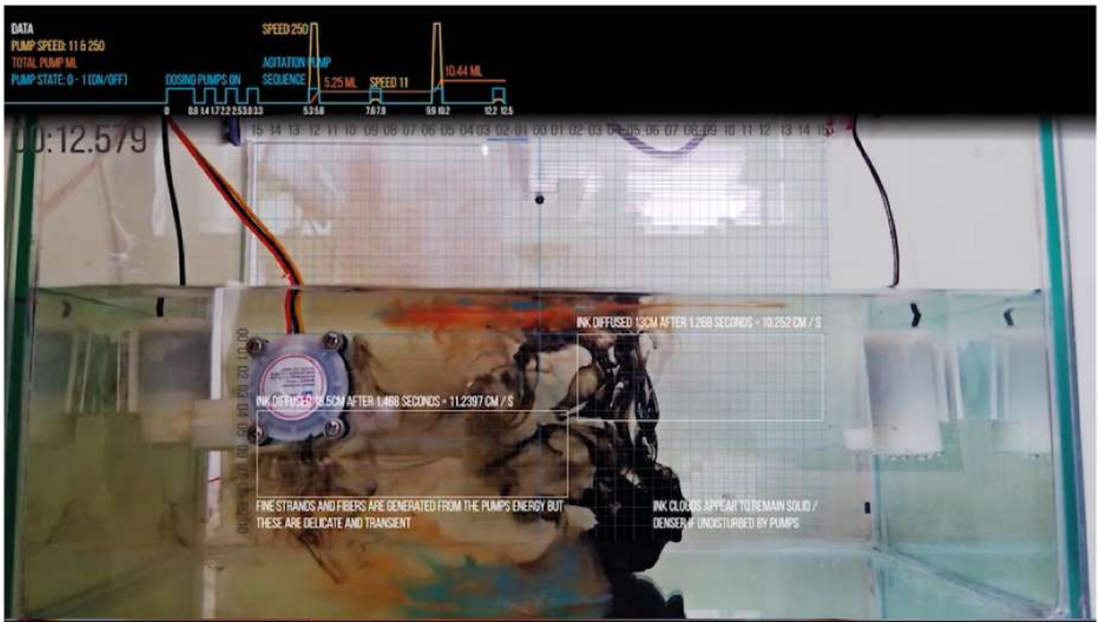
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
AGITATION PUMP SEQUENCE
5.15 ML
SPEED 11
8.97 ML
00:10.310
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED. FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.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SPEED 250
AGITATION PUMP
SEQUENCE
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SPEED 11
10.44 ML
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 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
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TOTAL PUMP ML
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SPEED 11
9.97 ML
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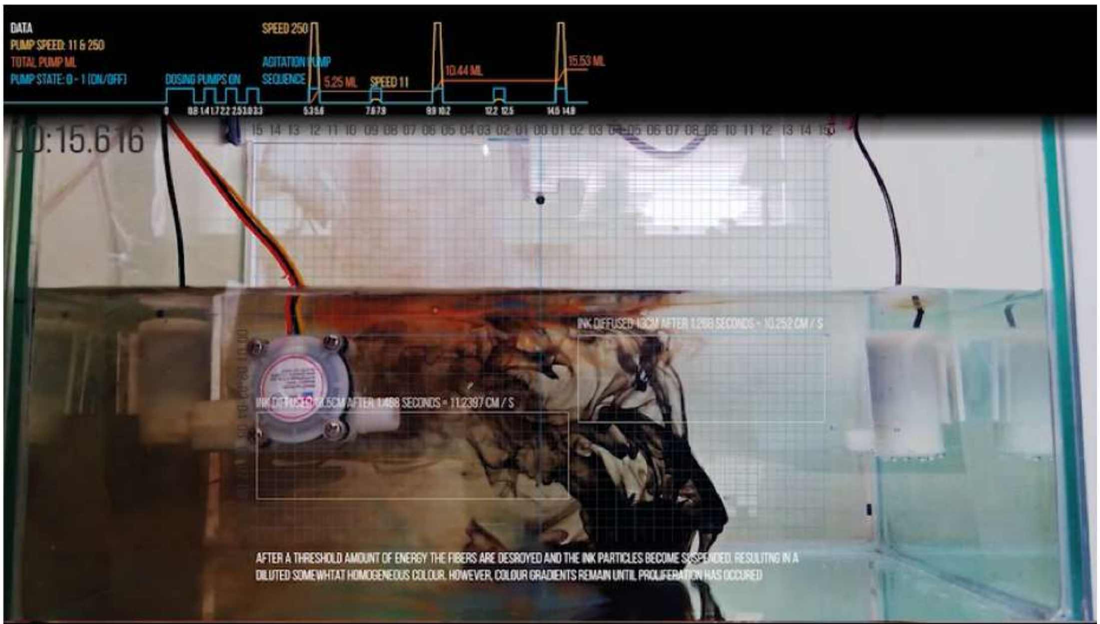
INK DIFFUSED 12CM AFTER 2.035 SECONDS = 5.896 CM / S
A MULTITUDE OF SHAPES ARE CREATED AFTER THE STIMULUS IS INTRODUCED, FROM FINE STRANDS THAT DIFFUSE INTO CLOUDS THAT HAVE COLOUR GRADIENTS WITHIN THEM TO MORE FINER AND SOLID COPPER PARTICLES.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AGITATION PUMP
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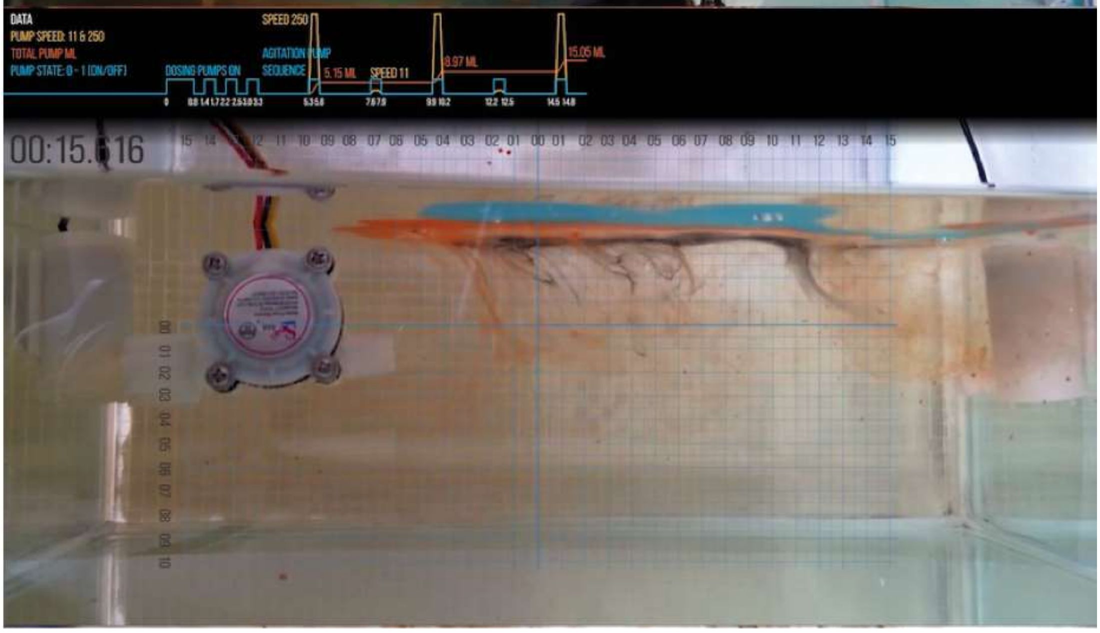
SPEED 11
10.44 ML
15.53 ML
INK DIFFUSED 13CM AFTER 1.268 SECONDS = 10.252 CM / S
AFTER A THRESHOLD AMOUNT OF ENERGY THE FIBERS ARE DESROYED AND THE INK PARTICLES BECOME SUSPENDED. RESULTING IN A
DILUTED SOMEWHTAT HOMOGENEOUS COLOUR. HOWEVER, COLOUR GRADIENTS REMAIN UNTIL PROLIFERATION HAS OCCURED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15.05 ML
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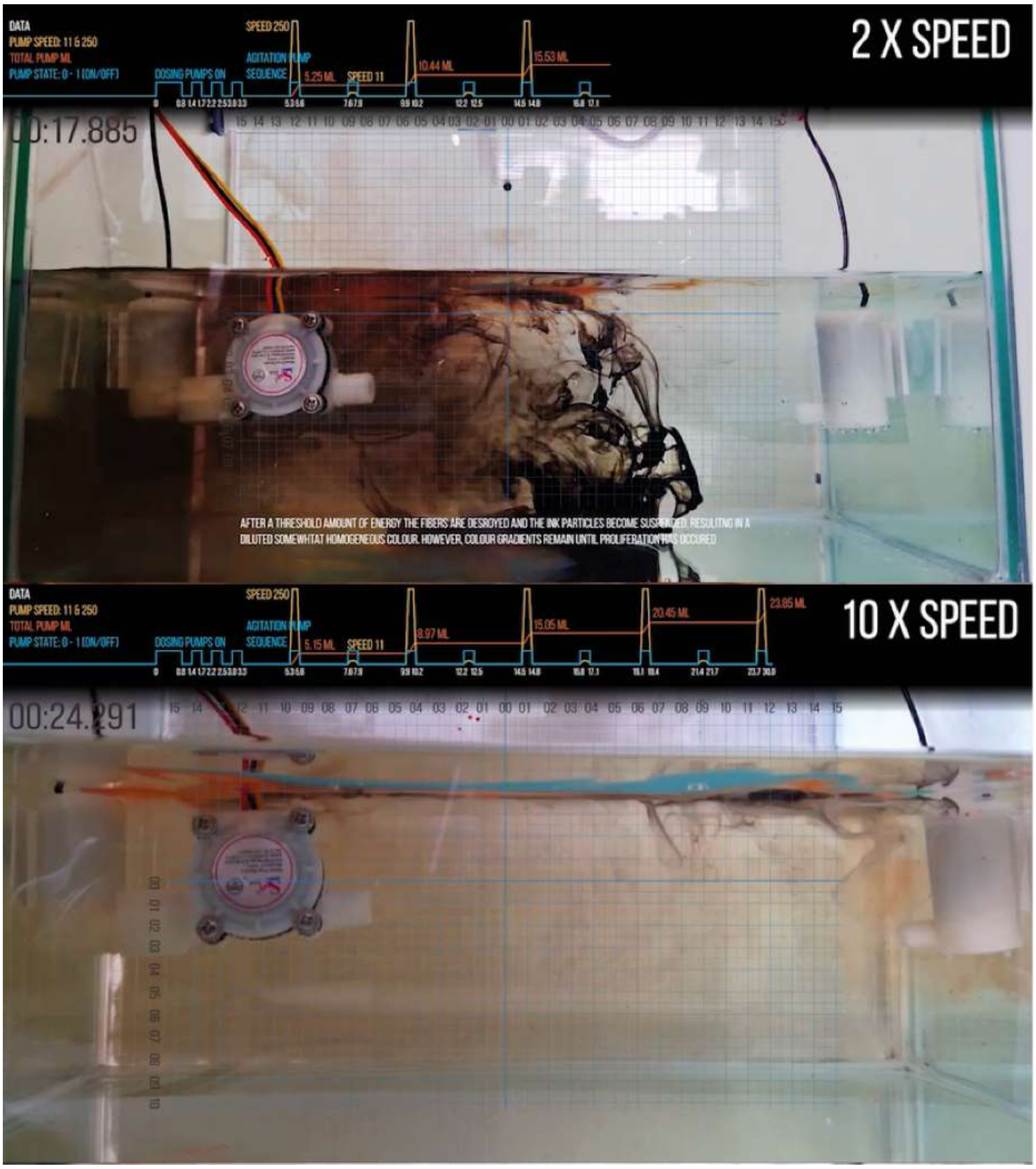
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SPEED 11
10.44 ML
15.53 ML
2 X SPEED
00:17.885
AFTER A THRESHOLD AMOUNT OF ENERGY THE FIBERS ARE DESROYED AND THE INK PARTICLES BECOME SUSPENDED, RESULITNG IN A
DILUTED SOMEWHTAT HOMOGENEOUS COLOUR. HOWEVER, COLOUR GRADIENTS REMAIN UNTIL PROLIFERATION HAS OCCURED
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
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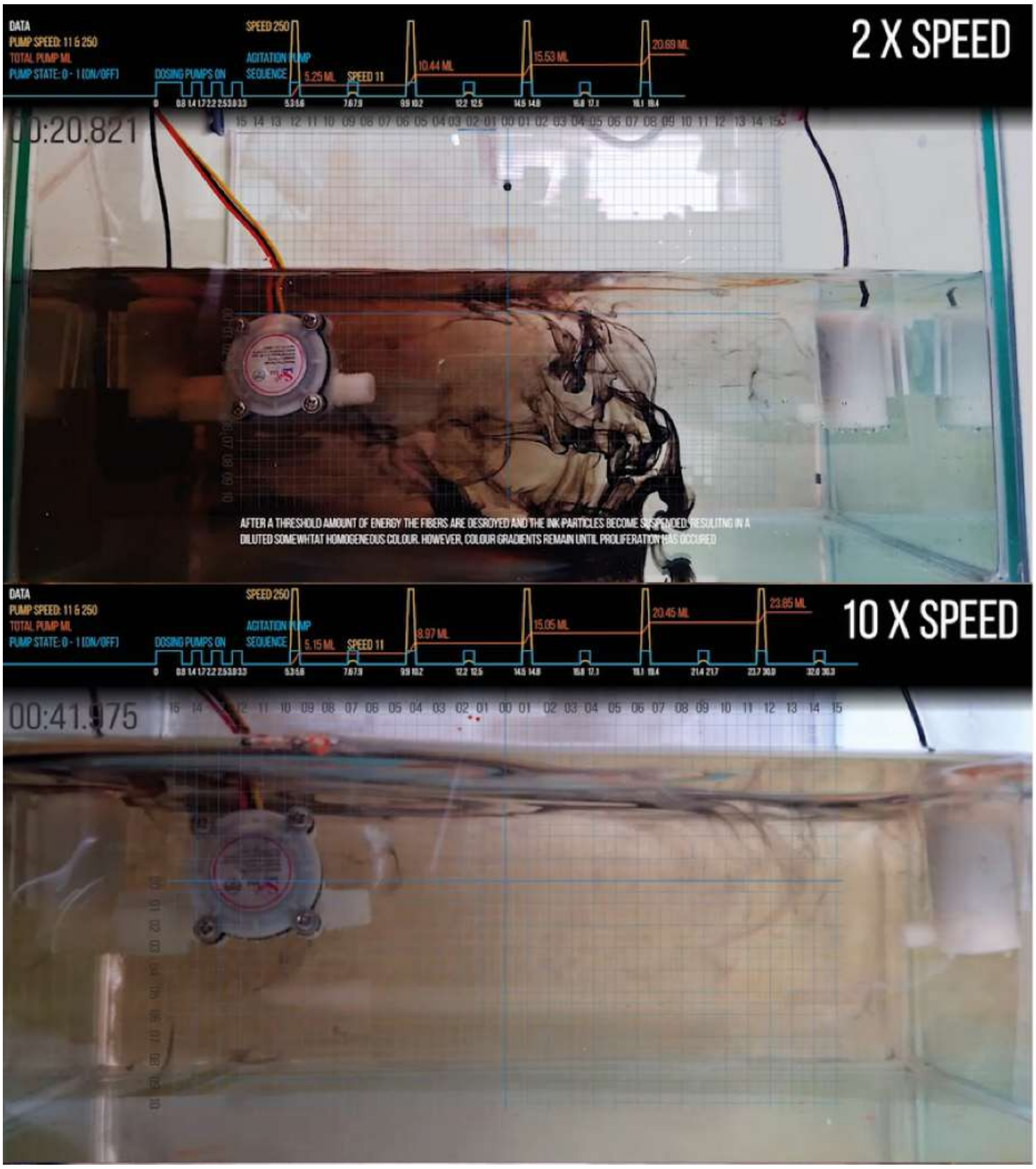
SPEED 11
8.97 ML
15.05 ML
20.45 ML
23.85 ML
10 X SPEED
00:24.291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SPEED 11
10.44 ML
15.53 ML
20.69 ML
2 X SPEED
0:20.821
AFTER A THRESHOLD AMOUNT OF ENERGY THE FIBERS ARE DESROYED AND THE INK PARTICLES BECOME SUSPENDED, RESULTING IN A
DILUTED SOMEWHTAT HOMOGENEOUS COLOUR. HOWEVER, COLOUR GRADIENTS REMAIN UNTIL PROLIFERATION HAS OCCURED
DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
SPEED 250
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SPEED 11
8.97 ML
15.05 ML
20.45 ML
23.85 ML
10 X SPEED
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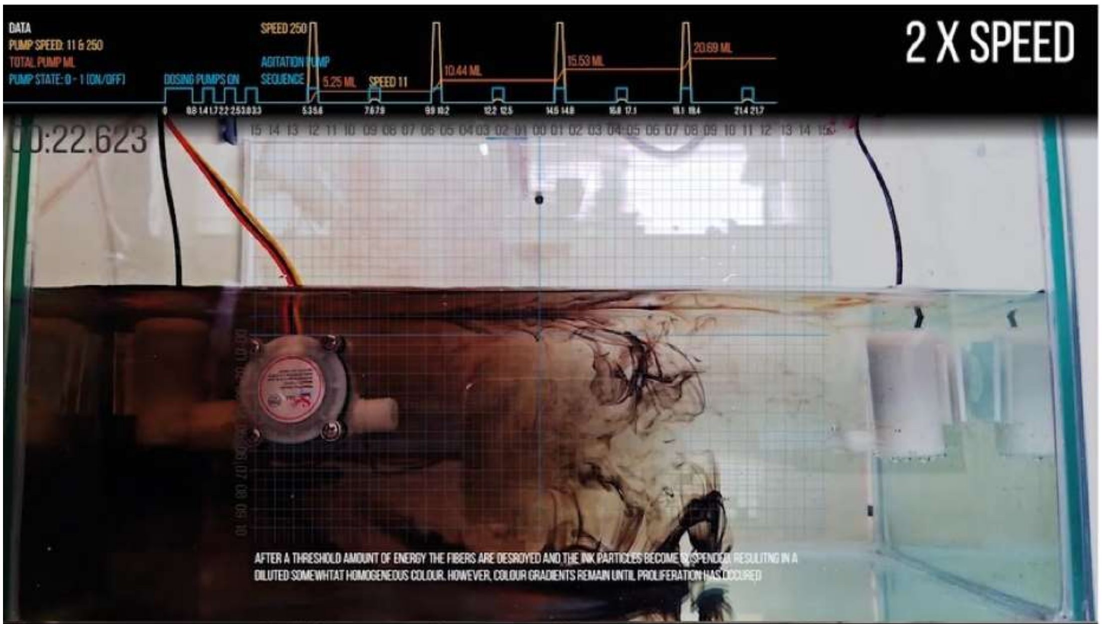
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AGITATION PUMP
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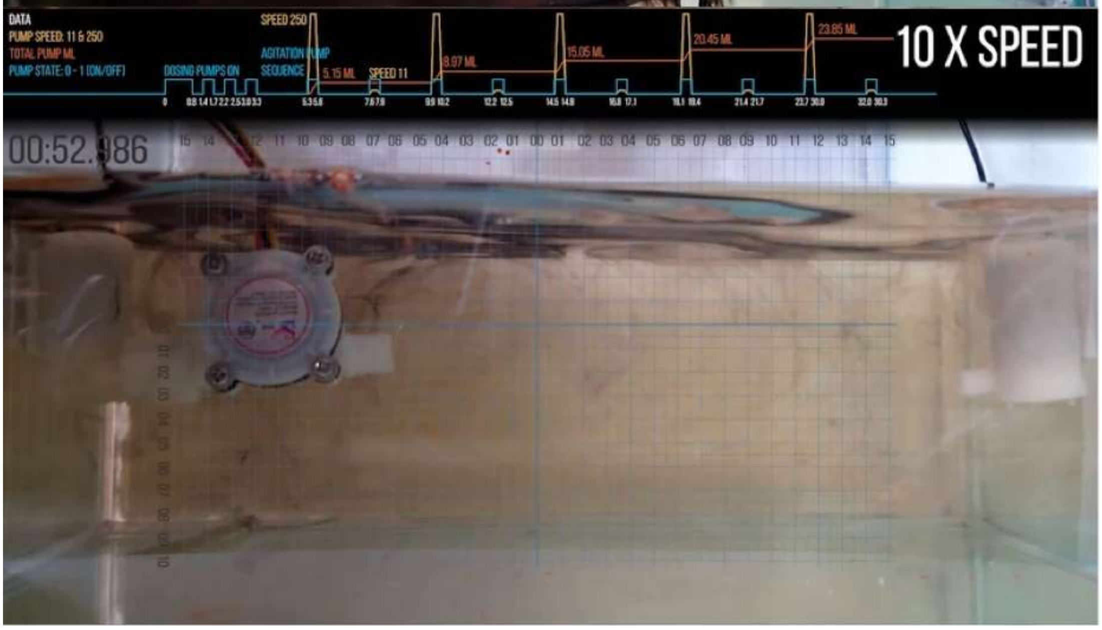
SPEED 11
10.44 ML
15.53 ML
20.69 ML
2 X SPEED
00:22.623
AFTER A THRESHOLD AMOUNT OF ENERGY THE FIBERS ARE DESROYED AND THE INK PARTICLES BECOME SUSPENDED RESULITNG IN A
DILUTED SOMEWHTAT HOMOGENEOUS COLOUR. HOWEVER, COLOUR GRADIENTS REMAIN UNTIL PROLIFERATION HAS OCCURED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TOTAL PUMP ML
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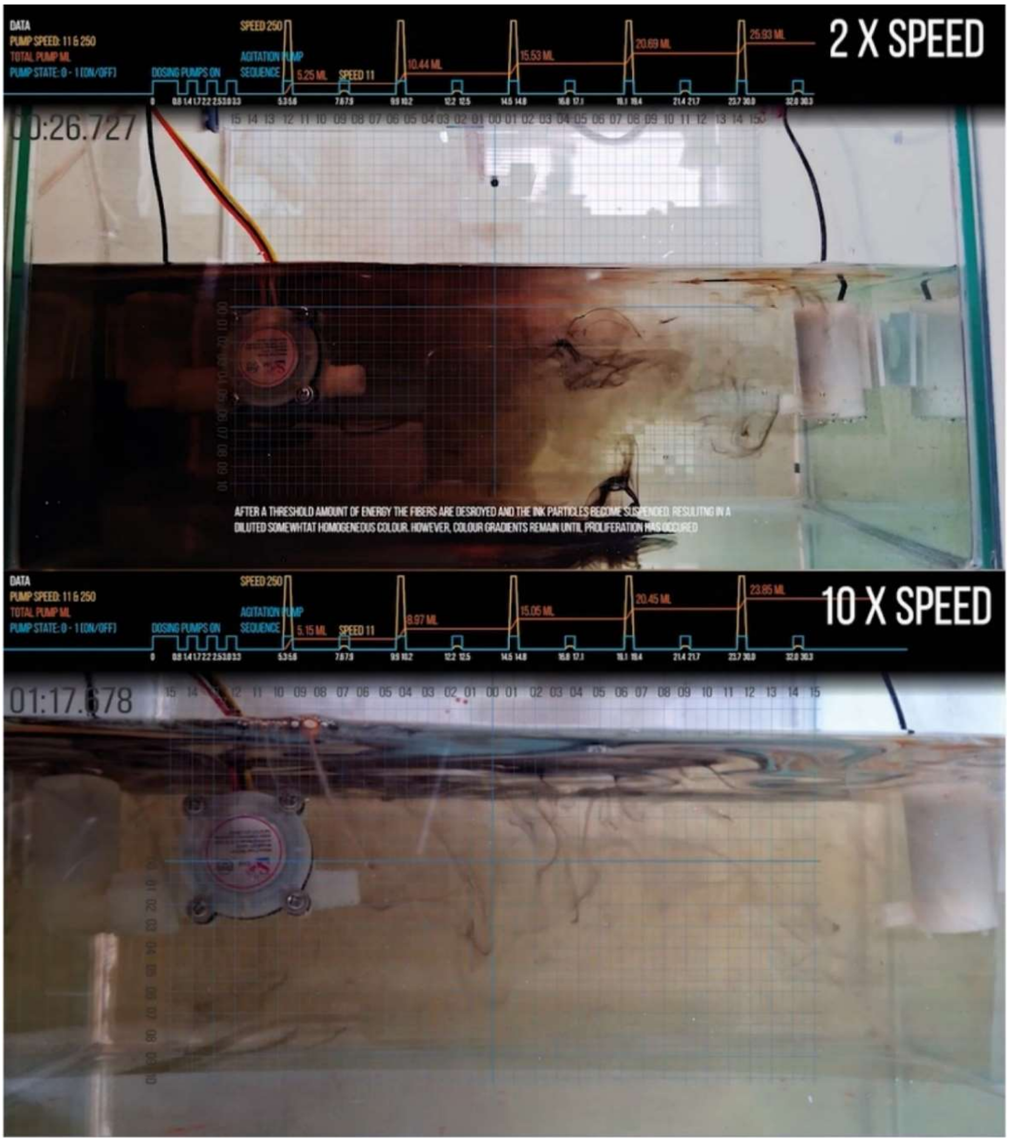
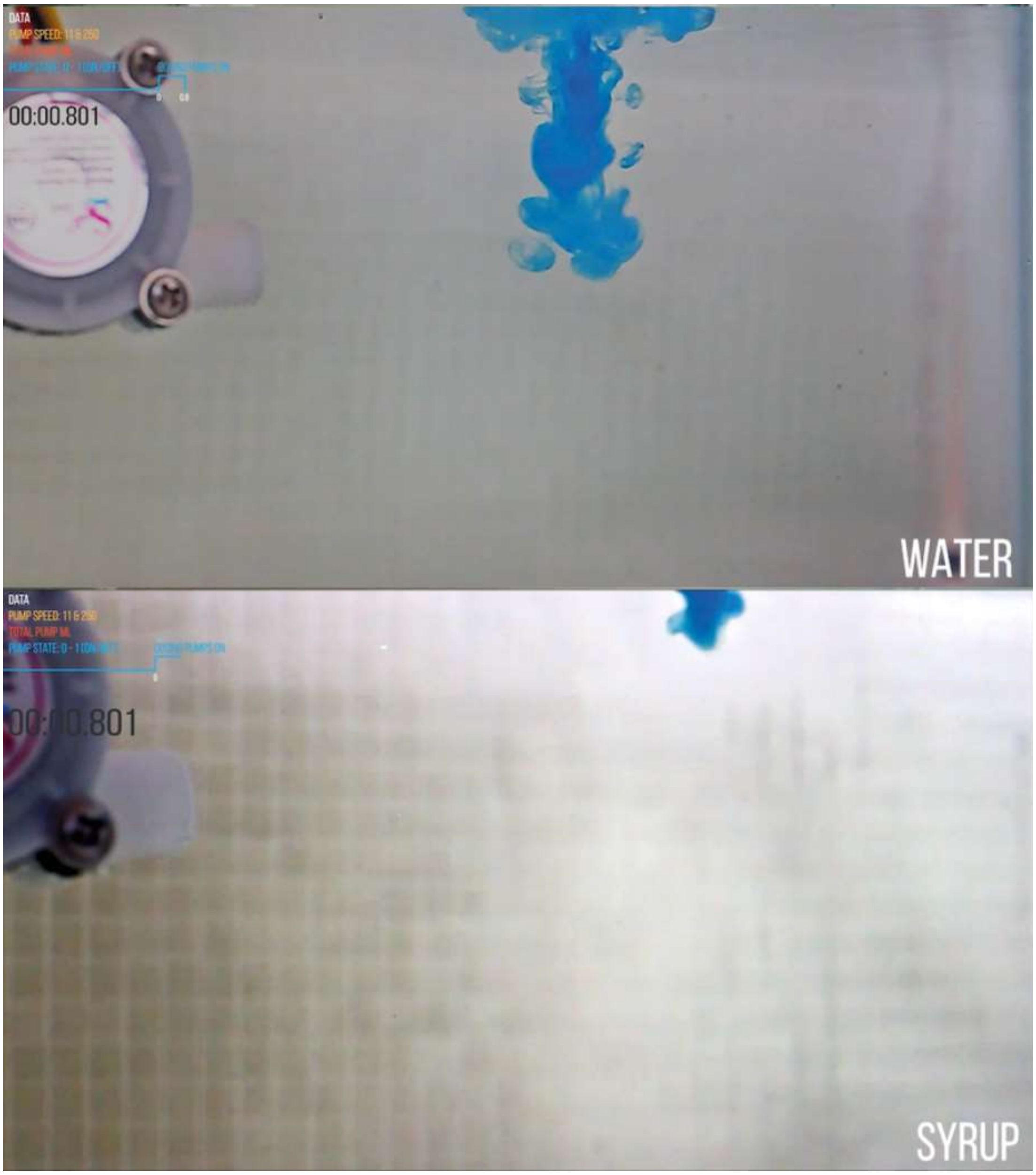


Figure 98: Sequence of images demonstrating the impacts support material properties have on volumetric ink pattern. Water enables the inks to diffuse and disperse more rapidly resulting in a homogenised volumetric colour and pattern. The sugar syrup initially prevents colours from sinking and results in 2D patterns forming at the surface. Over longer periods the colours begin to sink and result in delicate multi-coloured, volumetric fibrous patterns being generated, which are maintained for longer durations. 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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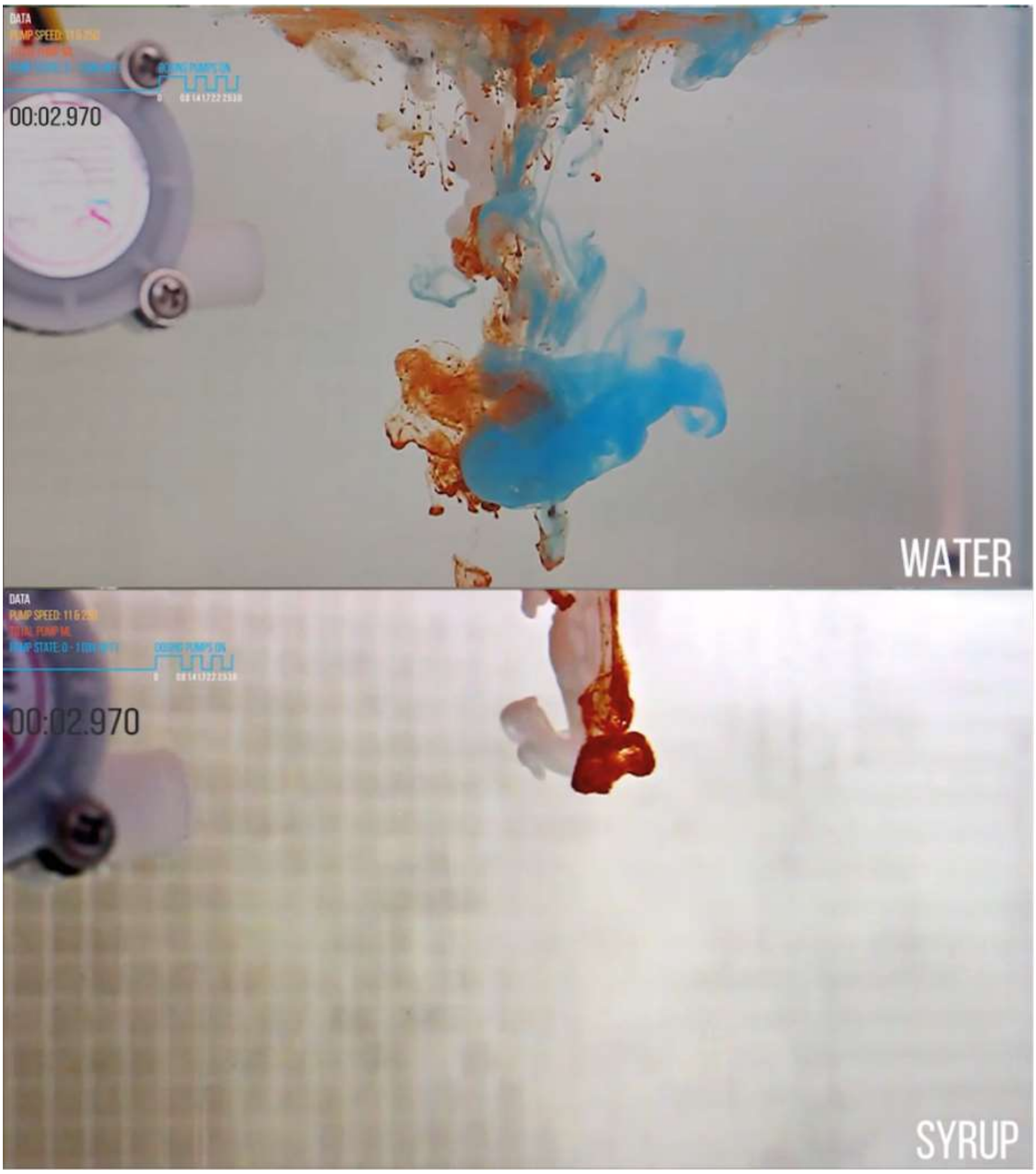
WATER
DATA
TOTAL PUMP ML
00:00.801
SYRUP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WATER
DATA
00:02.970
SYRUP


DATA
00:07.975


DATA
AGITATION PUMP
00:07.975


DATA
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PUMP STATE: 0 - 1 (ON/OFF)
SPEED 250
SPEED 11
00:10.310


DATA
PUMP SPEED: 11 § 250
00:10.310


DATA
PUMP SPEED: 11 & 250
DOSING PUMPS ON
SPEED 250
AGITATION PUMP
SEQUENCE
5.25 ML
15.53 ML
00:17.885


DATA
PUMP SPEED: 11 & 250
TOTAL PUMP ML
5.15 ML
8.97 ML
15.05 ML
20.45 ML
23.85 ML
00:24.224


DATA
PUMP SPEED: 11 & 250
DOSING PUMPS ON
SPEED 250
SPEED 11
00:22.623


DATA
TOTAL PUMP ML
PUMP STATE: 0 - 1 (ON/OFF)
DOSING PUMPS ON
AGITATION PUMP
SEQUENCE
5.15 ML
8.97 ML
15.05 ML
20.45 ML
23.85 ML

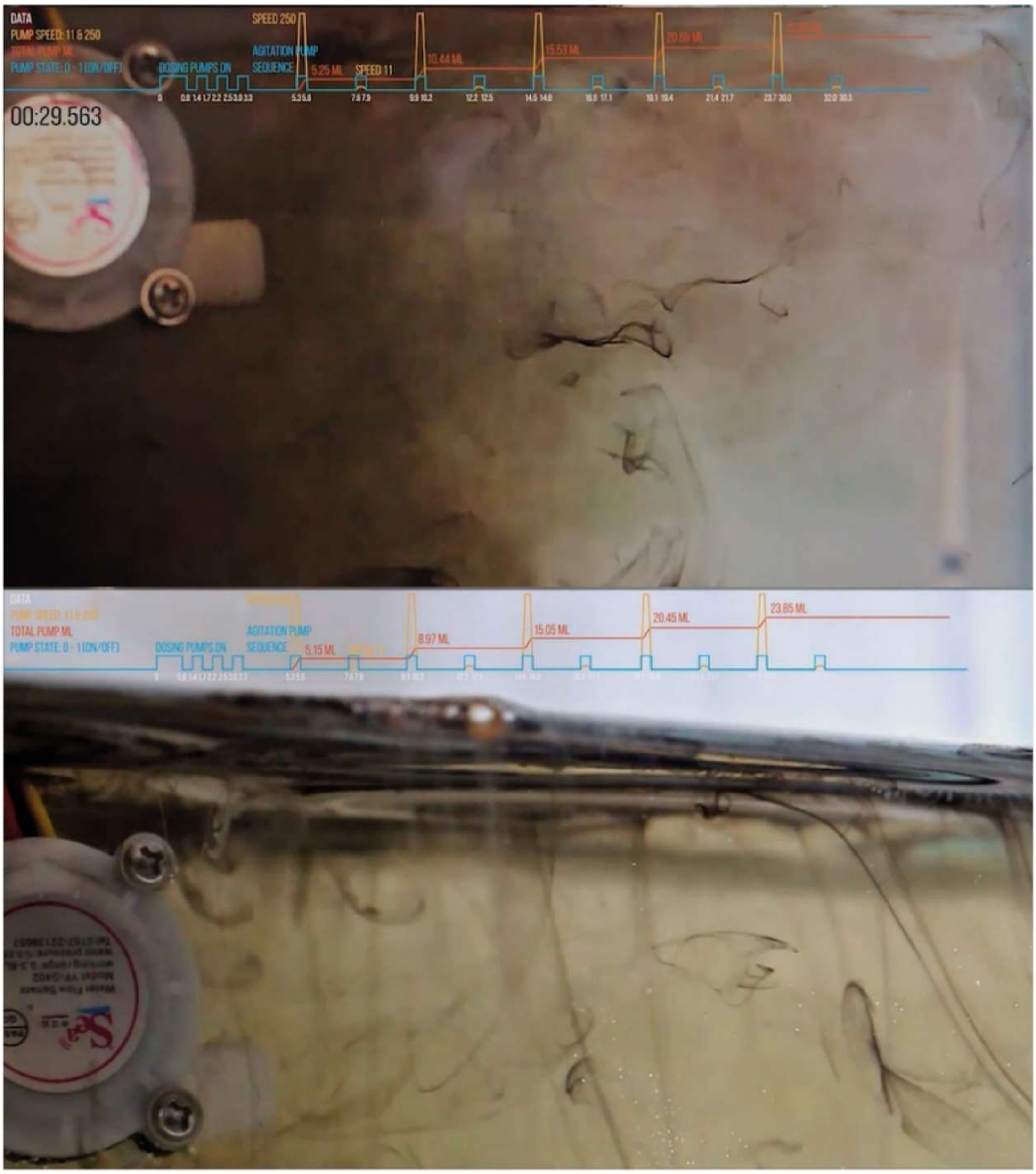


Figure 99: Sequence of images demonstrating the localised material properties generated from the two different support materials. Video link: https://vimeo.com/367431096

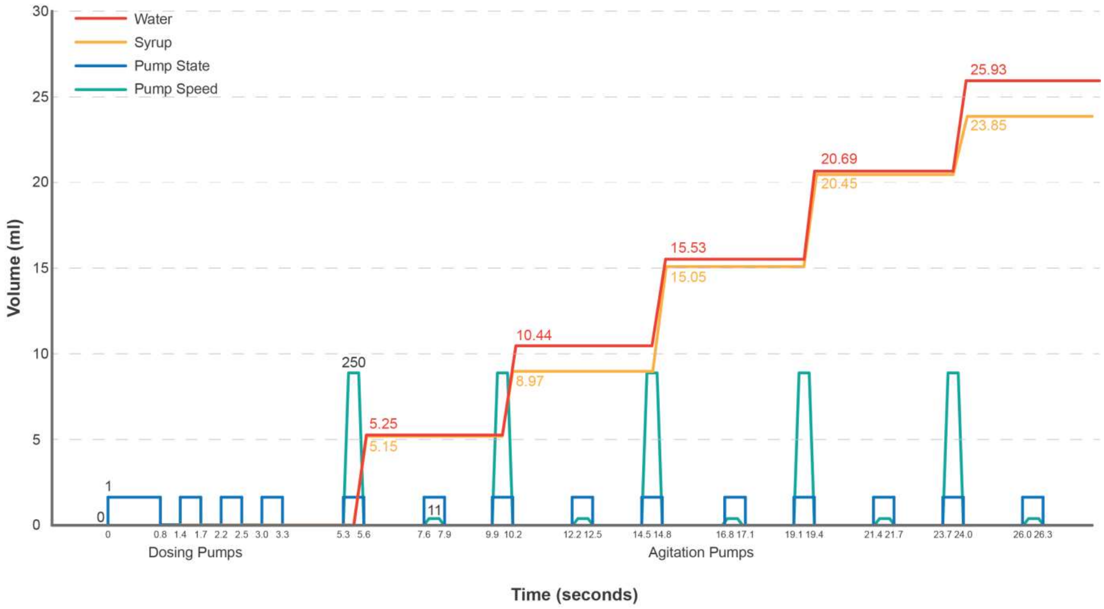


Figure 100: Flowmeter sensor data indicating less total volume recorded with the syrup support material. The reduced volume recorded, particularly during the 2nd and the final cycle reveal that the syrup support material reduces the energy supplied to the inks, which slows and could enable more delicate pattern adaption.

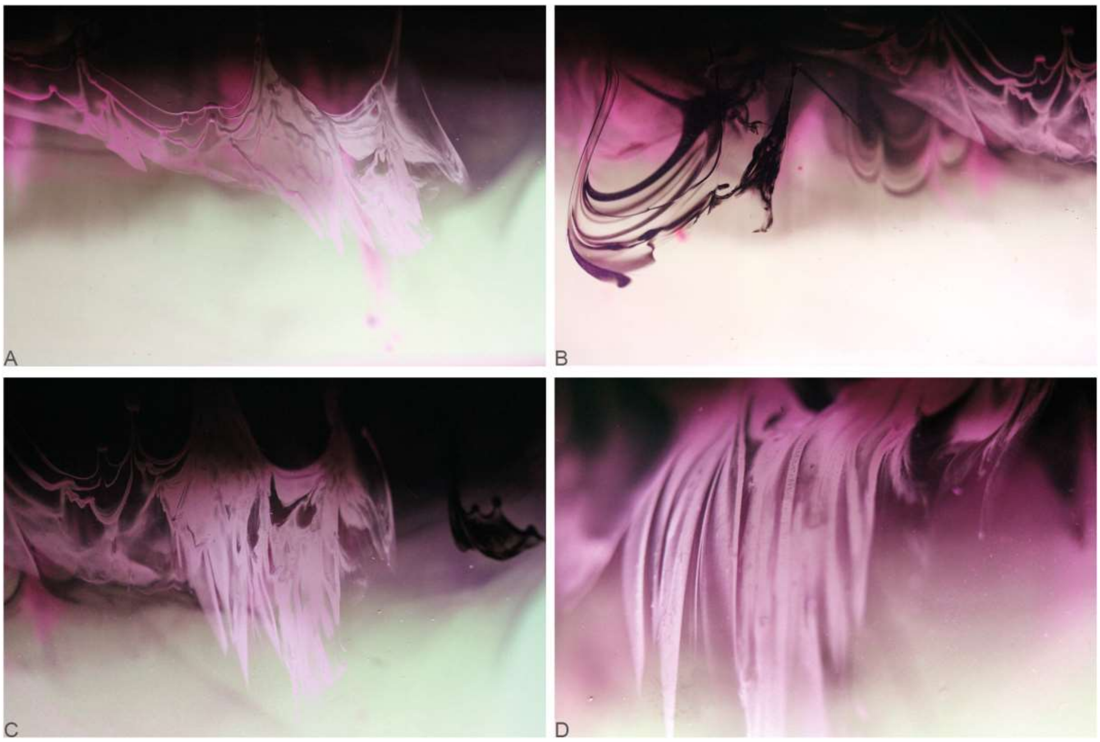


Figure 101: Inks were manually deposited into the vegetable glycerine and then manipulated manually moving a pipette around randomly. The viscous and dense support material suspends the diverse volumetric ink patterns in time. A multitude of properties are generated from web-like (A, C), curved-strand-like (B) to granular (D) as well as fine gradient dispersions.

8.11 Material probe 10: Conclusion

The conclusion is used to discuss: *first* the significant results of the material probe; *second,* 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.

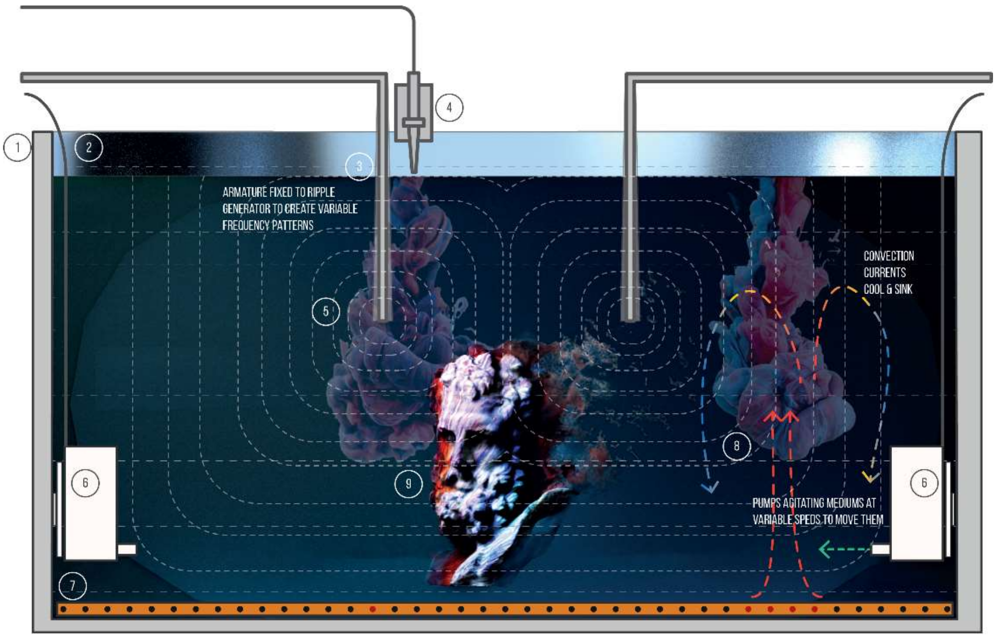
These multiple material properties have been achieved by again developing a fabrication process based on material computational processes but also by exploring the crucial role the support material properties can play in guiding these material computational processes, such as slowing and even suspending: 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 is attained based on *contrasting effects*, which could be detected via sensors or repeatable mechanisms so reliable patterns are created. In Section 3.1.3 it has been proven that high-frequency vibrations (Cymatics) can generate reproducible 2D patterns.

Figure 102 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, significant 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

in order to gain some aspect of control over material computational processes within this system.

- As the structures are fabricated volumetrically, they could lead to enhanced mechanical performance for gradient based structures, where the structure's internal material properties (e.g. density, architecture, composition) could be tuned and adapted throughout its volume.
- 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.



1) Glass tank
2) Support medium used to transfer engery to deposited materials. The support mediums' viscosity is manipulted to govern surface textures
3) High frequency oscillating armature used to create various wave patterns within support medium as demonstrated in cymatics
4) Print head to deposit various materials (inks, resins) via peristaltic pump
5) High frequency waves interacting with one another and used to guide diffusion patterns
6) Pumps used to agitate the solution at variying intensities to guide diffusion patterns
7) Locally controled heating plate to induce convection currents and guide diffusion patterns
8) Deposited material diffuses through support medium and the shapes are guided by various stimulus, such as: agitation, heat, light and vibration frequency waves
9) Speculative multi-material head formed by guiding diffusion patterns using various stimuli (agitation, heat, resonance)

Figure 102: Highly 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.

8.11.1 Paint and ink material probes' unit of matter

Within the series of paint and ink material probes, the units of matter directed to self-assemble are the paint particles and mediums used to either enhance the paints' and inks' flow (floetrol) or prevent them from mixing (silicone). These material probes have huge degrees of freedom and no determined associations and feedback with design tool parameters, making it difficult to generate functional and desirable material properties. However, they demonstrate that self-assembly can be guided using tuneable environments without predesigning properties of each material unit. Furthermore, without incorporating fixed scaffold structures to induce stimuli and inform aspects of the material unit's dimensions resulted in 2D and 3D patterns that could tune and adapt their structures across various scales, dimensions, durations, resolutions and material transitions (i.e. gradients). Figures 103 – 104 display the various units of matter within these series of material probes and their impacts on the patterns generated.

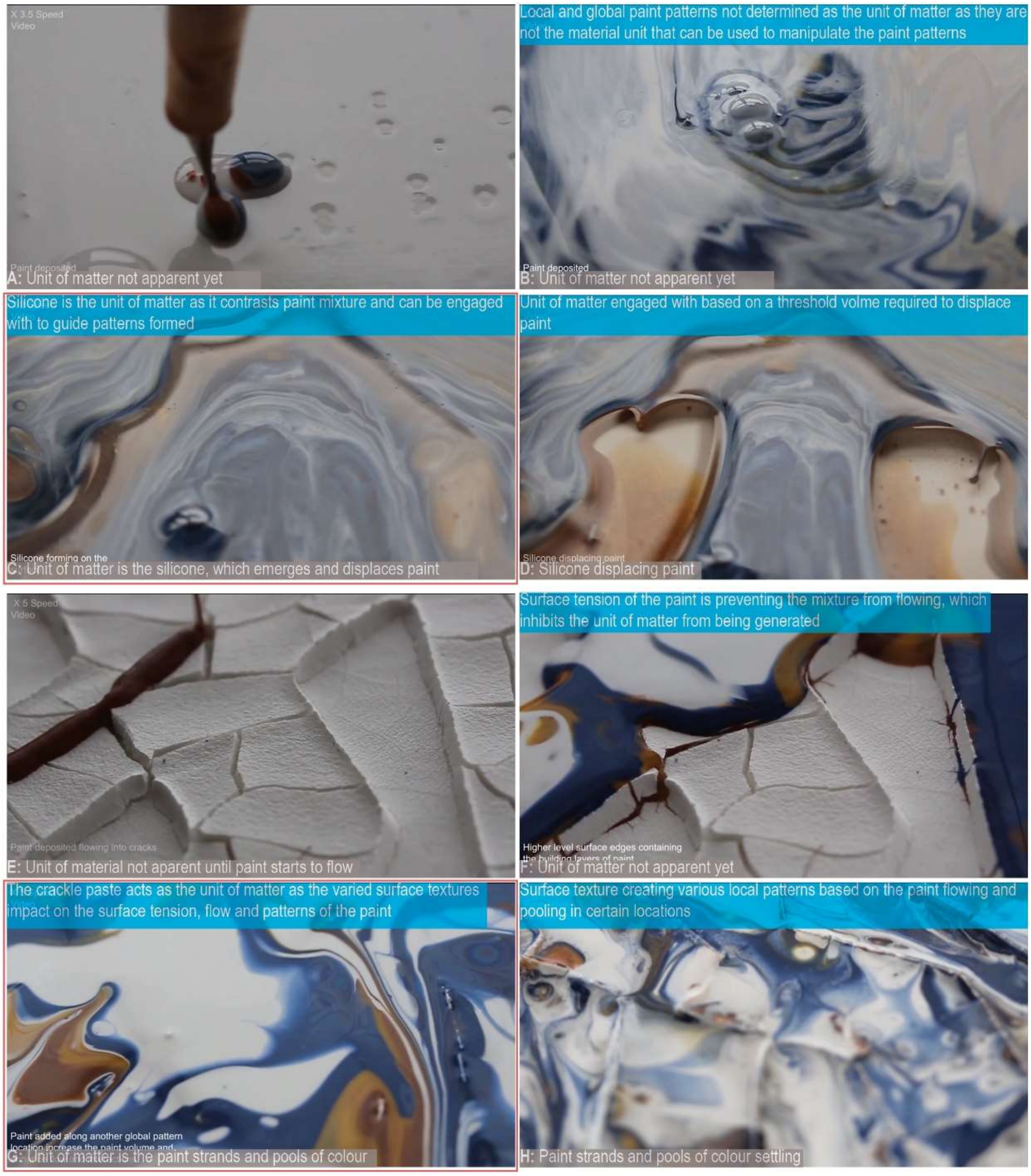


Figure 103: The volume of silicone acts as a unit of matter that can be varied to create void spaces and acts as a flexible scaffold (A-D). The random surface textures generated from the crackle paste act as a permanent scaffold again as the ridges and areas inform the paint mixtures flow and pools (E-H).

Figure 104: The oil and water interface created multiple units of matter that varied their properties as it generated ink droplets, 2D surface patterns and 3D ink diffusion patterns (A-D) The ink diffused in the tank of water and syrup show that units of matter can be manipulated with high degrees of freedom when varying support material properties (E-H). The vegetable glycerine suspended very delicate units of matter and clearly defines their resolution over longer durations (I-J).

8.12 Chapter Summary

The main areas of interest produced from the ink and paint material probe are briefly discussed

2D Generative Patterns

- **In-situ Interactions:** To achieve greater diversity of colour patterns, interactions must take place in situ if the materials are capable of mixing 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 indicated that 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 was 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:** To achieve functional and intended patterns, feedback, associations 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, which are discussed in three main areas, forming the order of the chapter. 1) How the research methodologies have been employed throughout this research and documented through an annotated portfolio, which highlights the key developments, explorations and factors of what they have enabled as well as their limitations. 2) The key principles the collection of material probes have raised and how they have extended existing knowledge in regards to design and fabrication processes that are based on material self-assembly within a design and fabrication context (Tibbits, 2016), as well as extending the knowledge of *persistent modelling* (Ayres, 2011; Ayres, 2012b). 3) The limitations of the research with a main focus on the mineral accretion material probes findings, which also highlight existing problem areas within *persistent modelling* and material computation/self-assembly based fabrication processes.

Detailed conclusions from each individual material probe are not discussed in this chapter as these have previously been discussed within the conclusion sections in previous chapters (Chapter 7 and 8). For this reason, the overall conclusions focus on the main principles highlighted from this research and the RtD/practice-based methodology employed.

9.1 Main Contribution: Tuneable Environments

The main contribution to knowledge generated from this research is the framework for creating *tuneable environments* as a way to programme matter. Significantly, the research extends current knowledge in the areas of:

1) *Self-assembly*, in an architectural design and research context, as this research establishes that matter can be programmed without pre-designing properties of the individual material units that self-assemble. Instead, modulating stimuli are used to guide self-assembling materials at extremely granular resolutions. This means that structures can tune and adapt multiple material properties (densities, compositions, textures, volumes, forms) compared to reconfigurable pre-designed global patterns when individual material units are pre-designed (Tibbits, 2014b). Significantly, fabricating structures using units of matter on granular resolutions could enable larger scale systems to self-assemble, such as cities that can change their properties with greater sensitivity as they do not have more rigidly defined geometries and patterns designed into them, because the fabrication process becomes increasingly non-deterministic the more undefined and the smaller the unit of matter used.

2) *Parametric design*, digital shape-changing abilities can be instilled within the physical materials, patterns and structures by creating associations between design parameters, stimuli parameters that can be modulated, and material properties. However, the linear nature of parametric design models results in limited discourse over the non-linear interrelationships within the system.

3) *Persistent modelling*, as design representations can be linked with granular material units so various properties can be tuned and adapted across the length scale of the structure, which are not constrained to the global form of an individual material unit and its inherent properties, such as the elastic limit of metal units when they are inflated as seen in *persistent modelling* strategy (Ayres, 2011).

As a result, t*uneable environments* highlight the possibility of building towards adaptive design and fabrication processes that have the potential to be scalable and less wasteful as they can generate structures that self-assemble, self-heal and self-adapt their properties across time. By engaging with material units at extremely granular resolutions, in this case, molecules, it appears to begin to enable systems that can adapt at greater scales instead of being constrained to the properties imposed upon a single structure or component, like in current self-assembling fabrication strategies. The smaller the material units used to self-assemble and fabricate structures, the larger the physical system can become, which can adapt its properties with increasing material sensitivity if properties and self-assembly processes are guided by stimuli. This points towards a future of urban contexts that behave like *'living material eco-systems'* where resources can be shared to meet fluctuating demands and address significant challenges facing the 21st century.

9.2 Contribution Breakdown

This section briefly describes 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 material probes.

This research aimed 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; and 3) utilising 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 rethinking design and fabrication processes, which could be applied to multiple areas, from architecture, fashion and medicine to manufacturing or novel physical displays.

First, 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 self-assembly.

Second the research contributes to defining novel 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 based on conditions induced and generated by the materials themselves.

Third, 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 computational processes without imposing form upon the material units, which can be associated with parameters of digital design representations/tools as highlighted in material probes 05 - 06.

Fourth, the research shows that feedback mechanisms within design and fabrication processes based on material platforms that can self-assemble: 1) do not require predefined properties (e.g. geometries); 2) cannot self-sense; and 3) have inherent interrelationships when subjected to stimulus which 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 that *favourable conditions* are created and maintained to initiate and sustain material growth. However, maintaining favourable conditions is dependent on engaging with the system's interrelationships by enabling feedback between all the system's components that induce stimuli that affect and are affected by the conditions generated in order to prevent proliferation.

Fifth, foundational/substrate materials used to support and initiate material 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 (described in material probe 07).

Sixth, exploring the impacts of support material properties within the ink and paint material probes that are contrasting and semi-permeable to the materials being deposited within them enables a diverse range of material abilities across various time scales and dimensions. These contribute towards rethinking 3D printing processes to enable new material abilities that can be rapidly fabricated, which can then be tuned and adapted by introducing stimuli (i.e. tuneable environments).

Finally, surveying the literature in combination with results generated from this research highlights the main challenge in regards to the limited resolution of design tools that are based on boundary representation and associative modelling strategies like those used in *persistent modelling* and within this research e.g. parametric design processes based on linear cause and effect relationships. To address these limitations, non-linear design models must be utilised, which can generate 3D digital models based on material units, typically voxels (Bader et al., 2016a; Richards and Amos, 2016).

These contributions and overall conclusions are sequentially discussed in greater detail next in the order they are mentioned above, to further unpack them and highlight how the contributions have been generated. Additionally, these sections indicate how the aim of this research has been achieved and can be further explored. Following these contributions, the limitations of the research are then discussed. The conclusions and contributions of the research methodologies are now discussed.

9.3 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 has enabled contributions to other areas of design research methodologies based on the previous definitions described by Forlizzi et al. (2009). The process of the research itself was explorative and was based on the development of a series of iterative material probes, which have been documented via an annotated portfolio to help highlight key aspects of thinking and reflections at each stage (see Figure 105). Significantly, the use of annotated portfolio felt extremely intuitive and helped to clarify a research process that is based on making, and explores an open area of how designs become materialised through fabrication processes. The contributions to design research are that this research provides a framework for design and fabrication processes that can guide processes of material computation without the need for pre-designing properties of the individual material units.

In regards to contributions for **Research on (or about) Design:** the series of material probes have illustrated a design process that centres around and engages with parameters of stimuli 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 base 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). However, the advancements in CAM/fabrication processes have typically enabled extremely accurate and multi-material properties to be achieved (Richards et al., 2017; Bader et al., 2018c) but still treat materials as inert and have a physical form imposed upon them. Thus, the CAM processes do not specifically leverage or engage with a material's ability to compute form, which ultimately limits the physical structure's 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, which, 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 material probes have shown a design process that: 1) guides material interactions by inducing stimuli to create turbulence within the closed system so desirable material activity is carried out.; and 2) indicates the requirement of non-linear design tools/process to maintain favourable environmental conditions so interrelationships can be determined and regulated so desirable material properties can be fabricated based on stimuli.

These strategies of inducing and maintaining 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) prevent closed systems from reaching a state of equilibrium, which results in material activity stopping (Armstrong, 2014). However, utilising 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 (Cejkova et al., 2016; Dade-Robertson et al., 2016).

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 and interrelated 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 conditions* by monitoring the stimuli's resultant effects. Feedback between digital design, fabrication, material properties and stimuli were not achieved within the system due to the complex interrelationships. However, this research establishes design principles and a framework for developing an adaptive design and fabrication system. These principles can extend the research within *self-assembly, parametric design* and *persistent modelling* by effectively combining them, without the need for predefining properties of the material units (e.g. geometry, interface connections, composition, density). An annotated portfolio has been used to document the RtD process and the thinking and knowledge embedded within the series of material probes, which help to highlight the development of tuneable environments (see Figure 105).

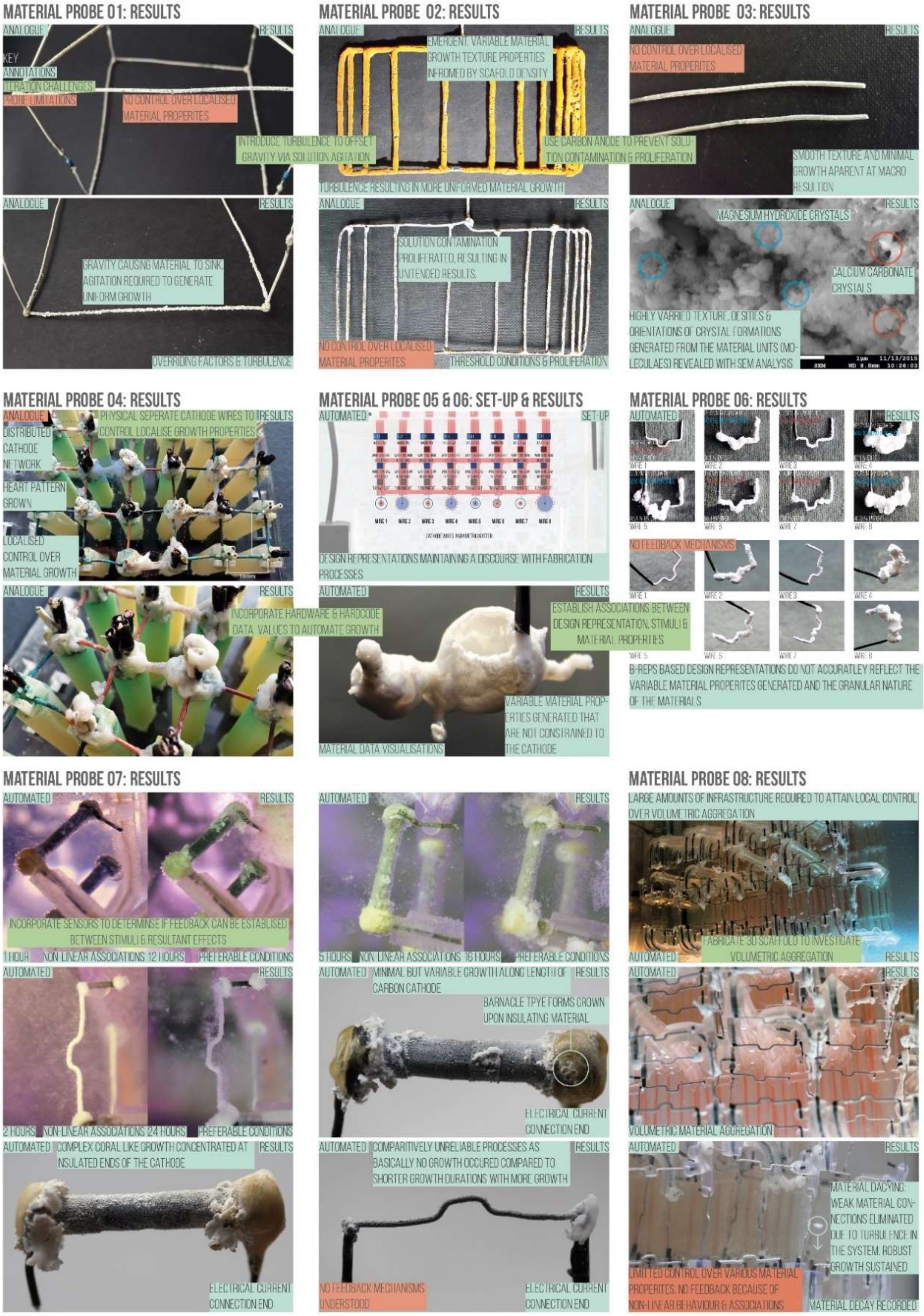


Figure 105: Annotated portfolio combining all the material probes within this research. They illustrate and explain the logics, thinking, process and aspects of interest further explored following each material probe.

9.3.1 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 reimagined 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; and 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. However, because of these two benefits, which have enabled explorations, an RtD methodology has become limited to the extent in which the material probes have been developed since it does not help to improve the control over the subtler material properties generated within both material platforms. For example, within the series of mineral accretion material probes, RtD has not enabled associations to be made between multiple stimuli, conditions and material properties (variable material porosity, density or surface textures) and how they are generated over time i.e. the non-linear associations between interrelationships are not robustly determined using RtD.

To address these challenges, a shift towards traditional science and engineering methodologies could be employed to help understand these interrelationships within the material probes 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/material probes has enabled interdisciplinary collaborations throughout this research, which indicates that a combination of methods and further interdisciplinary collaborations can address issues of control.

9.4 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 material probes and the material properties they enabled and generated.

9.4.1 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 emphasises 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 the material probes 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 to tune and adapt material properties by modulating parameters of stimuli (e.g. magnitude, location, duration). These interrelationships, and how they have been understood and developed through a series of iterative material probes, have 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. This shows that structures, objects or potentially wearables (e.g. medical splints or fashion) created using these methodologies could have their properties tuned and adapted based on their local and global properties as well as fluctuating stimuli. Imagine an architectural structure that could tune and adapt its material properties throughout its volume and across its length scale (from granular resolutions to global scale), or self-reconfigure based on aesthetic, climatic, performance demands, or self-heal 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, to understand the properties of the material platforms' interrelationships and to 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: 1) developing a fabrication process based on *'tuneable environments'* to interact with and guide the material platforms interrelationships; and 2) determining 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.

9.4.2 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 material probes helped to develop this idea and established that it can be employed as the fabrication process, where various stimuli (e.g. electrical current) and their parameters (e.g. time, magnitude, location) can be used to guide material computational processes (e.g. self-assembly) at granular resolutions. The development of a fabrication system based on tuneable environments further facilitates:

- Local properties (material composition) 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 established because two material platforms are used in the series of material probes within this research. material probes 01 - 07 use mineral accretion processes, where variable material volumes, textures, compositions and densities are grown upon cathode scaffolds. material probes 08 - 10 use 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 design tools that are based on non-linear associations to create favourable environments and understand interrelationships.

Varying the stimuli's parameters that make up the tuneable environment can be done manually (material probes 01 - 04) or via digital design representations/tools if hardware is incorporated into the system (e.g. micro-controllers and actuation devices) (material probes 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 self-assembly is incorporated. Additionally, a design and fabrication process based on tuneable environments and interrelationships also extends self-assembly research within an architectural design and fabrication context (Tibbits, 2012a; Papadopoulou et al., 2017). This is because the material results from the material probes establish that self-assembly can be guided: 1) on the resolution of molecules; 2) without the need for predefining properties of individual material units (e.g. geometries and connection details), which extends to role energy plays within the system; and 3) without the need for directly embedding material units with sensors or having to design material interface connection details. However, to achieve feedback and self-error correction when using granular material self-assembly design processes or material platforms must be developed or used, which can determine or mediate the interrelationships generated 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 medical or even entertainment. 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 be updated by reinserting them back into the tank of liquid and subjecting it to stimuli that could tune its properties based on recorded sensor data, 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 patient’s 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. *First,* issues of control over material properties; and *second,* the issue of feedback between stimuli induced and the material properties generated. Although these seem similar, they are discussed separately in the limitations section.

9.4.3 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 material probes. Additionally, the collection of material probes has helped establish 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; Gilpin and Rus, 2012; Romanishin et al., 2013). This offers an alternative strategy to this research, which enables high degrees of control due to the detailed information on neighbouring material interactions that can be achieved. However, it results in two primary limitations: 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, the predominant mechanism of fabrication was explored and addresses the objectives of this research. However, it is essential to tune and adapt as well as determine if desirable material properties have been grown when utilising stimuli as the fabrication mechanism feedback.

The series of mineral accretion material probes establish that direct associations between feedback mechanism (stimuli and resultant conditions) and material properties cannot be determined due to the complex interrelationships highlighted in material probe 07. Instead, the collection of mineral accretion material probes establish a series of design principles that build towards enabling feedback within a design and fabrication process based on granular resolutions of material self-assembly and stimuli. These principles are discussed in the conclusion of material probe 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; and 6) non-linear associations.

Exploring these principles further could ultimately lead to increased self-assembling material abilities, without the need for pre-defining the properties of material units. Enabling feedback would lead to improved abilities of self-reconfiguration and 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 self-assembly could be achieved but demonstrated that the materials are effectively emitting signals. An alternative approach to addressing the issue of feedback could be to directly embed material units with self-sensing abilities within the materials so they can respond to threshold conditions (Dade-Robertson et al., 2015; Čejková et al., 2018) However, these materials still have limited feedback with design representations but the notion of utilising materials that can emit conditions or signals could extend these areas of research to create increasingly sophisticated, reliable and robust material systems that are guided by stimuli.

9.4.4 Contrasting conditions.

Feedback is not achieved in material probes 08 - 10 because they explore how tuneable environments can be employed to guide material patterns without pre-defined scaffold structures. Instead, these material probes build on the idea of contrasting conditions to move away from the rigid scaffold structures used within the mineral accretion material probes. 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 material probes that incorporated silicone and the 3D ink diffusion material probes that used vegetable glycerine as the support material. The combinations of these materials enabled several robust material properties. These are:

1) 2D local void spaces and defined boundary edges are created but, critically, a threshold volume of contrasting material is required to inhibit paint interactions.

2) 3D volumetric diffusion patterns are inhibited and suspended in time and space as vegetable glycerine inhibited diffusion. Resulting in volumetric, delicate, multi-material patterns being generated.

3) The 3D ink diffusion material probes also show 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 material probes that use a sugar syrup support material and shows 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 combining contrasting materials indicates new possible 3D printing processes that could be: 1) rapid, 2) volumetric, and 3) 3D adaptive by inducing stimuli.

9.5 Summary of Material Probes & Limitations

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

Material probes 01 - 03

- The overriding factor of gravity needs to be offset 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 establishes 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 cathode typologies used, which are all physically connected.

Material probe 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.

Material probes 05 - 06

- Material properties can be grown based on data, which creates physically transformable data-visualisation
- Incorporating hardware enables digital design representations and its 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 does not generate accurate and reliable growth results as the fabrication process is non-linear and non-deterministic.

- Unreliable growth results denote the requirement of feedback between interrelationships of the system's parameters that can be associated with one another to achieve more reliable growth results.

Material probe 07

- Defines a series of design principles for developing a design and fabrication system that utilises stimuli as the fabrication mechanism to guide granular resolutions of material 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
- Rethinking fabrication processes to engage with material computation through stimulus highlights that inert materials do not have to have form 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.

Material probes 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 enables 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 realised. The main limitations of this research are discussed next.

9.6 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 direct associations between design parameters, material properties and stimuli. The limitations of the research methodologies have been discussed in Section **9.2.1**.

9.6.1 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 the material probes. This inability of the design tool to account for variable material properties is also highlighted within *persistent modelling* (Ayres, 2012a). These inabilities 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), a strategy that can also be applied to an extent within material self-assembly processes if they are based on a set of distributed parts, where the material units have been pre-designed and are effectively identical and homogenous (Tibbits, 2014b; 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 cannot 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); and 3) has inherent interrelationships within it when subjected to stimuli as there are high degrees of freedom within the non-deterministic fabrication process.

Gilpin stresses that converging the digital design representations with, and basing it on, the material unit's resolution enables localised material relationships or interactions to be represented accurately (Gilpin et al., 2010; Gilpin and Rus, 2012). The problem, though, is that the design tool itself has a low resolution, and is based on pre-designed 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 programmable material units (typically voxels) (Bader et al., 2016a; Richards and Amos, 2016). Incorporating these sophisticated forms of digital design tools could enable the diverse, variable properties generated within the material probes 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.

9.6.2 Limitations of Direct Associations

Dierichs and Menges have demonstrated that material interactions can be accurately simulated digitally 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 are not based on interrelationships between stimuli and variable material properties. Thus, the interrelationships within this research cannot be further understood when using design tools based on direct associations. 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 which can also generate associations between design parameters, stimuli and material properties. The generative design strategy developed by Richards and Amos, which uses CPPN-NEAT algorithms, enables these non-linear associations (Richards and Amos, 2015; Richards and Amos, 2016). Utilising these sophisticated design tools to uncover complex interrelationships within the system could allow for 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 totally new design and fabrication processes where complex multi-material structures can be volumetrically grown. Therefore, structures could have both their external and internal architecture and 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 in biological structures (e.g. scalability, self-healing, self-adapting and self-organising) and lead to urban cities that behave like *'living material eco-systems'*, which share material resources. These enhanced material capacities enabled by rethinking design, fabrication and material relationships, highlight new possibilities for future architectural structures and their materialities, which could pave the way for addressing current global crises like global warming, diminishing resources, excessive waste and increasing pollution levels.

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