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Designing Parametric Matter

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This paper presents a series of design experiments that seek to move beyond today's computer-aided design and computer-aided manufacture (CAD/CAM) technologies and investigates alternative material practices based on programmable self-assembly. When using CAD software, 3D designs can be rendered extremely flexible and adaptable such that changes to an objects size, colour, transparency, topology, or geometry can be made quickly and easily. However, once digital designs are converted into physical objects via typical CAM technologies, this capability for adaptation usually dissolves as objects are typically fabricated using inert materials and no consideration of a material's computational abilities. The series of design experiments discussed in this paper help to rethink and re-imagine the possibilities of design and making with adaptive fabrication processes. The design experiments explore mineral accretion and generative paint recipes. Mineral accretion is predominantly controlled via a process of electrolysis to produce adaptable crystal structures that are grown on cathode scaffolds within a volume of seawater. The generative paint experiments expand on the mineral accretion work to explore how material self-assembly can be guided using less restrictive scaffolds. The experiments reveal how 'contrast' can be exploited within the design process as a means of guiding and monitoring material scale self-assembly. Through reflection of these material experiments, this paper seeks to provoke discussion about the role of design within future manufacturing systems, and the possible physical properties of future designed objects.

Keywords: Programmable self-assembly; Parametric design; Adaptation; Tuneable environments; Interrelationships; Contrast; Mineral accretion

1 Introduction

Computer-aided-design (CAD) tools have changed the way we design a wide range of physical objects, from the scale of buildings to medical implants. Key to this transformation has been the ability to quickly model and reconfigure 3D designs based on sets of parameters (e.g. the depth of a steel beam being calculated as a function of its length). This form of associative 3D modelling using parameters is often called "Parametric Design" (Jabi, 2013) and has been especially significant within architectural design (Burry, 2011; Schumacher, 2009a, 2009b). The power of parametric design is that it allows 3D structures, shapes, geometries and volumes to be continually manipulated in real-time based on complex relationships with predefined numerical parameters. In an architectural context parametric design enables: (a) real-time feedback between design decisions and physical properties (i.e. aesthetics, material properties, function) (Bhooshan, 2017; Burry, 2003; Jabi, 2013; Leach, 2009; A Menges, 2012a; Woodbury, 2010); (b) description of increasingly complex geometric structures which can be structurally efficient and ornate (Block, 2016; Colletti, 2010; N Oxman, 2010a, 2010b; N Oxman & Rosenberg, 2007; Richards & Amos, 2015) (c) digital fabrication instructions / processes that can be produced directly from model data for robotic tools or units (Aejmelaeus-Lindström, Willmann, Tibbits, Gramazio, & Kohler, 2016; Dunn, 2012; Gramazio & Kohler, 2014; Keating, Leland, Cai, & Oxman, 2017; Achim Menges, Sheil, Glynn, & Skavara, 2017; Stuart-Smith, 2016; Willmann et al., 2012).

Indeed, much has been written about the impact that flexible parametric models have had on contemporary design practice (R. Oxman, 2006). However, a fundamental challenge remains that this flexibility only exists within the digital representation of the design, and is severely diminished or destroyed when objects are fabricated and brought into the real-world. The question that motivates this research is: *how can this capacity to adapt be programmed directly into the physical materials themselves?*

“Persistent Modelling” (Ayres, 2012b) is a research agenda that challenges this physical fixation. In persistent modelling, the relationships between the representational mediums of the designs processes (sketches, models, digital models) and final physical objects are emphasised and ‘persist’ throughout the lifetime of the object. The relationships between the two allow for time to be accounted for, so that change can occur via feedback between the digital design representation (e.g. the parametric model) and the situated physical structure. For example, Ayres (2011), demonstrates this concept by creating a real-time link between the parametric model and material by inflating metal sheets.

In this paper, we build on the persistent modelling concept by incorporating self-assembling materials. The key contribution of this paper is to synthesise and reflect on three-years of design experiments, which have set out to investigate how insights from domains of chemistry, materials science, and artificial life might help us imagine ways of growing physical structures with adaptive fabrication processes.

In these experiments, growth processes are guided and “tuned” in real-time through environmental stimulus, specifically electrical current but, pH, temperature and salinity can also be used to tune material properties. These environmental stimulus form 'tuneable environments', which are a set of physical stimuli that are adjusted via digital design tools to alter the conditions of a volumetric space that contain self-assembling materials. This paper aims to synthesise the lessons learnt and reflect on the key challenges and opportunities for designing with adaptive materials, as technical details are presented previously (Blaney et al., 2015; Blaney et al., 2016; Blaney et al., 2017).

The paper is structured in three sections. Firstly we contextualise the concept of programmable self-assembly via adaptive materials to illustrate the rich history of these ideas within architectural design and also point to potentially valuable areas of research that lie outside of design to highlight synergies and challenges that can be addressed by integrating digital strategies with self-assembly. Secondly, we present the design experiments in the style of an annotated portfolio (Gaver & Bowers, 2012), focusing less on the technical details of experiments, but instead on the material properties of the volumes grown. Finally, we reflect on the lessons learnt, and outline key challenges and opportunities for designing with adaptive materials.

2 Background

Parametric design has strong roots within architectural design as a means of generating and informing 3D designs both via analogue and more recently through digital processes (Bhooshan, 2017; Schumacher, 2016; Wiscombe, 2012). The physical form finding experiments developed by Frei Otto (e.g. using soap film models, woollen thread models, magnetic needle models) (Vrachliotis, 2016) and Antoni Gaudi's Catenary string models can be described as analogue parametric models (Burry, 2016), used to help generate exemplary architectural designs. Both Otto's and Gaudi's parametric models' setup conditions (i.e. a physical framework comprising of dimensions, tension, voids, boundaries) directly generated material forms and properties in response to these conditions.

The reason we can consider these early form finding experiments as analogue parametric models is because in these models the 2D patterns and 3D forms generated are: 1) inherently linked with the properties of the materials used and 2) use inherent material tendencies to self-organise forms when physical forces are imposed upon them; notably it can be argued that these sort of models perform “material computation” (A Menges, 2012b).

One of the major downsides of these analogue parametric models is that the process of generating and evaluating designs can be time consuming. Digital parametric models address this problem and make it possible to re-create aspects of these analogue parametric models using computers, which enable the designs' to be digitally transformed easily on the fly (Bhooshan, 2017; Burry, 2003; Jabi, 2013; Leach, 2009; A Menges, 2012a; Woodbury, 2010) along with the ability to monitor properties and determine desirable design features.

Whilst digital parametric models offer advantages in terms of speed, they also lose some of the richness of analogue form-finding models of Otto and Gaudi. Specifically:

- All associations between material, geometry, forces need to be explicitly and manually defined by the designer prior to digital form finding strategies. This imposes a limit of the ‘scalability’ of such methods, in that extremely complex conditions and associations require both significant time to setup, and computational power to process (Harding & Shepherd, 2017; Richards & Amos, 2016).
- Digital parametric models tend to assume perfectly uniform and homogenous materials that are crude abstractions of the materials found in the real-world (Michalatos & Payne, 2013; Richards & Amos, 2016).
- Due to the need to work with relatively simple parametric associations in digital models, and use rough abstractions of material properties, there is often a severe ‘reality gap’ or disconnect between digital models and the fabricated models. Notably, this gap occurs because there is no direct feedback between the physical and digital (Ayres, 2012a).

To address these challenges, a variety of approaches have been explored. These include, developing new digital representations of heterogeneous materials using volumetric pixels (or “voxels”) (Doubrovski et al., 2015; N Oxman, 2010a, 2010b; Richards & Amos, 2015, 2016); and use of bottom-up generative processes to eliminate the need to pre-parametrise all associations manually (Oxman & Rosenberg, 2007, 2007a, 2007b; Richards & Amos, 2015, 2017).

These approaches, whilst significant, retain a disconnection between the physical and digital models. That is, the adaptive capacity of the digital model is destroyed as soon as the physical design is constructed. Meaning the corresponding physical models cannot alter their material properties based on data, designed logics or relationships present within the digital model after they have been fabricated. Conversely these such adaptive abilities are universally present within biological processes of fabrication and structures (often cited as a key inspiration behind such designs), which have the ability to physically tune and adapt their properties across scales as design demands change (N Oxman, 2012; Speck, Knippers, & Speck, 2015), a feature which is particularly evident in bone-remodelling (AMGEN, 2012). These processes and enhanced abilities are the inspiration for rethinking how artificial materials can be interacted with throughout fabrication processes.

To address this challenge, “Programmable Matter” and “Persistent Modelling” are research areas that reconnect design representations with their physical counterparts to enable a richer connection between the two worlds, and the capacity to create adaptive physical designs. Critically, combining these two worlds could pave the way towards a future where structures may transform on-demand, reconfigure, self-heal, self-assemble and adapt.

One approach to producing programmable matter is called 4D printing (where the 4th dimension is time). In this approach, objects can be 3D printed in one shape, and transform into another programmed shape after being fabricated in response to specific environmental stimuli (e.g. pressure or heat). (Correa et al., 2015; A Menges & Reichert, 2015; Raviv et al., 2014; Reichert, Menges, & Correa, 2015; Tibbits, 2014a, 2016; Tibbits, McKnelly, Olguin, Dikovsky, & Shai, 2014; Wood, Correa, Krieg, & Menges, 2016).

A second approach utilises self-assembly and embeds information into the material components themselves, by designing their geometries and connection interfaces (Papadopoulou, Laucks, & Tibbits, 2017; Tibbits, 2012a, 2014b, 2016). The key idea with self-assembly is that in much the same way as the early analogue form finding experiments of Otto and Gaudi, whereby simple components respond to environmental stimuli and organise themselves into useful structures. The primary benefits of self-assembly that are of interest are:

- Materials can reconfigure and transform their structures when supplied with energy (Papadopoulou et al., 2017; Tibbits, 2012b; Tibbits & Flavello, 2013).
- The designed interfaces can result in self-error correcting construction methods (Papadopoulou et al., 2017; Tibbits, 2011, 2012a, 2012b).
- Scalability, as the fabrication is a bottom-up process based on the material components' interactions.

An exciting aspect of this approach is that the process reveals a space between deterministic and non-deterministic fabrication processes, which can produce surprising and often desirable outcomes that were initially not conceived by the designer (Tibbits & Flavello, 2013). This resembles Otto's work of setting up conditions and trusting materials to compute sophisticated and desirable forms. Currently, the use of and supply of energy to these programmed material components is limited (Papadopoulou et al., 2017; Tibbits, 2014b) and provides little feedback. However, it is a significant mechanism and plays a large role in the fabrication process and as Tibbits (2016) has noted is needed to achieve self-assembly. Related work outside of architecture has also been demonstrated that various intricate 3D forms can be grown at the microscale by varying the pH during crystal growth (Grinthal, Noorduin, & Aizenberg, 2016; Kaplan et al., 2017).

Persistent modelling is slightly different as it seeks to bridge the gap between digital and physical models by using feedback of physical stimulus (e.g. pressure) to inform digital models, which then inform the physical models. In this system, the stimulus acts as the energy that informs material deformations. The benefit of this is that the stimulus can be mapped to a relevant design demand and or logic that informs material manipulations (e.g. structural requirements or solar shading) (Ayres, 2011). The reconnection between digital model and physical model enabled by persistent modelling highlights two factors of interest, time and complex material behaviours, however, as the authors have previously demonstrated, the incorporation of material self-assembly extends these abilities and raises several other exciting factors and challenges.

3 Explorations in Parametric Matter

We now describe a series of design experiments that aim to expand the notion of persistent modelling by incorporating self-assembling materials. We first provide a brief description of each of the processes used and key findings, before reflecting on the series of experiments as a whole, in the form of an annotated portfolio (Gaver & Bowers, 2012) to highlight key themes, challenges, and potential impact on future design roles. Figure 1 shows a collection of prototypes developed over 3 years, which explore and develop the idea of tuneable environments as a fabrication strategy, which addresses subsequent challenges and consequently raises new ones in regards to informing properties of the materials grown using the mineral accretion process. The prototypes build towards and adaptive design and fabrications system that can manipulate variables of the mineral accretion process.

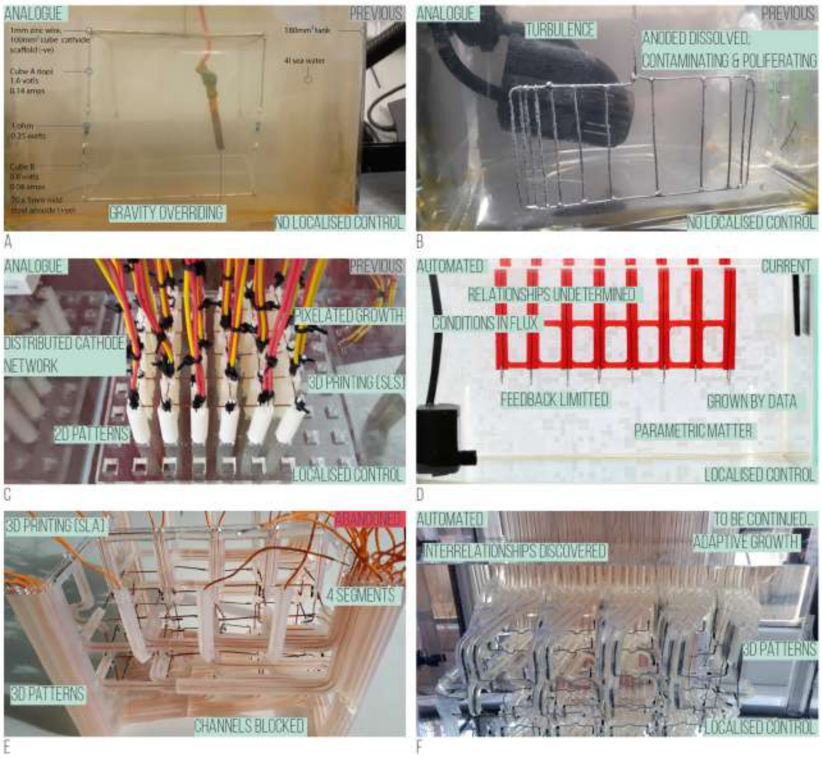


Figure 1. Highlights the sequential (A-F) prototype iterations created to-date. Each photo shows the set-up prior to material growth. The annotations reveal challenges raised by the previous experiment and addressed in the following, which has aided in developing a methodology for growing adaptive physical designs'. Source: Author.

3.1 Experiment 1: Multi-Material Crystal Growth via Mineral Accretion

Typically to design and fabricate physical structures composed of multiple materials a designer digitally defines where the selection of discrete materials are within the design's volume and either assembles the parts, or more often, fabricates it in one piece using layer-by-layer additive manufacturing technologies (C Bader, Kolb, Weaver, & Oxman, 2016; Christoph Bader et al., 2018; Michalatos & Payne, 2013; N Oxman, 2011; N Oxman, Keating, & Tsai, 2011; Richards, Abram , & Rennie, 2017). To challenge this traditional means of fabricating multi-material structures this experiment sought to start with a single superabundant source material, seawater, and explore how different types of materials can be made to self-assemble on a physical scaffold in response to controllable physical stimuli. To do this a metal cathode scaffold was submerged in seawater and subjected to various voltages (Blaney et al., 2015). Lower voltages grow calcium carbonate upon the cathode, whereas higher voltages produce magnesium hydroxide (Goreau, 2012; Hilbertz, 1978, 1979, 1981). *Scanning Electron Microscopy* (SEM) (Figure 2) analysis was used to validate that two material types could be grown.

The key points from this experiment are:

- The fabrication process is able to manufacture different materials from a superabundant source material of seawater, and simultaneously control the placement of that material on a scaffold structure in response to the stimulus of voltage.
- The growth is volumetric and therefore not limited to a layer-by-layer process.

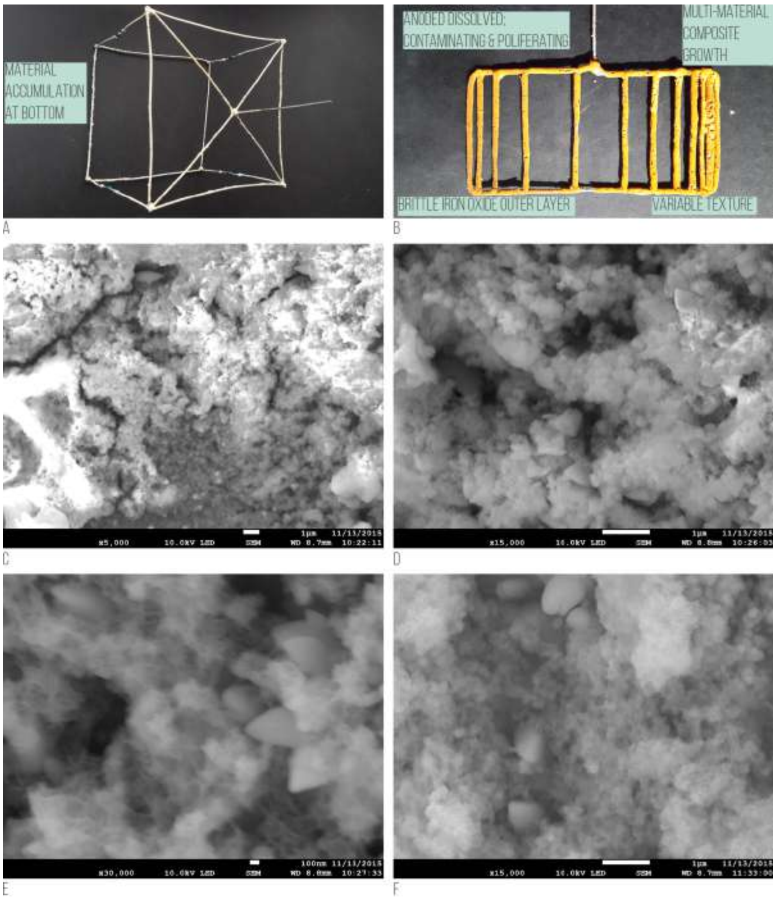


Figure 2. Crystals aggregate over 3D and 2D scaffold simultaneously. A) reveals no localised control over material growth but highlights gravity's effect on aggregation as greater volumes occurred on lower sections. Meaning agitation is required to suspend ions within the solution. B) shows multi-materiality and proliferation in the system as the steel anode dissolved, it coated the cathode, which proliferated throughout the system. C - F) SEM analysis validating multi-materiality; needle shapes reveal calcium carbonate; Dandelion shapes reveal magnesium hydroxide. Source: Author

Limitations of this experiment include: 1) control over localised material location, 2) volume and type due to the all cathodes being connected. Overriding conditions were discovered; chiefly gravity and solution contamination. Gravity resulted in increased volumes of material growing on the lower sections of the cube scaffold, which required turbulence to be introduced into the system to suspend ions and aid uniform growth (Blaney et al., 2015). Solutions contamination was due to the steel anode dissolving, which proliferated and resulted in iron oxide being deposited on the fence cathode.

Offsetting the overriding condition of gravity and proliferation/contamination was achieved by agitating the solution and using a carbon anode. A distributed network of cathodes was created to enable localised control over material properties (volume, location, type) (Figure 3) (see Blaney et al., 2016; Blaney et al., 2017 for full technical details). The scaffold enabled a pixelated heart shape to be grown based on analogue instructions (wires connected, voltages supplied and duration). However, only calcium carbonate or magnesium hydroxide can be grown at any one time as the higher voltage predominates throughout the seawater solution.

Figure 3. 2D network enabling localised control over material properties (volume, type, location). Source: Author.

3.2 Experiment 2: Growing a Data Visualisation

The first experiment provided a proof-of-principle that material properties and placement can be controlled by 'tuning' environmental stimuli (in this case voltages). However, control of this aggregation had proven difficult. This experiment sought to better understand how designers might control growth. To do this, we first sought to create a physical data visualisation (Jansen et al., 2015) based on the relative size of planets in our solar system. After this, we produced a simple digital interface (created in Processing) to control voltages supplied to cathodes for a second experiment, where the digital interface could control the processes of mineral accretion in real-time (figures 9-10).

Figure 4 documents the physical setup, values and phases of material growth. Significantly, the experiments sought to explore the ease at which the variables of the process (time and voltage) could be governed digitally through the use of hardware (figure 5). The system is an

Open Loop Control System (OLCS) and it highlights issues of control as the growth times were predicted and projected from preliminary experiment results.

The OLCS means that there is no feedback between the design tool that governs the induced stimulus and the resultant material properties and conditions created, as they are not monitored. However, there are multiple conditions that are in flux within this system (salinity, temperature, conductivity, pH, evaporation rates) (Goreau, 2012), which can be monitored via various sensors (Hilbertz, Fletcher, & Krausse, 1977). The benefit of early OLCS is its simplicity. They enable fast prototyping to get to grips with the initial variables of the system and how they can be interacted with.

The ability to offset and maintain these conditions is the next stage of development; creating more hospitable environments to guide material growth. Significantly, a contrasting effect occurs between material volume grown and electrical current. As material volume increases it insulates the cathodes (Goreau, 2012), resulting in a drop in electrical current (Hilbertz et al., 1977). It is this and other interrelationships that are explored in subsequent experiments to establish feedback between design tools and material properties. Determining growth volumes is one aspect of control; the results demonstrate a wide variety of material properties: smooth, porous, tubular, granular, variable densities, thicknesses and internal architectures (Figures 7-10).

The key point here is that by determining how or what conditions and interrelationships produce these results it would be possible to intentionally tune and adapt physical properties of a design manufactured from these material types. For example, imagine a building facade that could increase its insulating abilities as the climate cooled by growing more porous internal architectures. Additionally, if the materials constituting these structures are grown from a sustainable abundant source, like seawater for the mineral accretion process, the urban context could share material resources and behave like an ecosystem, mediating and addressing demands with passive strategies. Another example is medical splints that varied their composition to achieve improved healing to fractured bones and reducing the risk of post-treatment side effects, such as scar tissue accumulation in joints. These abilities could be achieved as the making and designing process is simultaneous and occurs throughout the design’s length and time scales.

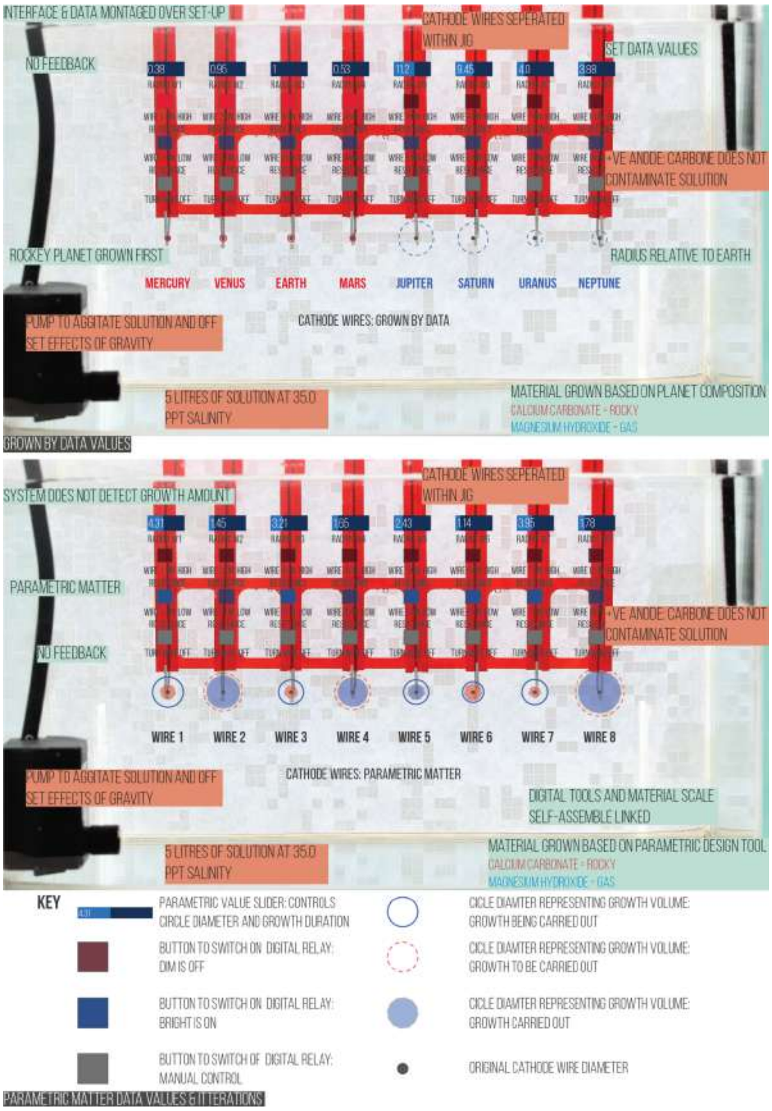
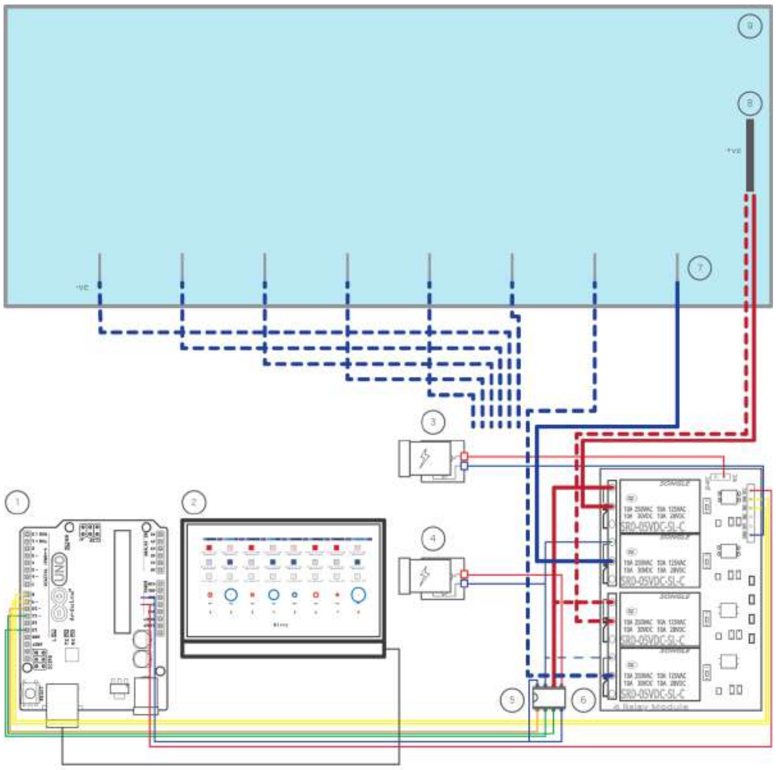


Figure 4. Setup of experiments titled 'grown by data' and 'parametric matter'. Data and interface imposed over physical prototype to convey the connection between design instructions governing material scale self-assembly. By adjusting the digital interface, a designer can impact the growth of the physical structures. Source: Author.



1)ARDUINO
2) DIGITAL PARAMETRIC DESIGN TOOL DEVELOPED IN PROCESSING
3) BENCH POWER SUPPLY FOR RELAYS
4) BENCH POWER SUPPLY FOR DIGITAL DIGITAL RHEOSTAT OR POTENTIOMETER
5) DIGITAL RHEOSTAT OR POTENTIOMETER
6) 4 CHANNEL DIGITAL RELAY
7) ALUMINIUM CATHODE WIRE
8) CARBON ANNODE
9) GLASS TANK CONTAINING BASE SOLUTION

Figure 5. Connection between data and or digital parametric design tool enabled by the hardware platform Arduino and serial communication. Source: Author.

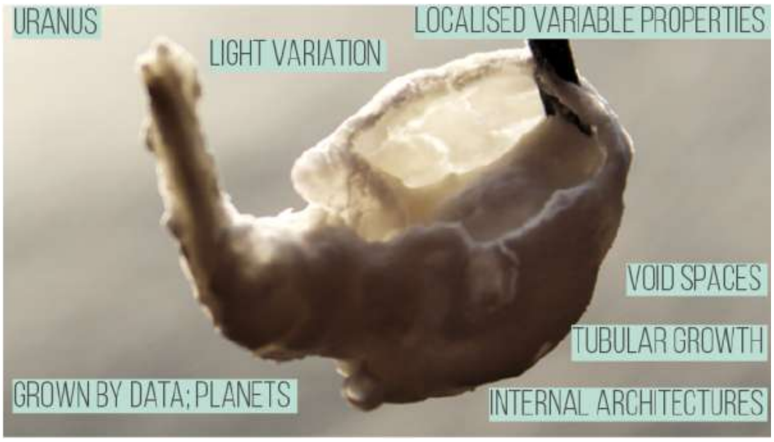


Figure 6. Close up photograph of growth reveals multiple material properties that would be difficult to create using existing digital fabrication processes. Here variable thickness, volumes, textures, densities and internal architectures are all grown. Source: Author.

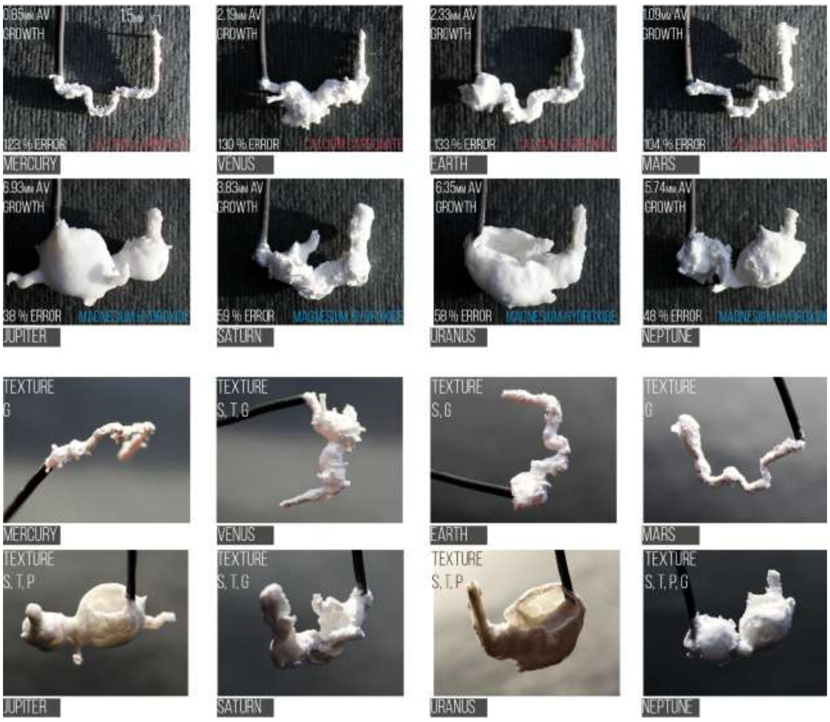


Figure 7. Physical data visualisation. A variety of volumes are grown and more interestingly extremely diverse textures, ranging from smooth to granular as well as volumes that are porous and have internal architectures, particularly evident in the largest material growth volumes of Jupiter and Uranus. Source: Author.

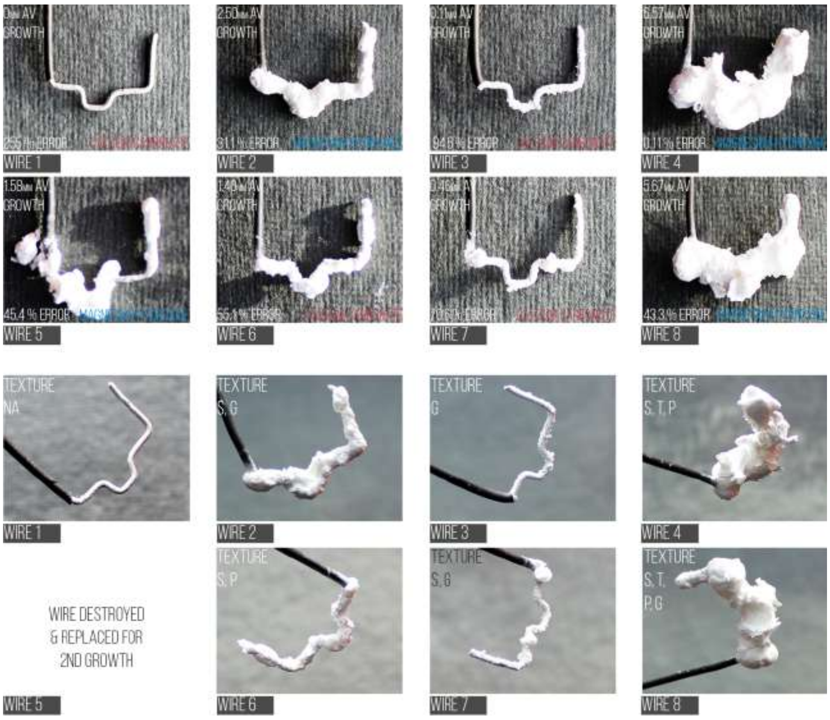


Figure 8. Physical data visualisation growth from the 1st iteration governed by the digital parametric interface. Source: Author.

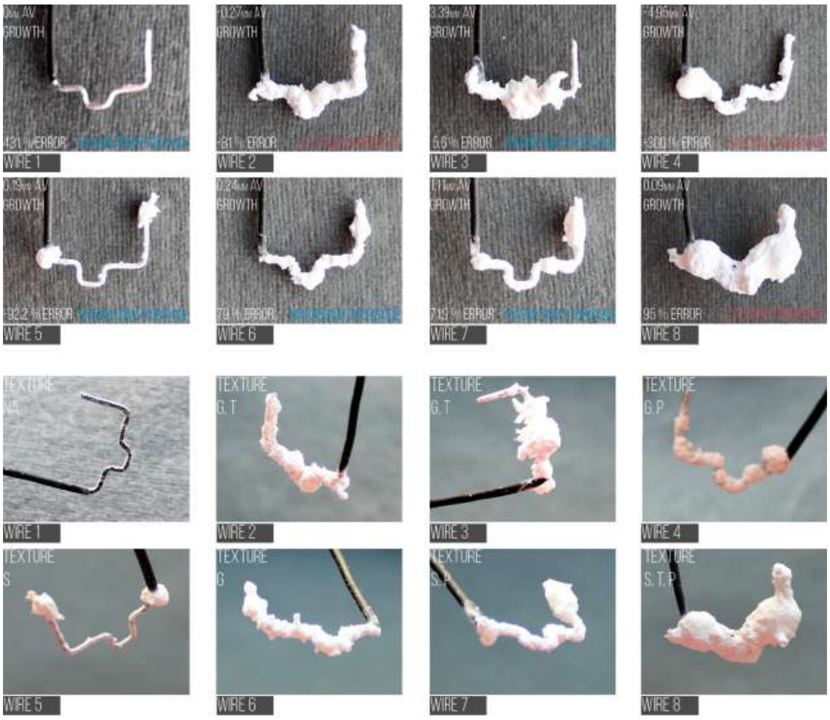


Figure 9. Physical data visualisation growth from the 2nd iteration governed by the digital parametric interface. Source: Author.

3.3 Experiment 3: Growing Pixels and Voxels

The next phase of experiments sought to move beyond the simple scaffold structures by exploring more intricate scaffold structures produced using additive manufacturing technologies. The goal here was to imagine how adaptive materials might be integrated into designs in the near future.

A first attempt (Figure 10) created a complicated 3D scaffold structure from 4 components, but was abandoned as numerous internal channels for feeding through wires became clogged with resin, combined with the tight radii and long length of some of the sections meant numerous connecting wires could not be fed through and attached to their relevant cathode element. A second design addressed this issue by increasing the size of the scaffold's design, which resulted in the internal paths no longer being blocked. This was also facilitated by using multiple shorter sections with larger radii, enabling all of the cathode elements to be connected. However, a trade-off of the multiple-sections approach is that connections between sections lean and distort the overall shape. This is significant as several of the cathode elements sizes do not match the other elements, which could result in anomalous results when comparing electrical current values to determine desired growth properties in those locations. Since this attempt these components of the scaffold have been re-fabricated and assembled, resulting in uniform cathode elements. A preliminary test of the 3D scaffolds again achieved 3D pixelated crystal aggregation (Figure 11 - 12). During this test, material decay occurred during growth as the bubbles that formed at the cathodes, due to electrolysis, bombarded material growth above them, which resulted in material decay and ultimately failure (Figure 10). A benefit of this could be seen as only robust material growth survives, which acts as a form of error correction and 'survival of the fittest' within the turbulent fabrication process. However, this remains for future research that would require interdisciplinary collaboration between designers, electrical engineers, and chemists.

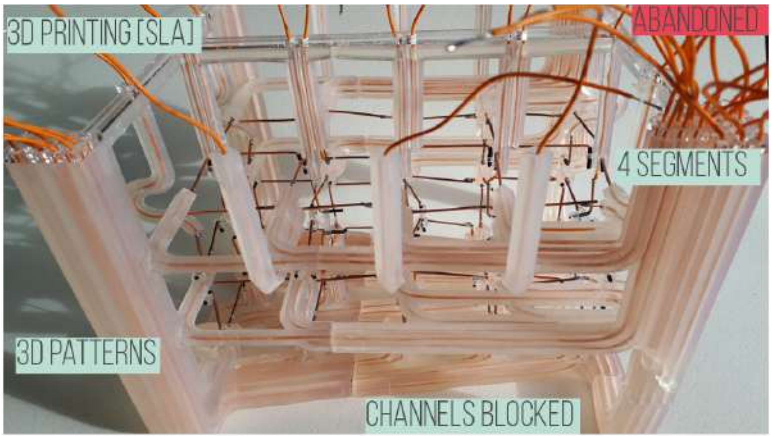


Figure 10. First attempt at 3D printed scaffold abandoned due to blockages within internal channels. Source: Author.

Figure 11. Second attempt at 3D scaffold with preliminary trial growth establishing designs can be grown at a pixelated resolution. Source: Author.

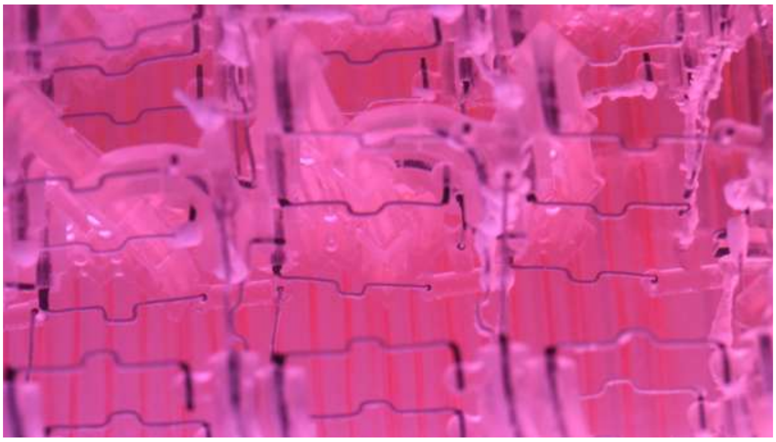


Figure 12. Close up detail of the second 3D scaffold system with preliminary growth testing carried out. Initial growth shows diverse textures again from smooth to branching and tubular textures. Source: Author.

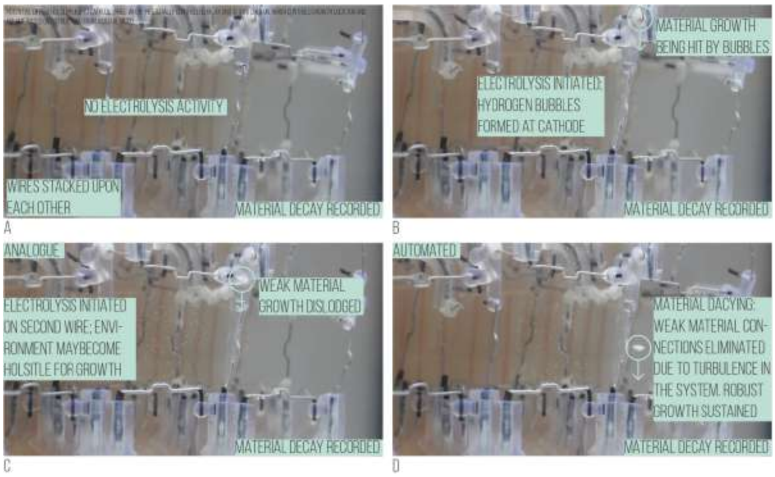


Figure 13. Material decaying from the cathodes due to turbulence induced within the system from electrolysis (hydrogen bubbles). The challenge of detecting this is still to be addressed, but it could be used as a possible error correction mechanism as only robust material growth survives.

3.4 Experiment 4: Using Contrasting Materials as Dynamic Scaffolds

An underlying challenge for these experiments has been the need to grow materials onto a fixed scaffold structure that ultimately defines the shape and form of the final structures. This experiment sought to remove the fixed scaffold, and explore control of viscous paint patterns using contrasting materials that act as dynamic scaffolds.

Significantly, the paint experiments question what constitutes a 'scaffold medium' by exploring how various material properties and additives to the paint recipes can effect pattern formations. The sequence of images below (Figures 15 - 19) highlights the various deposition process, ‘recipes’ and interactions. The key findings highlighted in each titled study are:

- ***Texture:*** Paints were deposited sequentially via a syringe controlled by a stepper motor so deposition rate was constant. The surface texture is uneven (created by crackle paste) and had a significant effect on the mixtures surface tension as it flowed over ridges, which informed streaks, bands and pools of colour.
- ***Location:*** Paints were deposited into a cup using a jig and the syringe system. The cup was flipped on the canvas, which resulted in the interactions taking place in situ. As a result, a diverse range of patterns was produced. As the isopropyl alcohol gradually evaporated the generation of patterns slowed; meaning the system has a form of metabolism, which needs to be replenished in order to keep generating patterns.
- ***Contrast:*** the paint mixture was deposited in one complete extrusion of the syringe system at the centre of the canvas, which meant the interactions between the paint’s colours predominantly occurred within the nozzle of the syringe and resulted in less diverse colour variations. However, this was not the case for the silicone additive as it contrasts with the water-based paint and they do not mix, resulting in void spaces and boundaries by displacing the paint. As such the volume of silicone informed the voids, streaks and variable paint layer patterns and more significantly, it highlights the potential use of contrasting materials as a strategy for guiding self-assembly process that is much more flexible them defined scaffold structures.
- ***3D Contrast:*** Moving into three dimensional volumes, inks were deposited into a volume of two contrasting mediums (oil and water), which form an interface. The inks form contrasting formations within each medium, spherical droplets in oil compared to ink cloud formations in water. The diffusion rates and support medium interface could be developed into a new additive manufacturing processes that create delicate structures volumetrically by tuning environmental conditions, particularity relevant to emerging rapid liquid printing methods (Hajash, Sparrman, Guberan, Laucks, & Tibbits, 2017).

Again there is no feedback between the design tool and process variables in this system but imagine being able to submerge your body parts into a tank, which could grow new types of fashion or medical splints directly onto your body. The location and type of materials grown could be informed and guided by coating your body parts in various contrasting liquids that inhibit and inform growth. Videos and further details on the recipes and deposition process can be found on the link (https://vimeo.com/user12085005).

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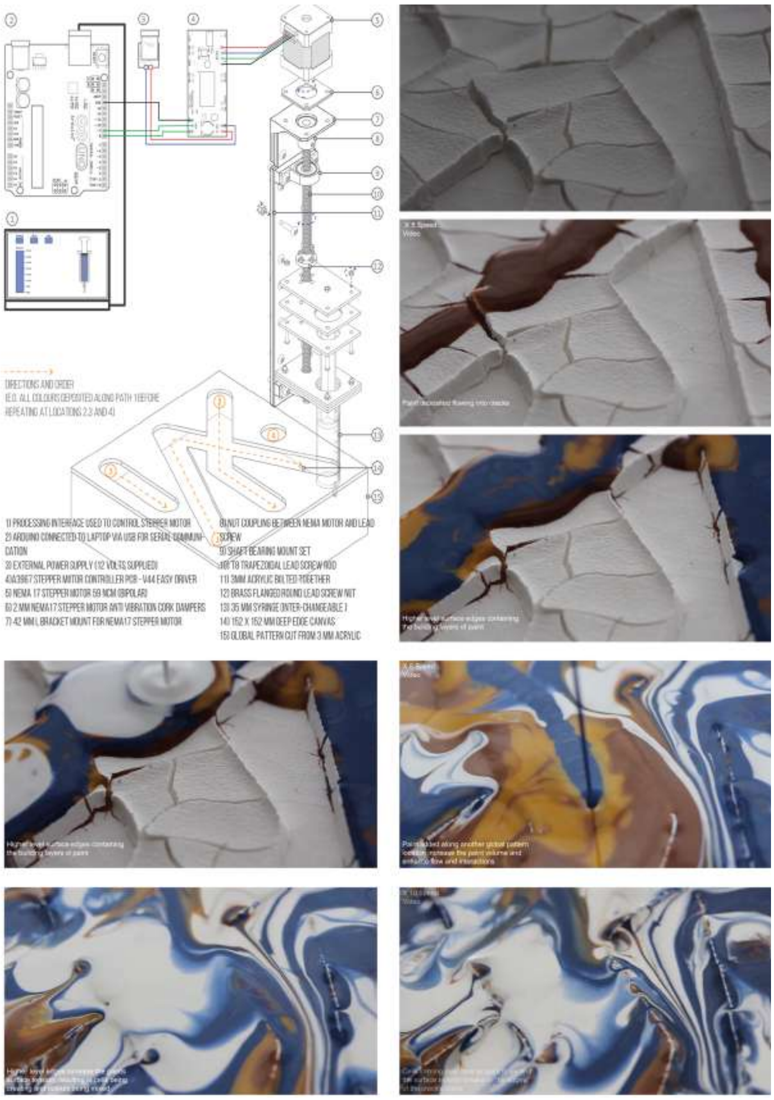

*Figure 14. **Texture**. Series of images revealing how surface texture effects paint interactions and the patterns generated. Source: Author.*

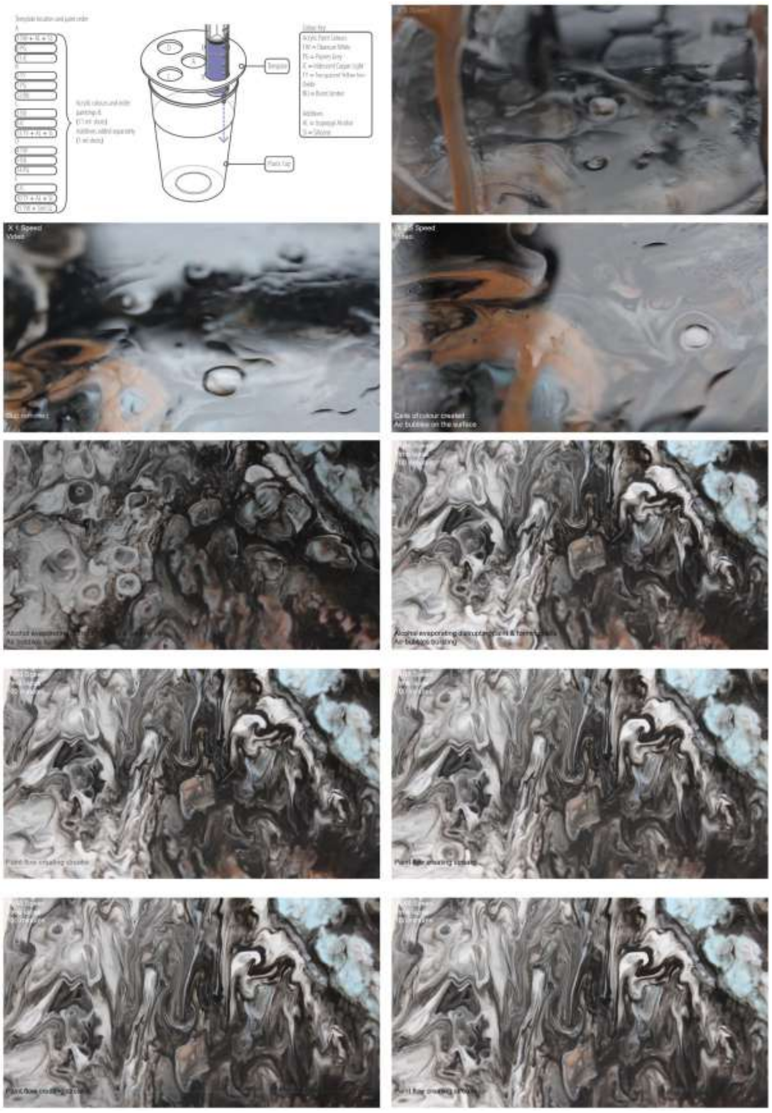

Figure 15. ***Location.*** *Images reveal interactions taking place in situ produces greater pattern diversity. Source: Author.*

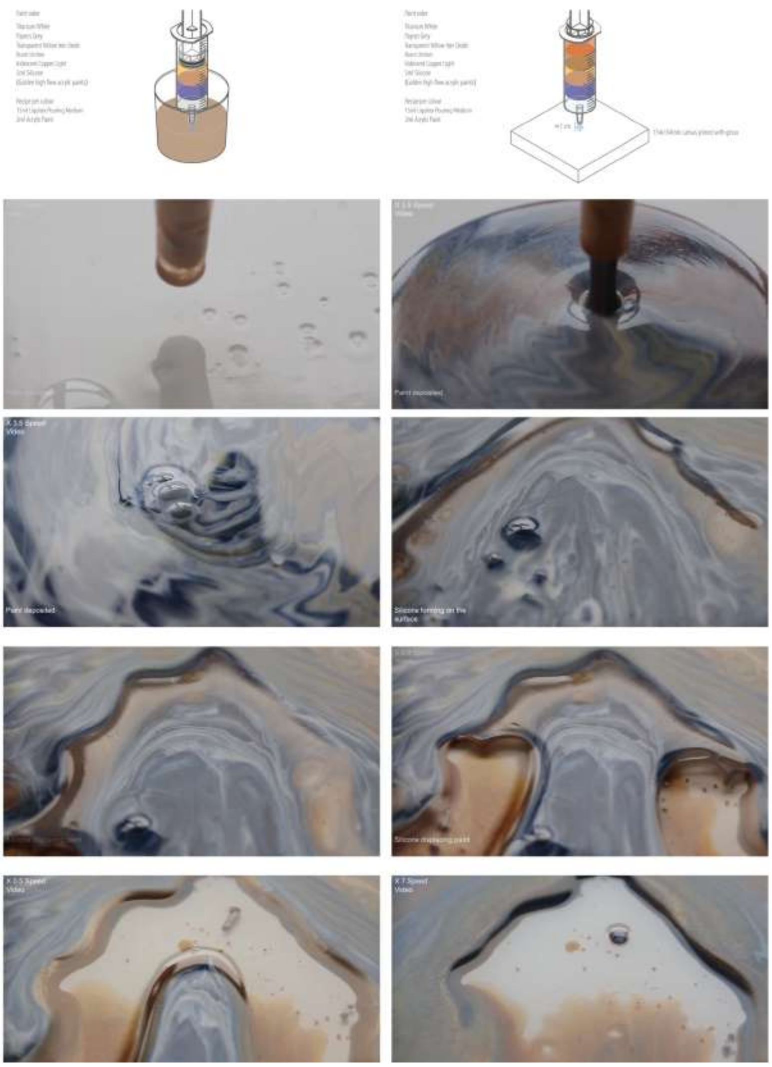

*Figure 16. **Contrast**. Silicone contrasts and displaces acrylic paint informing: voids spaces, boundaries, layers and streak formations, which highlights how contrasting materials can guide self-assembly. Source: Author.*

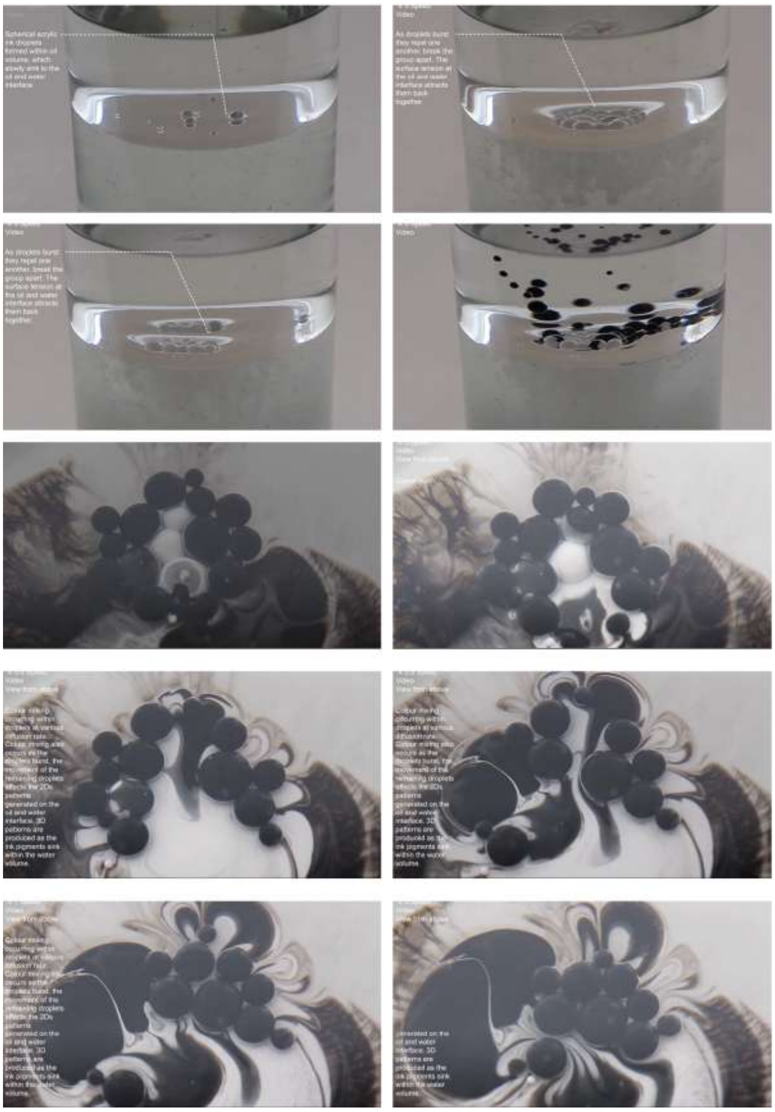

*Figure 17. **3D Contrast**. Reveals ink behaviour within contrasting support volumes; bursting at the oil and water boundary to form ink clouds. Source: Author.*

A

B

*Figure 18. Detailed images of **Texture**. Source: Author.*

A

B

*Figure19. Detailed images of **Location**. Source: Author.*

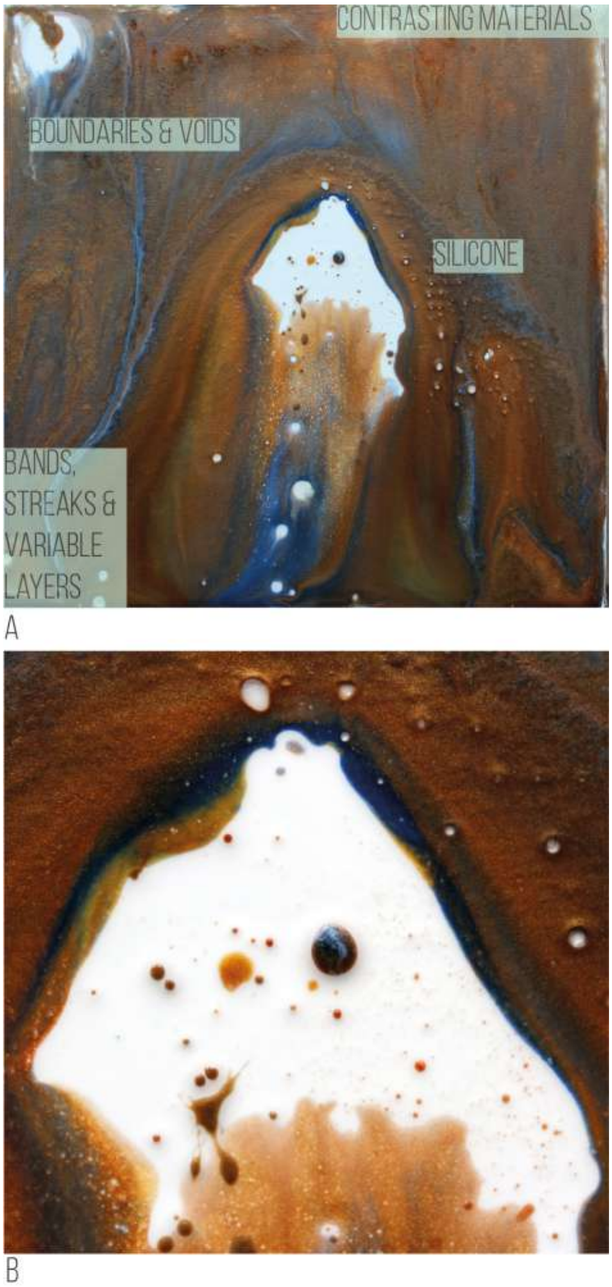

*Figure 21. Detailed images of **Contrast**. Source: Author.*

4 Discussion

This paper has presented a series of design experiments that have sought to explore future design and manufacturing processes based on what we term ‘programmable self-assembly of adaptive materials’. The goal of this paper has been to provoke discussion and instigate further inter-disciplinary collaborations that seek to create new forms of parametric physical matter that possess similar levels of adaptability and flexibility as their digital counterparts. Figure 22 summarises how digital design, fabrication stimulus and self-assembling materials have been used throughout these experiments to offer a framework for further work in this area.

A key component of these experiments has been shifting how design and fabrication processes are controlled – moving from direct control of designs, to control of environmental stimulus that indirectly informs the growth of designs. Throughout this work, we have come to understand that the notion of ‘stimulus’ become multifaceted, nuanced and challenging the more it is interacted with based on the results and highlighted by the annotations of the experiments. We conclude this paper by reflecting on aspects of control, feedback and impact for design.

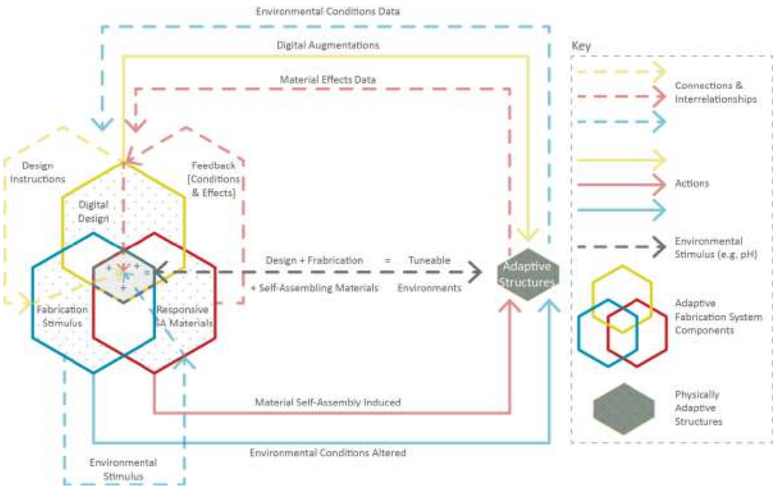

Figure 21. Connections between digital design, fabrication and self-assembling materials enabled via stimulus. Source: Author.

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4.1 Reflections on Findings

The series of experiments have highlighted various strategies and design processes for fabricating adaptive structures. Combining the key aspects from the experiments and casting back to the analogue parametric models of Otto and Gaudi highlights two key points of interest when engaging with processes of self-assembly at the material scale by inducing stimulus.

Firstly, this work supports a design and fabrication process that is iterative but also based on interrelationships between stimulus, resultant conditions and the design’s material properties across scales, which opens up a complex and nuanced territory. This is because the fabrication process is non-deterministic and the material properties are not predefined in how they can be fabricated and through interactions multiple processes and phases could be discovered and evolved to generate designs. Significantly, the process is non-linear as computational material processes are informed and affected by multiple stimuli and inherent properties (DeLanda, 2015), which is challenging but opens up new fertile grounds such as physical adaptation. In order to engage with and understand these complex material interactions and interrelations computational design processes that are not associative are required and highlight a key area for further research.

Secondly, the experiments suggest that the idea of contrast both in resultant conditions and materials could leverage: a) the ability to more accurately guide and determine if desired material properties have been fabricated. Monitoring contrasting conditions between stimulus and resultant material properties, as per the variation in electrical current based on material growth during the mineral accretion process enables feedback between design tools and materials that do not have the capacities to self-sense and fabricate informed designs based on stimulus. b) Contrasting materials point to the potential for developing less restrictive scaffold structures for guiding material scale self-assembly processes, liberating them to become more ornate and achieve more flexible transformations which are not constrained to scaffolds.

4.2 Reflections on Augmented Design Role

As designers, we typically seek to impose form upon materials to craft objects. This work suggests an inversion of this standard operating system, which augments traditional design roles and challenges disciplinary boundaries much like those documents by (Ginsberg, Calvert, Schyfter, Elfick, & Endy, 2014) We hope the experiments outlined in this paper provoke debate about the role we wish to take in shaping future design and manufacturing processes with advanced technologies.

We suggest that the next frontier in digital fabrication may be wet-ware technologies that allow physical designs to heal themselves, respond to change, generate energy, and enable new forms of radically sustainable and vernacular architecture. The first steps towards this vision will require further design experiments that seek to control materials with tuneable environments. Interestingly, this process of making may resemble those of Otto and Gaudi again by engaging with material computational abilities. These sorts of design and fabrication strategies could enable interactions with the complete materiality of objects (local and global properties). Meaning internal architectures and compositions that are based on, and inform, global shape and aesthetic changes, which could lead to: 1) more holistic design solutions, 2) improved material efficiencies and 3) novel design typologies that can be adapted on the fly as the fabrication mechanism is based on stimuli and caters for time.

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