Material Units

Uploading information into matter via stimuli and the challenges of determining feedback

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Associative and generative design processes are capable of creating complex digital models, which can have their digital material properties (size, aesthetics, performance) infinitely adapted or radically transformed, relative to design demands, if they remain in their digital environments. Imagine, if physical materials and structures had these abilities, where design updates could be uploaded into a structure's physical material makeup at molecular resolutions. This could begin to enable a physical structure's matter to be reprogrammed so they can adapt across their length scales with high sensitivities and multi-material properties. To leverage these abilities, novel design and fabrication processes need to be developed, which enable interrelationships between design parameters, assembly mechanisms and material properties. This paper presents key findings and implications of two final prototypes, from a series, which developed a design and fabrication approach termed tuneable environments that enables interrelationships and design information to be uploaded into matter at granular resolutions.

Keywords: *tuneable environments, programmable matter*

INTRODUCTION

Biological design and fabrication processes maintain continuous discourse and interrelationships between material properties, design demands and fabrication processes. As a result, structures can continually tune and adapt their global (shape) and local properties (material, composition, location, volumes) across time. This is particularly evident in bone remodelling, where consistent mechanical loading demands (e.g. running vs sedentary) inform the properties of an individual's bones (Frost, 1990). The mechanical loading demands in this context induce stimuli (proteins/hormones), which informs cellular activity to update the material properties of bone (Hadjidakis and Androulakis, 2006). Importantly, the bone remodelling process demonstrates the role stimuli can play in generating interrelationships and in programming a structure's material properties. Significantly, these interrelationships and material processes enable highly desirable physical abilities, such as; scalability, multi-adaptive structures, self-healing and material cycles, all at high material resolutions. These desirable abilities are yet to be fully leveraged within artificial design and fabrication approaches as typically, form is still imposed upon matter and linear modes of design, fabrication and consumption dominate. This raises the question; how can desirable abilities present within biological processes/structures be instilled with artificial processes/structures?

The motivation behind this research is to fundamentally rethink how design and fabrication processes interact with matter, so multi-adaptive structures can be developed at high material resolutions. To do this, Research through Design (Frayling, 1993) is employed as a flexible approach (Gaver et al., 2004) to investigate; how updates from digital design tools can be uploaded into matter to reprogram it at high material resolutions?

The paper presents two final prototypes from a series, which collectively developed a design and fabrication approach termed tuneable environments (Blaney et al, 2019). These prototypes investigate how stimuli can be used to program matter at high material resolutions. To do this, tuneable environments modulate stimuli parameters (duration, location, magnitude), which have interrelationships with design parameters and material properties. As a result, 2D patterns and 3D structures can have multi-material properties updated because information from design tools can be 'uploaded' into the structures' matter (Blaney, 2020). To contextualise this approach and reflect on its implications and opportunities the paper is divided into four sections: Firstly, previous approaches to programming matter and the role stimuli plays within them are discussed. Secondly, a final mineral accretion prototype is presented that investigates the implications of feedback. Thirdly, a final diffusion prototype is presented that investigates the impacts of 'scaffolds'. Finally, key principles and implications from the two prototypes are discussed.

BACKGROUND

Previous approaches to Programmable Matter have highlighted new potentials within design and fabrication processes. The various examples discussed within this section can all be seen as a form of programmable matter based on how it has previously been defined; "a material that has the ability to perform information processing much like digital electronics" (Tibbits, 2017, pp.14). By examining different approaches to programming material units/-components, the role of scaffolds and the potentials of stimuli to programme matter becomes increasingly apparent, especially when form is not imposed upon individual material units and resolution increases. However, challenges of feedback between design tools and material units become apparent when hardware is not directly embedded into individual material units, which makes it difficult to determine what material properties have been generated and what further design updates would need to be uploaded so desirable/intended materials properties can be generated.

Programming matter by embedding hardware directly into individual material units has enabled reconfigurable structures as units can have self-movement, self-inspection and self-adhesion abilities (Romanishin et al., 2013). The hardware enables digital information to be uploaded into each material unit and actions can be physically executed (Gilpin and Rus, 2012). External stimuli do not play a role within these hardware-based approaches if the material units have self-moving abilities. However, this embedded hardware comes at a cost, as material resolution (size) and scalability become limited. Removing this self-moving ability can somewhat miniaturise each material unit (Gilpin et al., 2010) but results in the requirement of external stimuli being supplied to the units so they can move around and interact with one another. The approach of programming matter by embedding hardware highlights several main challenges of interest: 1) scalability due to cost, 2) material resolution, 3) only geometric reconfigurations are possible.

MIT's self-assembly lab has developed an alternative approach to programming matter through a series of practice-based investigations (Tibbits, 2016). Instead, material units are pre-programmed by designing the geometries and the material interfaces of individual material units, which still enables computational processes such as self-error correction (Papadopoulou et al., 2017). It also enables increased material resolution and an increasingly scaleable process due to material unit cost and ease of fabrication. However, because the hardware has been removed, external energy/stimuli (e.g. fluid agitation) must be supplied to the material units to enable autonomous-assembly (Papadopoulou et al., 2017). Tolley and Lipson demonstrated that by controlling the energy supplied to these types of material units the rate of assembly can be increased (Tolley and Lipson, 2010). This illustrates the beneficial role modulating parameters of external stimuli can play in fabrication processes and potentially, how it could be employed to programme matter. The removal of hardware raises the challenge of enabling a discourse between design tools and material units, which prevents new information from being uploaded from design tools and determining the properties generated. Being able to 'upload' information into matter is desirable as it would enable increasingly flexible material systems that can accommodate unforeseen design demands, which would avoid redundancies and significant material waste. This opens up two main challenges at this point: 1) how can stimuli begin to programme matter? 2) How can a discourse between design tools and material units be achieved based on modulating stimuli?

Ayers demonstrates a continued discourse between design representations and material units can be achieved if design tools are used to modulate parameters of stimuli (water pressure) that deform the global shape of metal components (Ayres, 2011). These global shape changes are reversible up to the elastic limit of the material but beyond this point, deformations are permanent and the ability to upload design information into the material units becomes limited. This issue could potentially be avoided if material processes are based on assembly. Importantly, Ayers reveals how stimuli can be utilised to create continued interactions with matter, so information from design tools can potentially be uploaded into matter i.e. using stimuli to iteratively programme matter.

These approaches to programming matter highlight the potential role stimuli can play in guiding/informing various material properties across a range of material platforms, especially when form/geometric properties are not imposed upon individual material units.

Čejková et al further demonstrate the role of stimuli plays in systems to do not impose form upon material units, with initially simple decanol droplets dynamically changing shape based on evaporation of water, which results in complex multi-armed structures being created at high resolutions (Cejkova et al., 2016; Čejková et al., 2018). These complex structures are small in size, typically occurring on the nano-scale to cm-scale, unlike the meter-length scales of approaches that pre-design the geometries of material units. This obstacle of scale reveals the role and tradeoffs 'scaffolds' play to overcome issues of scale.

Smith et al demonstrate how product-scale structures can have highly complex colour and surface texture patterns generated when subjected to stimuli post-fabrication (Smith et al., 2019). In this instance, the structures are 3D printed using growth mediums, which have 'preprogrammed' bacteria incorporated into them. Here, the 3D printed structures act as a scaffold to guide material properties generated. Additionally, within the developing field of fungal architecture, scaffolds are created using growth substrates to grow large-scale mycelium-based structures (Goidea et al., 2020). Previously, McGilivary and Gow demonstrate how stimuli can be used to alter material properties of mycelium, if kept alive, as hyphal branching can be tuned by exposing it to an electric field (McGillivray and Gow, 1986). Importantly though, to leverage desirable abilities, such as self-healing, the material must be kept alive (Adamatzky et al., 2019) but this can result in scaffolds being digested by the mycelium materials (Adamatzky et al., 2021). This highlights a balance between guiding material growth via stimuli, the longevity of pre-designed scaffolds and the need to continually supply the material units with resources to enable growth. The later challenge highlights the need for these bio-material systems to become integrated with existing biological ecologies and material cycles so resources can be shared and replenish one another.

Surveying these various and diverse approaches to programming matter highlights the important role stimuli can play in enabling interactions with material units at highly granular resolutions. However, the trade-off between increasing material resolutions and removing hardware results in the discourse between design tools, the structure and its material properties being lost.

I have investigated how modulating parameters of stimuli can be used to programme matter at high material resolutions through a series of iterative prototypes (Blaney, 2020). This approach to programming matter via stimuli is termed tuneable environments and enables information from design tools to be uploaded into matter (Blaney et al, 2017, Blaney et al, 2019). These previous prototypes represent open-loop control systems and are based on predetermined associations between stimuli, design parameters and material properties. Two final prototypes are now presented with the first investigating how feedback between material properties and stimuli could be determined, with the aim of developing a closed-loop control system. The second prototype presented investigates how material units can be interacted with without using constraining scaffolds, with the aim of increasing material resolution and flexibility.

MINERAL ACCRETION PROTOTYPE

To discuss the parameters of this final prototype a brief overview of the mineral accretion process is discussed in order to highlight the processes and mechanisms used to develop a closed-loop control system.

The mineral accretion process is essentially the electrolysis of seawater. Hilbertz demonstrated it is a multi-material system that can aggregate volumes of either calcium carbonate or magnesium hydroxide crystals upon large cathode scaffolds submerged within seawater (Hilbertz, 1978). The predominant means of starting and stopping the aggregation of matter in the mineral accretion process is by switching on or off voltage supplied between an anode and cathode. Longer durations produce increased volumes (Hilbertz, 1978). Voltage magnitude informs the material type grown, with 1.23-1.5 volts predominantly producing calcium carbonate and over 3 volts producing magnesium hydroxide (Goreau, 2012). Importantly, the mineral accretion process results in multiple chemical reactions being generated, which can proliferate and affect material properties in a closed system if they are not offset. Goreau also highlights that as material volumes grow they insulate against the electrical stimuli (Goreau, 2012). Importantly, this insulating property acts as a contrasting effect to the stimuli induced. Because of this phenomenon, it provides a way to begin to determine associations between material volumes grown relative to dropping electrical current values, which can be monitored. It also highlights how materials can emit signals, so directly embedding sensors may not be needed to determine associations and establish feedback. Hilbertz et al illustrated how this contrasting material effect can be used to monitor material growth by embedding an array of sensors (exposed wires) at set distances perpendicular to the cathode scaffold (Hilbertz et al., 1977) i.e. effectively the sensors are embedded in the material units because of the cathode scaffolds required. Additionally, this set-up was carried out in the open ocean (i.e. open system) so conditions generated during the chemical reaction did not proliferate, for example, increasing pH levels resulting in magnesium hydroxide growth predominating.

The previous experiments Hilbertz et al carried out did not use design tools to alter stimuli parameters that inform material aggregation properties, which means the properties of the material volumes grown are not 'programmed'. This provides an opportunity to extend this mineral accretion research to understand how stimuli can programme matter at molecular resolutions by uploading information from design tools. To illustrate the development of this approach; firstly, the parameters of the mineral accretion process are discussed. Secondly, previous prototypes and their challenges are discussed. Thirdly, a final mineral accretion prototype is presented that investigated the challenge of determining feedback between the stimuli and material properties generated.

Previous prototypes I have developed using the mineral accretion process have informed how matter can be programmed by pre-defining associations between design parameters, stimuli parameters and material properties. Previous prototypes have demonstrated; 1) cathode scaffolds composed of physically separated elements enable localised stimuli to be induced, which informs local material properties (Blaney et al, 2017). 2) Inducing localised stimuli makes it possible to grow low-resolution 2D shapes with variable material compositions and volumes informed by analogue and digital design tools (Blaney et al, 2019). 3) Material aggregation can occur volumetrically, which makes it possible to tune material properties across the whole of a 3D structure at various times, unlike 3D printing processes that are constrained to layer-by-layer build-ups (see figure 1).

These past prototypes highlight an alternative approach to programming matter, where material units are not pre-programmed by imposing form upon them. Instead, they demonstrate how matter can be materialised and programmed on-demand at molecular resolutions by modulating stimuli informed by design parameters. Additionally, tuneable environments open up the potential for discourse with design tools to be maintained with a structure's material properties, so shapes and volumes of material can have their properties updated based on augmentations to design tools (Blaney et al, 2017; Blaney et al, 2019). The challenge from these previous prototypes is that they represent open-loop control systems, which means there was no feedback between stimuli and the material properties generated. Because there is no feedback, it is not possible to robustly determine if desirable material properties (e.g. volumes of material) have been generated relative to design parameters.

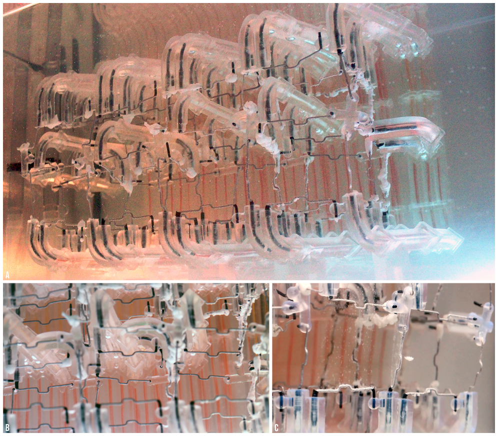

Figure 1
3D cathode scaffold highlighting volumes of material that can be updated simultaneously in 3D space.

This final mineral accretion prototype investigates how material properties generated relative to stimuli can be determined, which is a fundamental challenge for developing functional material properties, adaptive structures and reprogrammable matter at high resolutions. To achieve high material resolutions, sensors will not be directly embedded into the individual material units. This final prototype will investigate how feedback can be determined based on materials emitting signals that contrast with the stimuli induced, so a closed-loop control system can be created. For these reasons, this prototype incorporates multiple sensors that are external to the cathode scaffold (see figure 2).

To begin to determine relationships between the intended stimuli supplied (voltage) and material growth volumes produced the conditions generated from the chemical reaction need to be maintained within threshold ranges because a closed system will be used. This is done so associations between induced stimuli, corresponding electrical current sensor values and material growth volumes generated can be analysed reliably. In order to determine associations between stimuli and material properties, electrical current sensor values will be compared with time-lapse photography to document material volumes grown relative to sensor values.

Mineral Accretion Setup and System Actions

The initial solution for the prototype is made up of 39.5 litres of tap water with 1.5kg of marine salts added, which creates initial electrical conductivity and pH values. To maintain the solutions initial conditions, a pH and electrical conductivity (EC) sensor will be used (see Figure 2). The real-time pH and EC sensor values inform dosing pump actions and which liquid to dose into the solution. Solution temperature is monitored as it has a direct effect on solution conductivity values but the temperature values will not induce a system action because the heating element used self-regulates. Figure 3 highlights all the system's actions governed by an Arduino as a way to potentially enable discourse between stimuli, sensing, design parameters and material properties.

Previous prototypes were relatively complex as they were composed of multiple cathode wires, which makes them not suitable for determining initial relationships between stimuli and material properties. For this reason, only two cathodes will be used in this prototype (see Figure 2). To generate a more robust data set, the prototype will be carried out 3 times with three different cathode types. Firstly, carbon cathodes with a smooth sur-

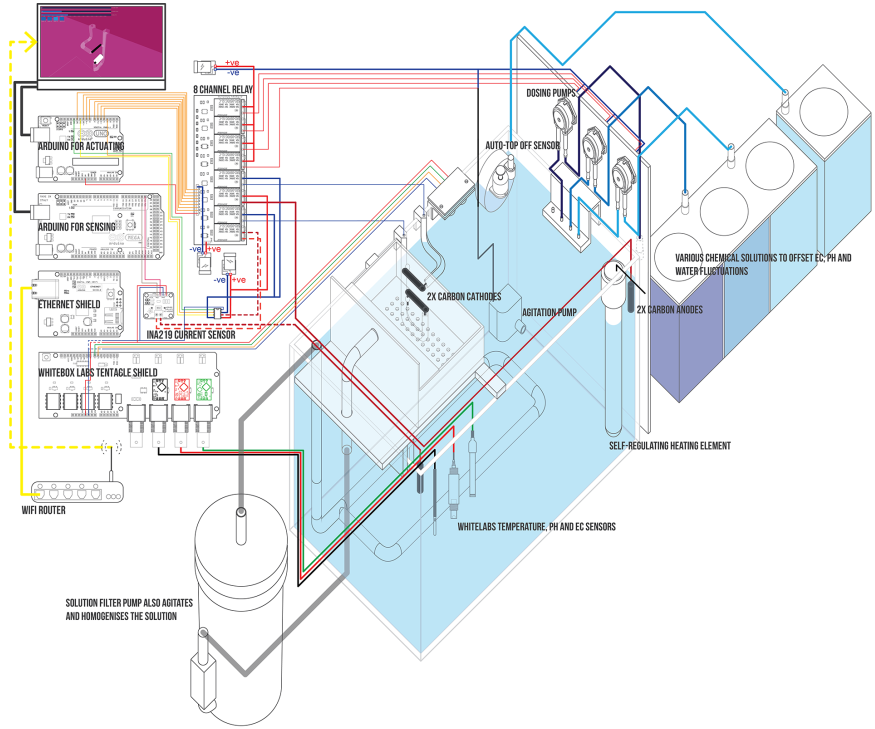

Figure 2
Set-up diagram of a mineral accretion prototype with all sensors external to the material units

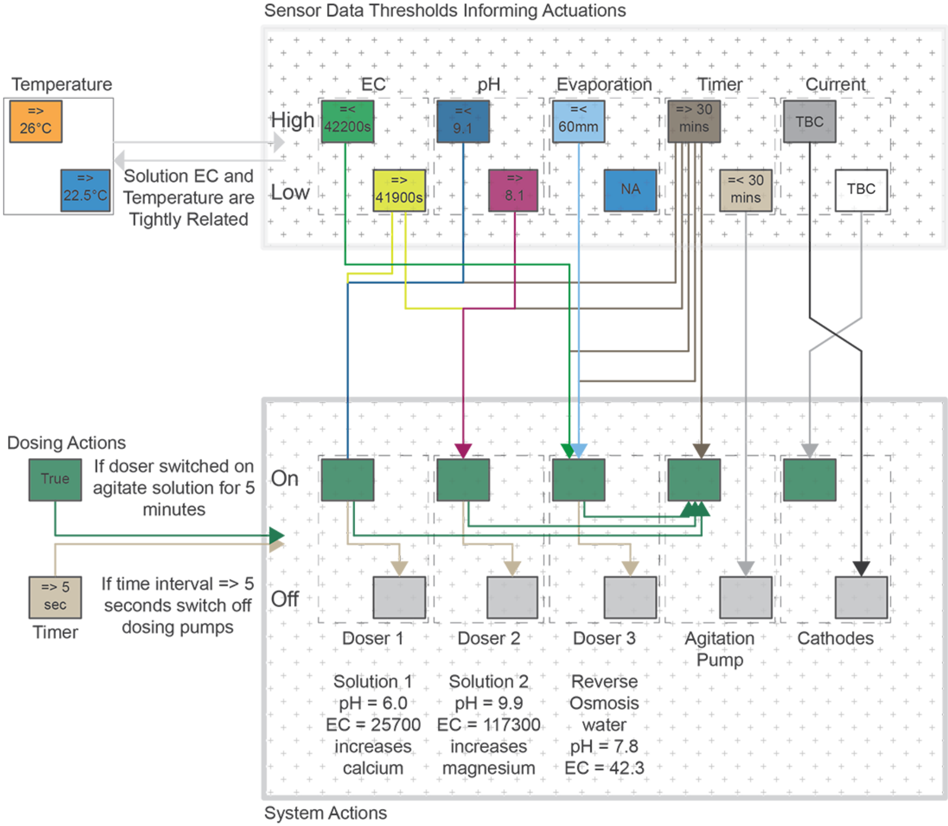

Figure 3
System actions and pre-defined relationship diagram

face texture (40x6.3mm). Secondly carbon cathodes with a rough surface texture (40x6.1mm). Finally, aluminium cathodes with a rough surface texture (40x1.2mm). A set voltage of 4.00 V will be supplied via a bench power supply for 24 hours, as this generated comparatively large volumes of material growth in previous prototypes (see Figure 4).

Mineral Accretion Results

Time-lapse photography for all three studies highlighted minimal material growth and compared to the carbon cathodes, the aluminium cathode generated the most material growth. In previous prototypes, considerably more growth occurred when using an aluminium cathode over the same duration, which is frustrating (see Figure 4).

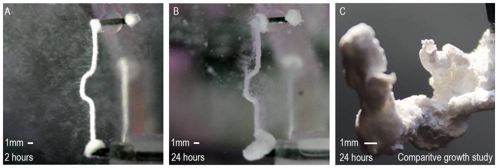

Figure 4
Time lapse photography highlight minimal material growth over a 24hr period. Image C compares material growth that occurred over a 24hr duration from a previous prototype. Video: https://vimeo.com/380528892

Figure 5 plots the various sensor values and system actions recorded during the aluminium cathode growth. Although solution temperature stayed within an accepted range, the solution conductivity continually rose irrespective of temperature fluctuations. The system actions attempted to offset the solution conductivity by dosing reverse osmosis water. This condition appears to be significant as average current, voltage and power values all decreased even with very minimal material growth occurring. Additionally, comparing the values with all three cathode types highlighted that no direct linear-associations could be created between stimuli and current sensor values as no linear cause and effect relationships/trends can be identified

The minimal material growth and varying sensor values generated from this final mineral accretion prototype raised personal reflections on what constitutes a successful investigation. The aim was to understand how feedback could be determined and developed within the system so matter could ultimately be reprogrammed. Defining if the prototype is successful based on only growing material volumes does not fully capture the system's intricacies. This is because using stimuli to interact with material units has effectively given them agency and multiple degrees of freedom. Because of this, the material units will only do what they deem suitable in their fabrication environments. In this case, not accumulating increasing volumes of matter irrespective of how long the stimulus is supplied for. The fact to no material has been grown highlights that ideal conditions must be created for growing materials even when 'non-living' materials are used. This reveals implications of robustness in this initial system and the ramifications of turbulence within the environment in order to create ideal environments (Kelly, 1994). Alternatively, Hilbertz et al demonstrate linear associations and robust growth can be achieved within these material systems if sensors are directly incorporated into the material units/scaffolds (Hilbertz et al., 1977). Comparing with Hilbertz experiments, the results demonstrate that monitoring relationships between stimuli and material properties using external sensors to monitor materials emitting signals leads to complex and non-linear associations being generated when

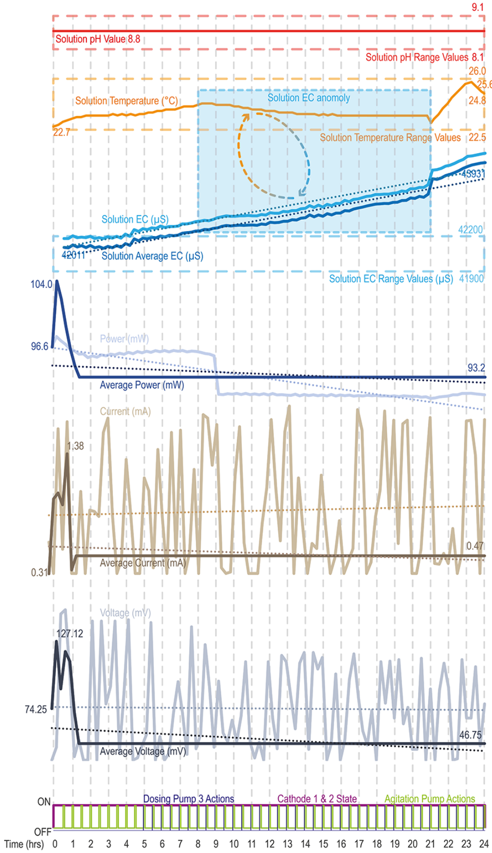

Figure 5
Sensor values recorded over a 24hr period using an aluminium cathode. Notably, as solution temperature varied there was no impact on solution conductivity as this continually rose. The average current sensor values also decreased over time, which is unexpected based on previous research. These results highlight non-linear behaviours being generated when sensors are not directly embedded into material units. This illustrates that design tools/processes based on pre-defined associations are unsuitable/not reliable for programming matter at high resolutions.

form is not imposed upon matter. Because of these non-linear traits, digital design processes based on non-linear associations will be required to begin to programme matter. Richards and Amos demonstrate how non-linear design tools can programme digital material units (voxels) to generate high-resolution and multi-material structures (Richards and Amos, 2016). Further work is needed to determine how digital design processes based on non-linear associations can be incorporated and if they could more robustly programme matter at high material resolutions.

These non-linear behaviours based on programming matter via stimuli highlights several opportunities but the challenges appear to be shared issues within similar architectural research areas that do not impose form upon matter. These will be outlined further in the discussion section. The next prototype presented is used to investigate further how the material resolution could be increased by removing the constraining cathode scaffolds and the implications of this.

DIFFUSION PROTOTYPE

A personal area of interest with the mineral accretion prototypes is that the aggregated material is constrained to the pre-designed and rigid scaffolds. This effectively results in low-resolution, pixelated structures being created at the global scale of the system. To investigate how materials could be interacted with via stimuli with less constraining scaffolds a prototype was developed based on 3D ink diffusion patterns.

Diffusion Porototype Setup:

The diffusion prototype injects 4 different water-based ink colours into 3 different volumes (5L) of support liquid to investigate how ink diffusion patterns can be interacted with via stimuli. Figure 6 highlights the system's set-up and components. The three support liquids are water, sugar syrup (1 parts sugar to 2 parts of water) and vegetable glycerine. The support liquids vary in density and viscosity, with water being the lowest and vegetable glycerine being the highest. The same volumes of ink are deposited at set intervals using dosing pumps controlled via Arduino. The stimulus in the system is liquid agitation, which is induced via two submersible pumps and the parameters (magnitude, duration, intervals) are defined by a user interface created using the software Processing. This loosely enables information from design tools to be uploaded into matter again. The stimulus is monitored via a flow meter attached to one of the pumps, which will highlight energy transferred to the material units (ink) within each support liquid but significantly, the stimulus is not associated with any design demand and there is no attempt to develop a closed-loop control system. The aim is only to investigate the implications on material properties and material resolutions when rigid scaffolds are removed.

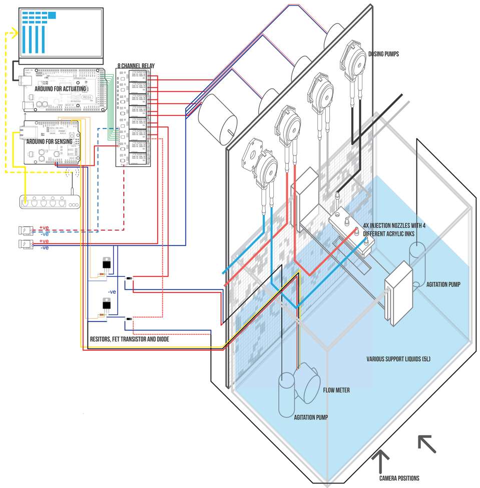

Figure 6
Ink diffusion prototype set-up

Diffusions Results

Figure 7 documents the various patterns generated as inks are deposited into the three support liquids and then agitated. Water resulted in the ink clouds homogenising and proliferating much faster than the sugar syrup, which is also highlighted by the flow meter values. Because the vegetable glycerine is so dense and viscous the inks dink not sink and could not be manipulated by solution agitation (pumps), which is also highlighted by the flowmeter values. Instead, the vegetable glycerine patterns had to be generated by manually manipulating the inks. The photographs reveal delicate patterns suspended in time (see Figure 7). The combined results from each support liquid highlight how different forms of scaffolds and the potential of using stimuli to guide, tune and suspend complex 3D diffusion patterns.

Interestingly, the comparative properties of the support liquids and patterns generated highlights the possibility of changing the material properties of scaffolds to inform their flexibility. For example, us-

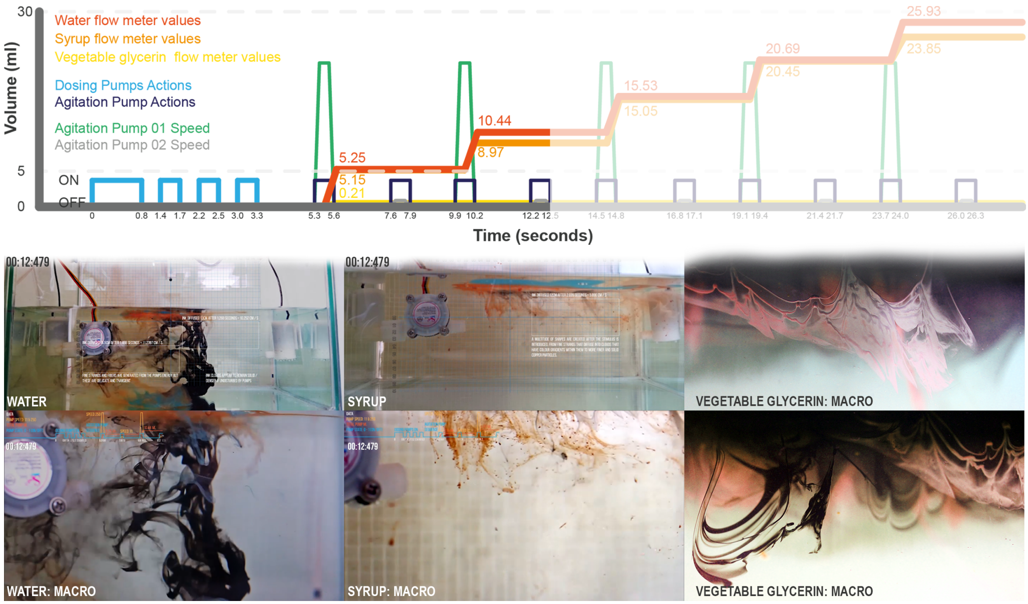

Figure 7
Ink diffusion comparing 3D forms generated in support solutions with varying viscosities and densities. Video link: https://vimeo.com/367431096

ing heat to reduce the viscosity of the support liquid to rapidly generate 3D ink patterns, induce stimuli to manipulate ink patterns with higher fidelity, and then temporarily freezing these patterns in time by increasing the support liquid's viscosity by cooling it back down. Based on these insights, it could be imagined how tuneable environments could be incorporated with novel 3D printing developments, such as Rapid Liquid Printing (Hajash et al., 2017). Imagine, materials deposited in support liquids to create precise structures and then the support liquid is used as a tuneable environment to fine tune or update the 3D printed structure's properties via stimuli by placing them back in the tank. Developing precision and functional properties of this prototype is a long way off and it was not the aim. However, it does begin to illustrate how modulating stimuli can be applied to various material platforms and open up new ways to interact with and begin to programme matter at high material resolutions and increased flexibility.

These two prototypes along with previous investigations highlight the potential of iteratively programming matter at high resolutions using tuneable environments. They also raise key considerations and potentials for developing design and fabrication processes based on interrelationships instead of imposing form upon matter.

DISCUSSION

This research demonstrates how tuneable environments can be used as an alternative approach to programming matter. Tuneable environments contribute to programmable matter as it enables information from design tools to be iteratively uploaded into a structures' material makeup. Meaning, structures can be updated and radically transformed at highly granular resolutions (molecular). This is possible because tuneable environments do not impose form upon matter but instead, creates design and fabrication processes based on interrelationships, which can leverage desirable abilities present within biology, such as self-healing and potentially adaptive structures if feedback is achieved. Furthermore, tuneable environments also appears to act as a universal language for interacting with matter, as highlighted by the role stimuli can play in enabling discourse across a range of material platforms.

Iterative prototyping has been used to investigate subjective areas of interest as the process of programming matter via stimuli develops. The two final prototypes in this series specifically investigate issues of feedback and the roles of scaffolds. Their results highlight possible application areas along with future implications of programming matter via stimuli, which appear to be emerging in other areas of research.

Implications of Feedback and Adaptive Architecture

The mineral accretion prototype highlights issues of feedback when attempting to determine linear associations. Instead, the results reveal non-linear associations occurring between stimuli and material properties generated when sensors are not directly embedded into matter. Further investigations are required to understand how digital design tools can be utilised to determine material properties generated in non-linear systems. Achieving feedback within the system would lead to high resolution physically adaptive and self-healing structures. But this then opens up the implication of; what would constitute desirable adaptations, especially within complex design issues, such as urban design? Adamaztky et al also discuss a similar issue of feedback so functional material properties can be developed within fungal architecture (Adamatzky et al., 2019). This highlights a shared and emerging issue when interacting with materials via stimuli.

Applications and Developing Reprogrammable Matter

The diffusion prototype illustrates how support liquids can act as flexible scaffolds, so complex 3D patterns can be rapidly generated, tuned and suspended in time if the material properties (viscosities) of the scaffolds can be varied via stimuli. This opens up the potential of incorporating tuneable environments with 3D printing processes, such as Rapid Liquid Printing (Hajash et al., 2017), so 3D printed structures could be repaired or updated once fabricated if they are placed back in their tanks/fabrication environments. Imagine future medical prosthetics or splints that are rapidly fabricated by submerging a patients' limb into a tank, which can also be further updated as the patient heals or grows. A main obstacle to overcome in beginning to achieve these material abilities is the ability to upload and temporarily freeze assembly instructions into the deposited material, so structures can be taken out of the tank but also updated when subjected to stimuli again.

CONCLUSION

This research highlights how matter can be interacted without imposing form up material units. This is important as current linear modes of fabrication impose form upon matter. Resulting in significant material waste, damaged ecosystems and greenhouse gas emissions, most notably witnessed within the fashion (EDGExpo) and construction industries (Fisher, 2020). Developing design and fabrication processes capable of updating multiple properties of a structure at high resolution would address these issues as circular materials would be possible. This is because matter could be infinitely reprogrammed, so fluctuating and unforeseen design demands can be accommodated. Future research aims to investigate how matter can be reprogrammed at high resolutions so adaptive structures can be generated, which are capable of sharing material resources and lead to new material ecosystems.

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