Parametric Matter:

‘Pushing’ Updates into Materials and the Implications of Legacy and Lag

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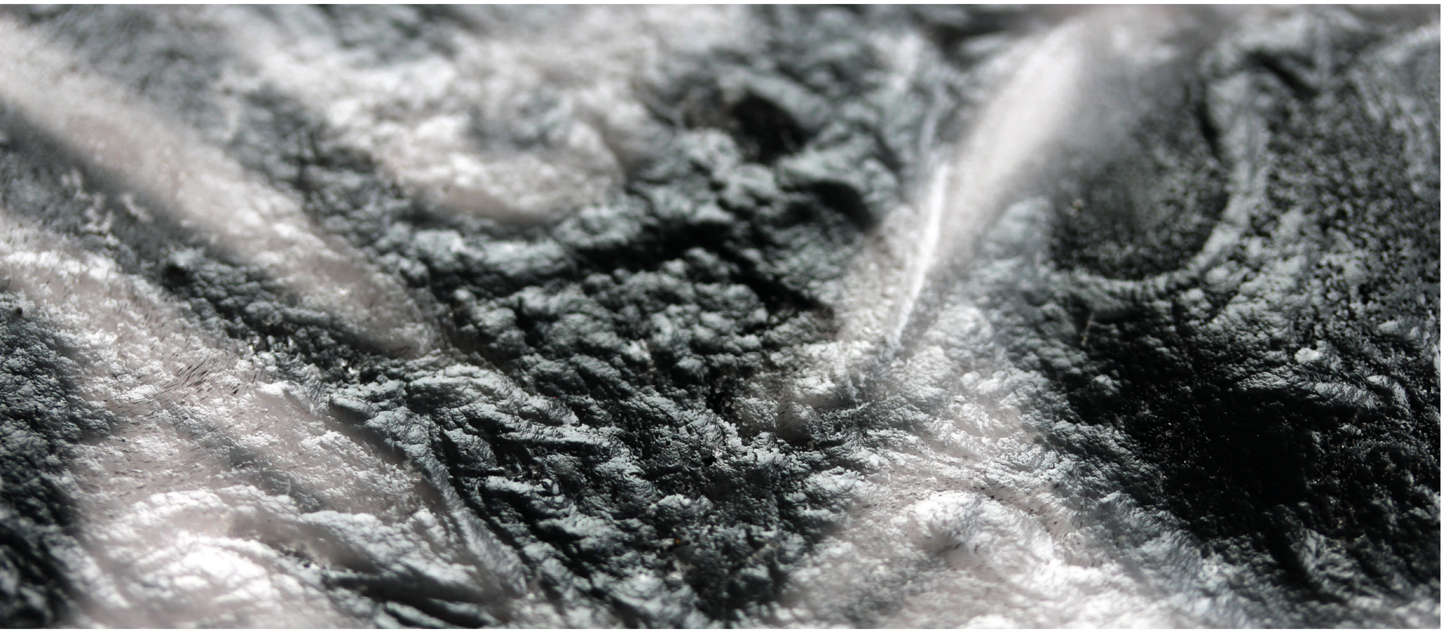


ABSTRACT

This paper discusses an ongoing interdisciplinary research project that develops a design and fabrication approach termed; tunable environments. This is an explorative approach, which enables updates from a digital parametric interface to be ‘pushed' into a 2D, 18x18 cm material sample, by modulating stimuli, so multi properties can be updated/tuned at high resolutions. Our prototype explores how iterative updates can be achieved, which can be temporarily frozen in time. This opens up the idea of creating Parametric Matter/circular materials, which could reduce waste that can be attributed to typical linear processes. Additionally, highly bespoke, ‘time-based’ structures could be achieved. However new implications for design and fabrication arise based on: time-lag of materials, a legacy of interactions, resetting materials as well as challenges of determining associations and desirable material properties.

INTRODUCTION

Developments in digital design tools have enabled designs to be infinitely updated if they remain in their digital environments. However, typical design and fabrication processes are linear, which means, that the final fabricated structures lose the ability to have multiple properties updated (shape, composition, color, texture). As a result, significant material waste, pollution and resource depletion is generated when a design becomes outdated (aesthetics, capacity, environmental, etc.) or damaged. This inability to update a physical structure's properties is due, in part, to no discourse or associations being maintained between design parameters, material properties and fabrication mechanisms over time. To address this issue, new design and fabrication approaches are required that are capable of leveraging material's computational abilities at high resolutions (granular/particles, molecular). In doing so, materials could be continually interacted with, finely tuned and self-healed when damaged. Achieving these abilities build toward a notion of circular materials.

This paper presents initial findings from our feasibility project that is aiming to develop these types of updatable/circular materials at high resolutions. We present 2D, material samples that can have multiple properties updated, at high resolutions, by modulating two stimuli (heat and magnetism). We term this design and fabrication approach; tunable environments (Blaney et al., 2019). Employing tunable environments as a design and fabrication approach opens up this idea of circular material abilities (Blaney et al., 2021), as the materials can be self-healed when damaged, as well as enabling updates to be 'pushed' into materials remotely. This is possible because a discourse is maintained between design tools and material properties. However, this study highlights new design implications when iteratively interacting with and 'programming' non-linear materials via stimuli, especially as the material samples are scaled up in size.

To further explore this area, the paper firstly, contextualizes our design and fabrication approach and how it relates to existing research. Secondly, we present our method outlining our prototype set-up, how and why we will interact with materials via a simple digital interface, material sample development and how we recorded our results. In regards to our methodology, Research Through Design (Frayling, 1993) is employed as a flexible approach (Gaver, 2012). This is because the research carried out is explorative by nature, which is guided by an overall aim; how can updates be pushed into materials to leverage material computation at high resolutions? Thirdly, we present our results to date from scaling up to an 18x18 cm material sample as an annotated portfolio (Bowers, 2012). Finally, we discuss our key insights and our future intentions.

STATE OF THE ART

Physical materials demonstrate the ability to compute form when stress/stimuli (gravity, magnetism, tension etc.) are induced upon them. However, typical design and fabrication processes remove, or, do not leverage these abilities as materials are typically treated as static and or inert. Material computation has a rich history within architectural design processes to generate geometric forms, such as Gaudi's catenary strings. These tension-based models create highly sculptural forms that can be translated into pure compression-based construction (Burry, 2016). Additionally, Otto's form-finding experiments further demonstrate how various analogue models/material platforms (soap bubbles, strings, polystyrene chips) can respond and reconfigure when a stimulus is induced to generate various design solutions, such as tensile and branching structural systems (Otto and Rasch, 1995) as well as urban distribution models (Otto, 2003).

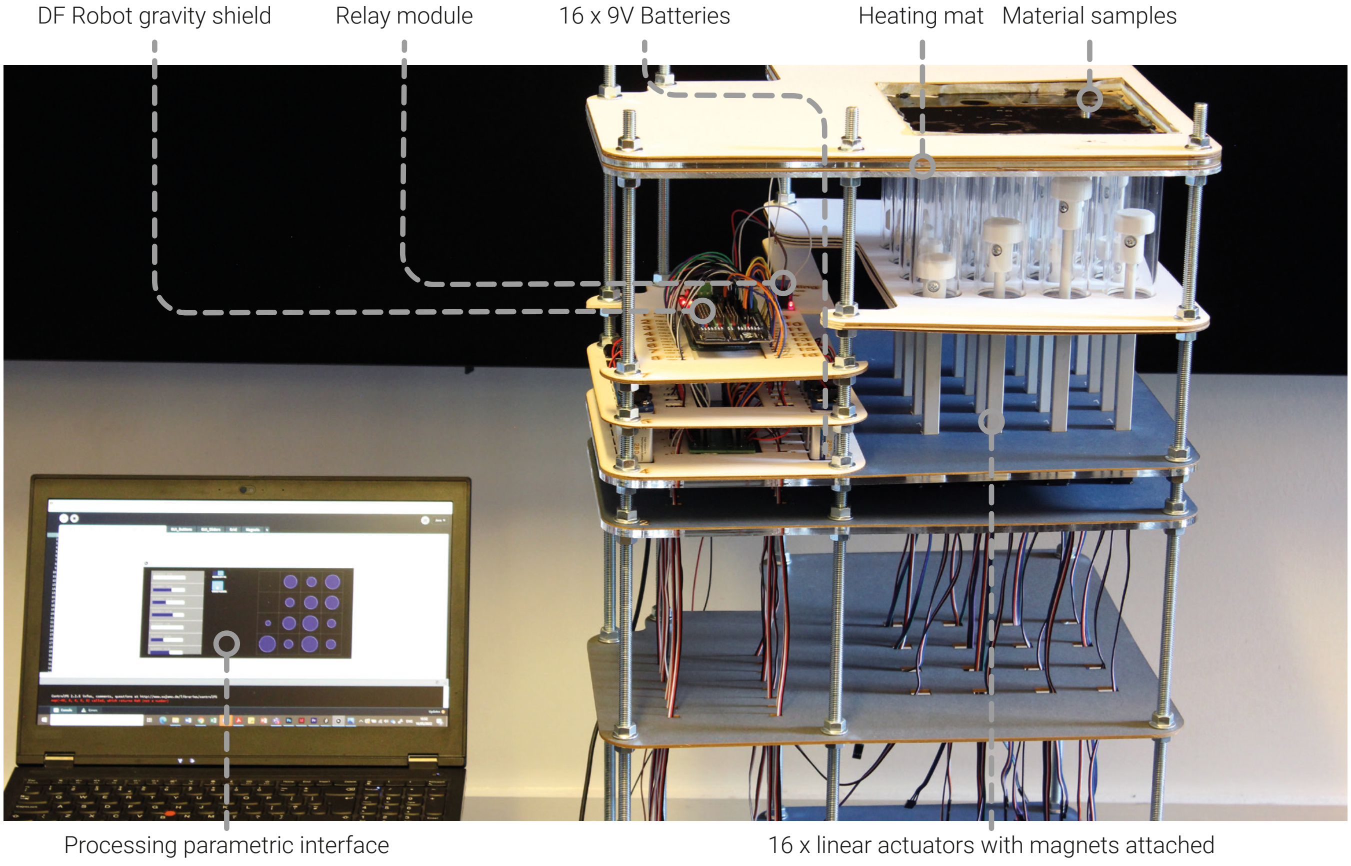
To create highly adaptive, circular materials and continually customizable objects and structures we believe material computation needs to be embedded within an object's/structure's material make-up, so it can be leveraged on demand. We now discuss how related research and how developing stimuli-based design and fabrication processes can open up these abilities, enable continued interactions and high material resolutions.

Maintaining Discourse & Material Assembly

In regards to the role of stimuli; Persistent Modelling developed by Ayres (2011) demonstrates how modulating stimuli, water pressure, based on a digital design representation (i.e. a digital parametric model) can be used to iteratively interact with and deform the global shape, up to the material elastic limits (Ayres, 2012), of predesigned metal components. Significantly, this approach enhances a structure's material capacities as Ayres demonstrates how a structure can change its shape to meet fluctuating design demands based on associations (Ayres et al., 2014). However, the implication of shape-changing abilities being constrained to the material's elastic limit highlights opportunities for incorporating tunable stimuli with material processes capable of autonomous assembly. Principally, the idea of using stimuli to interact with materials that can be governed by a design representation opens up the design space for iteratively updating multiple material properties of a structure's material make-up that we are investigating.

MIT's self-assembly lab has developed approaches to programming matter, which are capable of autonomous assembly and geometric reconfiguration/responses (Tibbits, 2016). This approach, preprogramme individual material units by designing their geometries and the material interfaces, which creates reconfigurable structures and achieves computational processes, such as self-error correction without embedding hardware (Papadopoulou et al., 2017). Interestingly, the role of external stimuli becomes increasingly apparent within this approach because, to achieve autonomous assembly, the material units are supplied with random external energy, such as fluid agitation (Papadopoulou et al., 2017). Tolley and Lipson demonstrate that by 'tuning' the fluid agitation supplied to these types of material units the assembly process, which is stochastic, can be speeded up (Tolley and Lipson, 2010). This illustrates the beneficial role modulating parameters of external stimuli can play in fabrication processes based on the assembly of individual material units and how continued interactions can be achieved. Designing the geometry and interfaces of individual units as an approach to programming matter enables robust geometric assembly and reconfigurations, as well as visual evidence when the assembly process is complete. However, what if higher material resolutions and multi-material updates are desirable? Could tuning multiple properties lead to increasingly customizable/bespoke design solutions that can be finely tuned to a user's demands? We are interested in exploring how Persistent Modelling can be combined with material platforms capable of autonomous assembly could open up continued material interactions and higher material resolutions so increasingly flexible systems can be created.

The concept of programmable matter first defined by Toffoli and Margolus (1991) outlines a vision of a universal material platform capable of high flexibility, scalability and material resolutions. More recently, Ishi et al describe 'Perfect Red', a speculative vision for programmable matter capable of performing actuation, sensing, and communication at molecular resolutions (Ishii et al., 2012). The ability to programme and continually interact with matter at this resolution highlight how multiple material properties can be finely tuned so a design solution can become increasingly bespoke based on user interactions. However, the challenge of miniaturization becomes difficult when the material units have hardware embedded into them to achieve sensing and actuation (Gilpin and Rus 2012). Various magnetically responsive material platforms have been developed that we see as capturing the original idea of programmable matter/Perfect Red. For example, the global shape-change of slime-like materials in response to magnetic stimuli developed by Dickey (2017), which are capable of performing as soft robots (Wang et al., 2021). Within architectural applications, Goldman and Myers demonstrate how magnetic stimuli/fields can be used to extrude materials and then frozen in time to create highly sculptural and detailed 3D forms (Goldman and Myers, 2017). These magnetized material platforms provide a sound starting point. However, we aiming to be able to iteratively update multiple properties to increase



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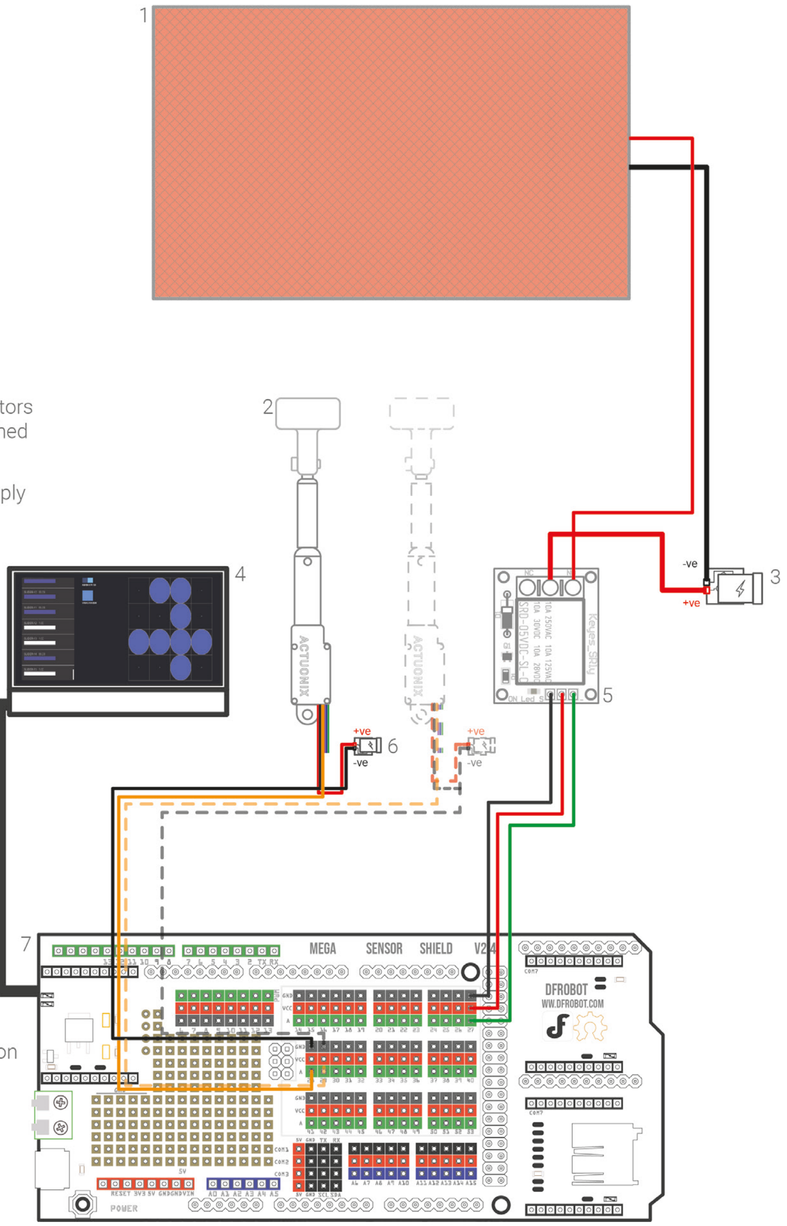
1 The prototype set up with a material sample being interacted with



1) 1 x Heating mat

2) 16 x Linear actuators with magnets attached

3) Bench power supply

4) Processing interface

5) Relay module

6) 16 x 9v battery

7) DfRobot Gravity Shield for Arduino-Mega.

Serial communication with Processing

2 System hardware and connections between components highlighted.

their flexibility. To do this we explore how modulating stimuli can open up new potential and resolutions for programmable matter.

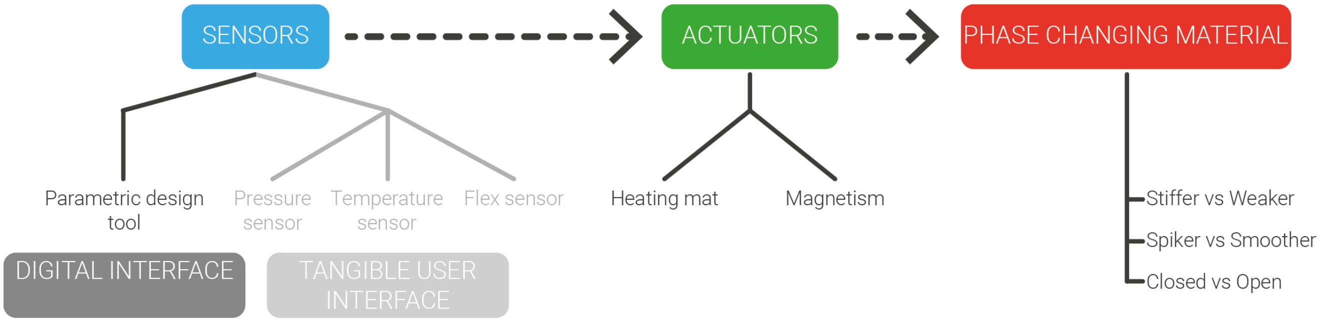
Previous research by the authors highlights how modulating stimuli based on digital design tools can update multiple material properties at high resolutions (molecular) when using chemical platforms (Blaney, 2020). Additionally, previous research by the authors demonstrates how modulating stimuli can be applied to bio-material platforms to parametrize their properties (Ozkan et al., 2022). This highlights the flexibility of modulating stimuli and how it can interact with and programme matter. However, determining reliable feedback between material properties generated with associated design parameters becomes an issue when not directly embedding sensor so material resolution is not compromised (Blaney, 2021).

This current research incorporates state-changing magnetized materials and a multi-stimuli system to achieve iterative multi-material actuation at high-resolution and investigate the implications of this when developing design and fabrication processes for interacting with non-linear materials.

METHOD: DEVELOPING PARAMETRIC MATTER

To test and support our thinking regarding design challenges when developing circular materials that can have multiple properties updated, we designed and built a prototype set-up. The set-up is capable of inducing two stimuli: heat and magnetism, which are used to interact with state-changing, magnetized material samples.

To discuss this process, we describe: firstly, our prototype set-up.



3 System relations highlight there is no feedback between the digital interface and properties generated and specific design demands enable by further sensing

Secondly, material sample development. Thirdly, a simple digital interface for interacting with the materials. Finally, how our samples have been documented to present our results.

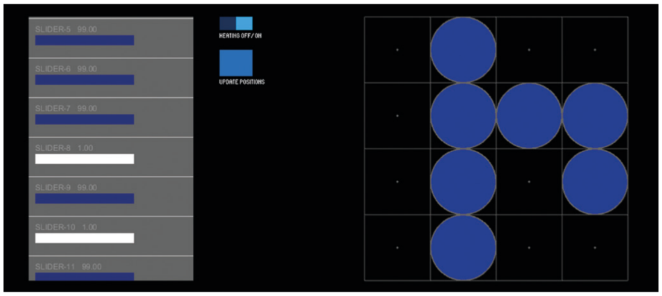
Prototype set-up

The set-up modulates two stimuli: heat and magnetism. Figures 1 and 2 document the system's hardware and components that allow us to modulate the two stimuli. Importantly, there is no feedback mechanism at this stage between the design tools and material properties generated (Figure 3). Essentially, the system is an open-loop control system.

An ArduinoMega is used to control multiple actuators based on data sent from a basic parametric interface developed in Processing (Figure 4). A digitally controlled relay module is used to control a heating mat, which the material samples were placed upon to melt them. 16 magnets are connected to 16 linear actuators in a 4 x 4 grid, which was positioned directly below the heating mat. By connecting the magnets to the actuators, the strength of the magnetic force induced upon the material sample could be varied by changing the vertical position, which produces a dissipating effect. The combination of two stimuli and state-changing materials is used to explore; how multiple properties can be iteratively updated across the sample's area, such as; global shape-change, patterns, rigidities, volumes, porosity/openness and surface texture. This is because updates can be 'pushed' from design tools into materials and temporarily frozen in time. In doing so, it should make it possible for the samples to be taken out of their fabrication environment, interacted with and then re-fabricated/updated or healed if they became damaged or outdated by placing them back in the fabricator.

'Pushing' Updates into Materials: User Interface Development

A simple parametric interface is used to manually control the positions of 16 magnets (see Figure 4). This is done over serial communication between Processing to Arduino. On the interface, two magnets (in the top left corner) will be kept at position zero to act as a control area. The proximity of the other 14 magnets will be changed randomly. Since the magnets have a dissipating effect on the samples, the further they are away, the less impact they have on the material. Varying this stimulus will be explored to understand the type of material responses that can be elicited and the impact of time. The closest a magnet can get to the material sample is 1 mm and the farthest away is 100 mm. For each sample, multiple iterations will be carried out by varying the positions of the magnets and solidifying or melting the sample by turning on or off the heat supplied to it. The re-melting and varying of the magnet's position to interact with the sample act as one iteration. Iterative interactions will be explored to understand their implications on design and fabrication processes.



4 Simple parametric interface used to control material patterns developed in Processing

Material Sample Development

The chemistry department produced multiple biodegradable and non-toxic material samples of Poly ε-caprolactone (PCL), which is FDA approved semi-crystalline aliphatic polyester (Patricio et al. 2013, Asvar et al. 2017). In the design experiments, polycaprolactone with six different molecular weights (530, 900, 2000, 14000, 45000 and 80000 Da) and Iron (II, III) oxide (Fe_3O_4) with two different particle sizes (powder (P) < 5 μm and nanopowder (N) 50-100 nm) were used. The Fe_3O_4 powder and nanoparticles had good adhesion and dispersion of the particles in the polycaprolactone matrix. While the molecular weight affected material viscosity, the particle size of iron oxide gave ferromagnetic properties to the samples and affected their magnetic behavior. The samples became less viscous with heavier molecular weight and exhibit super magnetic behavior with smaller iron oxide particle size (Rezai et al. 2021, Wu et al. 2010).

Fe3O4-PCL composites were prepared by dissolving the PCLs (300 mg) in tetrahydrofuran (THF, 3mL) solvent using an ultrasonic cleaner at room temperature. Then nanopowder or powder-sized iron oxide (30 mg) was added and sonicated for an hour. Lastly, the mixture was cast, and the solvent was removed.

Figure 5 documents the various small-sized (approx. 2 x 2 cm) PCL samples that were developed. The main criteria to select samples for further development and scaling up were: 1) mechanically robust when solid. 2) Enabling properties to be updated when in a liquid state, with a focus on; global 2D shape-changes, material gradients, surface texture, volumes, and rigidities. In line with the desired criteria, the chemistry department further developed two final samples discussed in the paper.

The smaller sample, P-2 80 50:50, was composed of 250 mg of PCL with a molecular weight of 2000, 250 mg of PCL with a molecular weight of 80000, and 50 mg of Iron (II, III) oxide powder size. The ratios (50:50) indicated the mass ratio of polycaprolactones with different molecular weights. The 18x18 cm sample P14 50:50, was produced on a larger scale, 25 grams of polycaprolactone with a molecular mass of 2000, 25 grams of polycaprolactone with a molecular weight of 14000, and 5 g of Iron (II, III) oxide powder size.

Recording Interactions and Responses

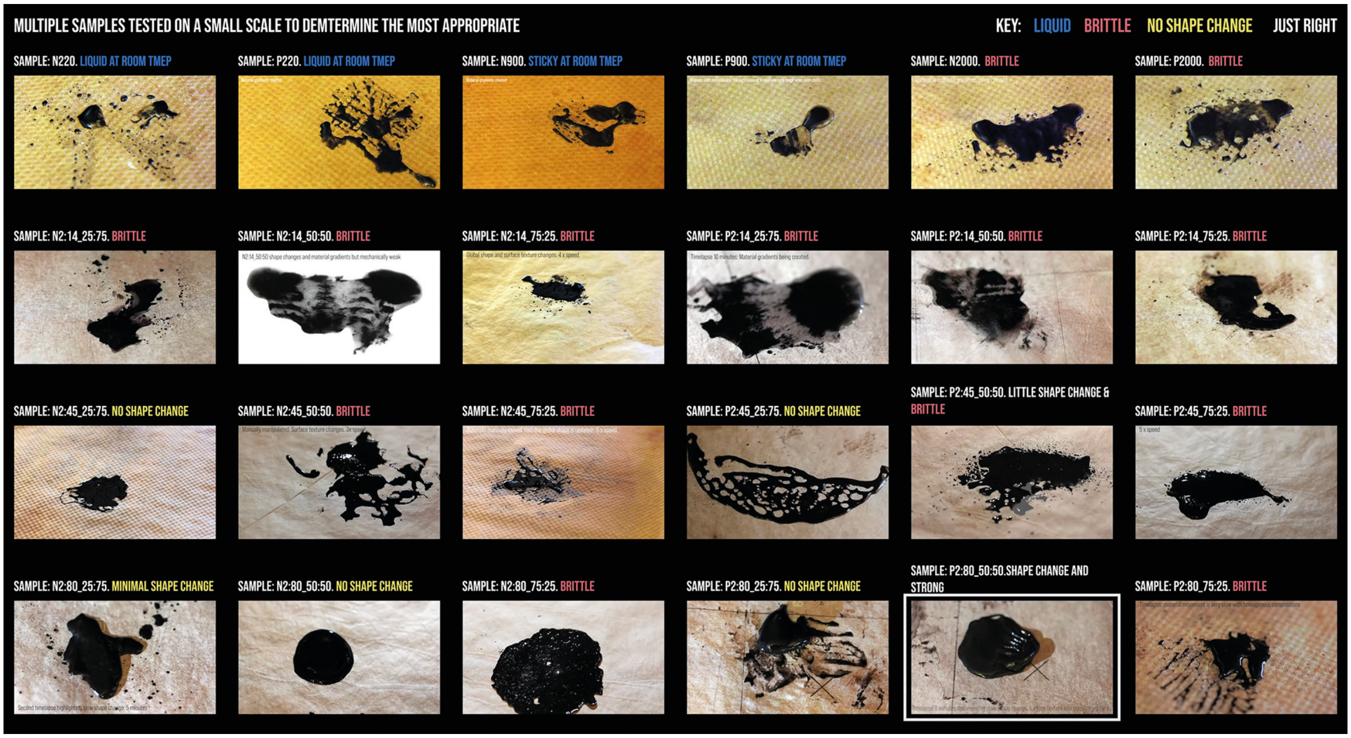
The changes in the material have been documented using photography, time-lapse and videography. The camera used is a Canon EOS 600D with an f/2.8 Macro USM for macro images (fine detail). A 3.5-5.6 Zoom EF-S 60mm is used for less detailed videography. Videography has been used to reveal real-time responses. Time-lapse photography is used to reveal slow and high-resolution responses. This is because time plays an important role in documenting various responses that occur at different rates. Importantly, documenting time using these strategies highlights the implications of developing design strategies to interact with materials.

RESULTS

The properties of the P-2 80 50:50 and P-2 14 50:50 samples and the performance of the set-up are now discussed.

Initial results from P-2 80 50:50 sample

The 2x2cm sample response rate was evident but slow in sample P-2 80 50:50, it changed shape and relocated on the heating mat, as seen in Figure 6 A-D. Surface texture, volumes, rigidities, and mono-color gradients were observed while interacting with the sample.



5 Video still of multiple samples tested on a small scale to determine the most appropriate samples to be scaled up. Video available

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6 A-D. Time-lapse photos (11-minute duration) of 2x2 cm sample melting at 98°C and slow response to magnetic stimuli. E. Solidified 2x2 cm sample. Annotations highlighting multiple properties achieved. F. Time lapse (12-minute duration) of 5x5 cm sample demonstrating expected movement to magnet locations. G. Solidified 5x5 cm sample. Annotations highlighting multiple properties achieved.

As a next step, the sample area and volume were increased in size to 5x5cm. The sample demonstrated global shape changes, as assumed, to magnet positions defined (Figure 6 F) as well as various surface textures, which were unexpected. This was due variations in heat throughout the sample, which created a thin 'skin' being formed on the sample's surface as it was colder than the volumes in direct contact with the heating mat. However, this could still be associated with magnetic stimuli and material volumes as the greatest surface texture variations were evident where the magnetic stimulus is most significant.

Results from P 14 50:50 Sample

Iterations with sample P14 50:50 demonstrated that multiple material properties could be updated at high resolutions. Figure 7C documents the multiple updates, such as global patterns, gradients, reflectance, surface texture, material height, volume and translucency. Comparatively, on the whole, P14 50:50 responded faster than P-2 80 50:50 but the finer patterns/gradients and became more apparent via time-lapse photography. It was observed that the material becomes stiffer and opaquer on spots where more material is located. This was only tested manually by hand. Additionally, the material gradients, from clear to black, impacts material stiffness. The ability to iteratively update material stiffness, shape-change and textures could be applied to further customize medical prosthetics. The ability to update these properties is important as patient's physiology changes over their life (Turner et al, 2022) along with other demands fluctuating (seasonal heat) (Ghoseiri and Safari, 2014), which leads to ill-fitting devices, discomfort, sores and if they become damaged or unfit, the need for a new device.

It was witnessed that increased material volumes, which generated global surface bumps reduce over time. Initially, the material would create large lumps where the magnets were positioned at 100% height, which would make them stronger. However, after some time, the material bumps reduce dramatically (see Figure 7video link). This highlights the significant implications of time windows and constraints for the designer to interact with the material to elicit certain material properties they can achieve. This means there are trade-offs over time as certain material properties become more apparent (e.g. gradients, global patterns) whilst others diminish (e.g. bumps/ volumes, surface textures). Meaning, hierarchies need to be defined for given applications.

Lastly, a second iteration was carried out where the sample was re-melted and magnet positions updated. This demonstrates that multiple properties can be iteratively updated based on digital design updates. However, this also highlighted that properties from previous interactions remain. This reveals implications of 'legacy' within the patterns (Figure 8D). This becomes more apparent if the neighboring magnets do not induce a strong enough effect on the materials. Due to this legacy, there is a need to reset the material (especially in larger samples) to a blank canvas. Resetting the sample gives it a clean slate, a uniform black color, which would help to not restrict future interactions. To test if resetting the material sample could be automated, various magnet positions will test to see if the magnetized particles can be evenly distributed across the sample.

Resetting Materials

To determine if the resetting process could be automated via stimuli, all magnet heights were set at 85% (15mm away from the material sample) (Figure 9A). Then 2 magnets were lowered to 60% height (Figure 9B). This step was followed by lowering all neighboring magnets (Figure 9C-D), and the assumed and witnessed direction of magnetic particle movement is illustrated using arrows. The stages of the material responses were photographed every 3 minutes while changing the magnet heights. The sample was most effectively reset when any directly neighboring magnet was lowered so it had no impact. This allows the black (magnetized) particles to reconnect to neighboring areas (see Figures 9D and 11). To automate the process via stimuli the shortest distances between neighboring magnets were reconnected via trails. To achieve more through mixing, magnets that tessellate together would be needed or an optimal proximity between them would need to be determined. Additionally, the top area (Figure 9E) was mixed by hand using a metal spatula to test resetting it manually, which allows it to be done rapid and generally made homogenous mixing possible.

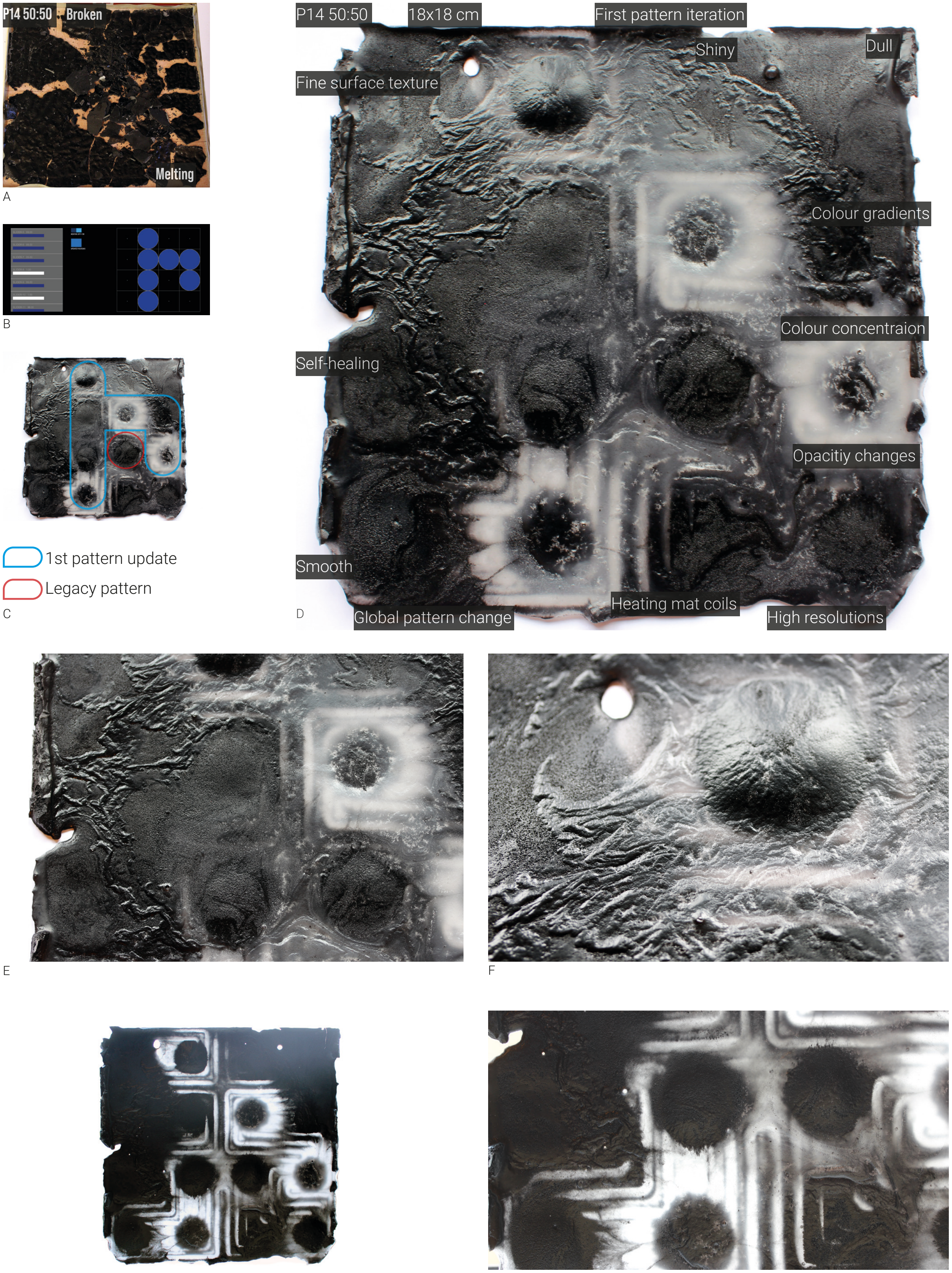
CONCLUSION

7 A: The initial state of the sample P14 50:50. B: Simple parametric interface used to control patterns. C: The first iteration of global patterns demonstrates multiple properties. D: 18x18cm sample demonstrating multiple properties, highlighted by annotations, across its area. E - H: Multiple material properties at high resolutions are highlighted, such as gradients, textures, reflectance, and opacity. Video available.

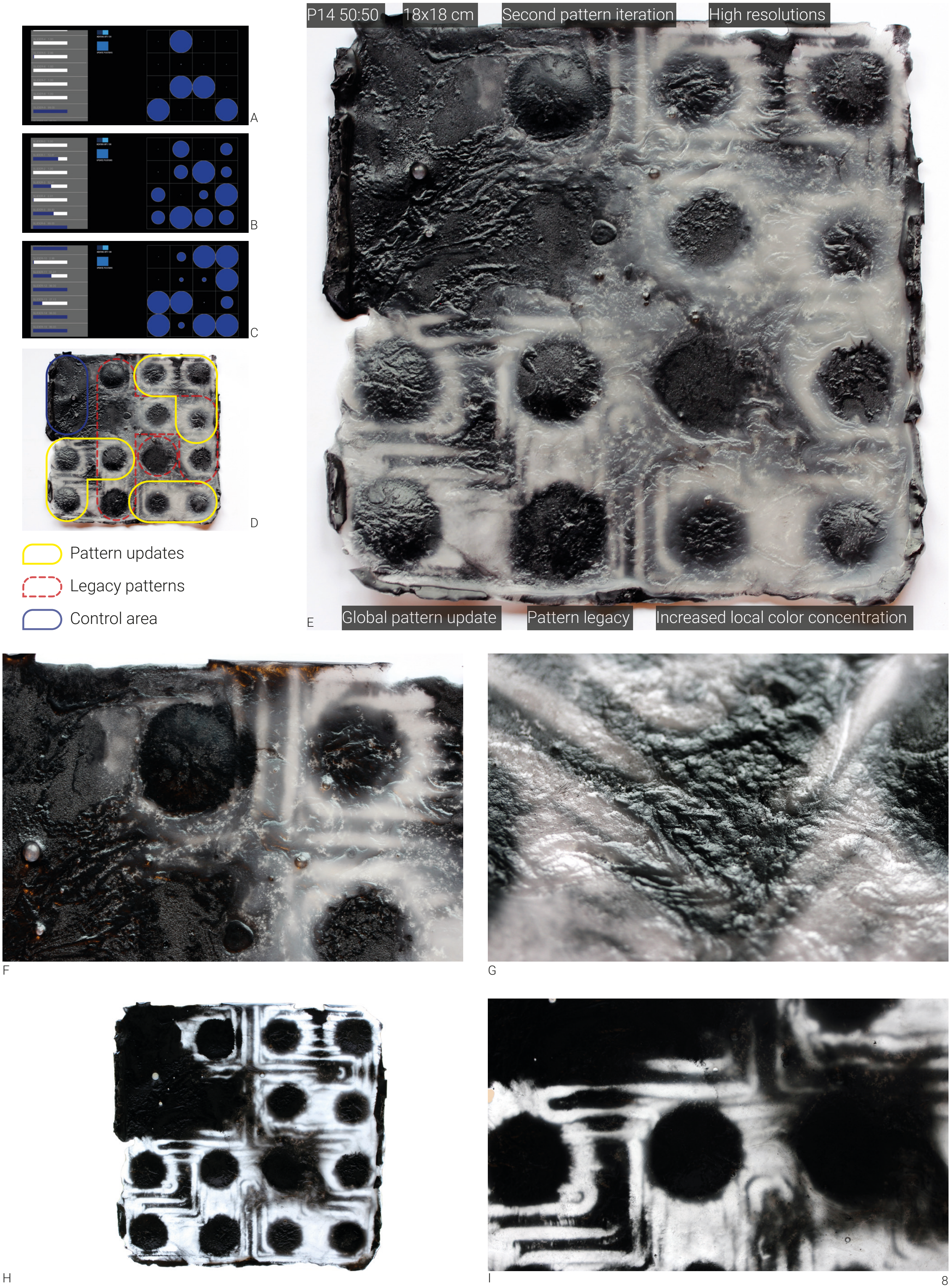
8 A – B: The induced patterns upon the sample before finalizing on the final fourth pattern. C: The final pattern is used to inform material properties. D: The photograph highlights significant 'legacy' properties from the first and two other prior interactions. E: Sample P14 50:50 in its second iteration demonstrates multiple material properties that have been updated. F – G: Highlights multi-material properties updates at high resolutions.

9 A - D: Patterns tested to reset the sample. E: Material mixed by hand manually to reset as a low-tech solution. F: Photographs documenting the sample becoming material reset in areas compared to the previous iteration. G: Area that was manually reset highlights an area that is more thoroughly mixed compared to the stimuli reset a reas.

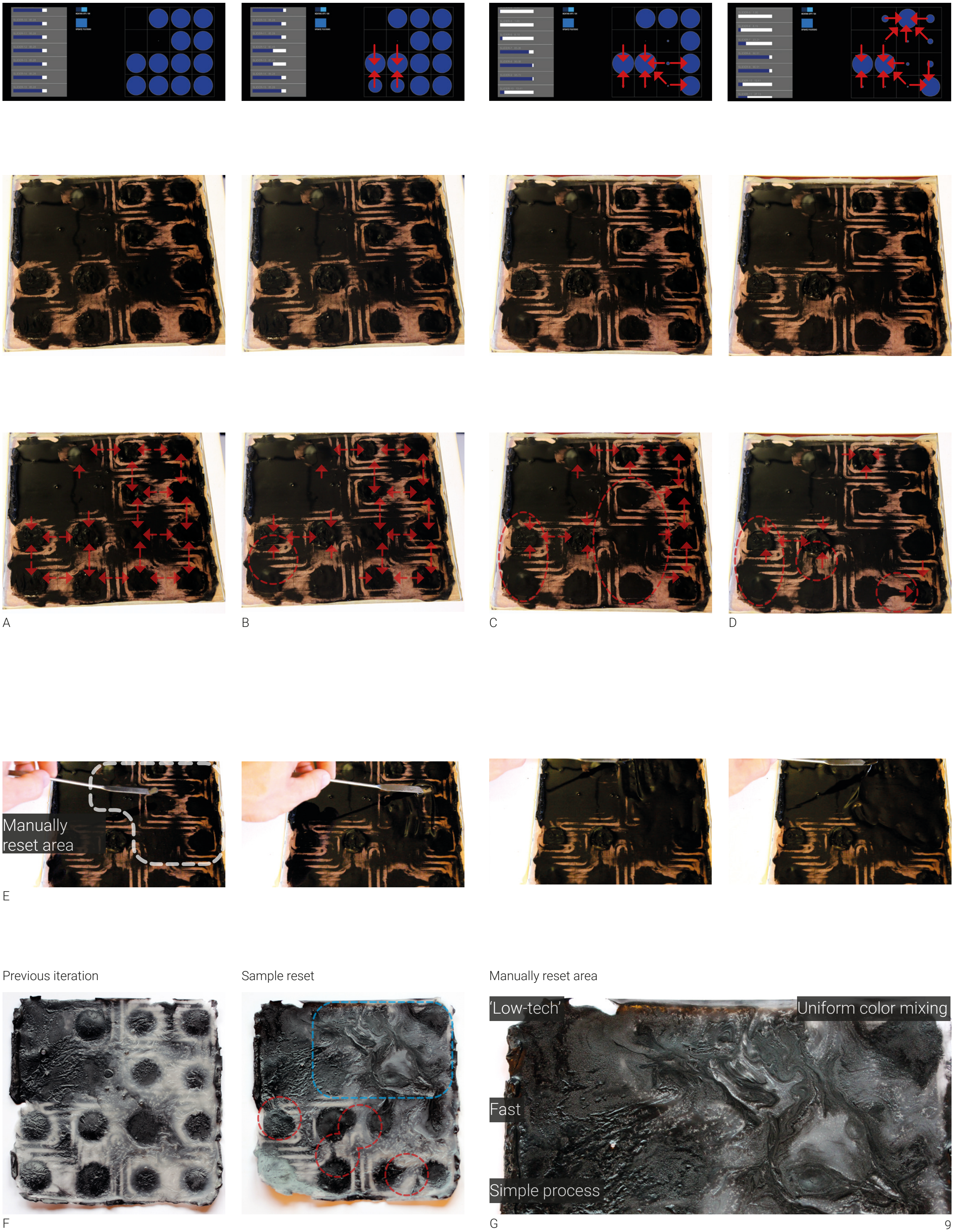
10 Highlights the different areas where the sample has been reset. Close up photographs presenting the color-connection and transition of the sample P14 50:50.


P14 50:50
Broken
Melting
A
B
1st pattern update
Legacy pattern
C
P14 50:50
18x18 cm
First pattern iteration
Shiny
Dull
Fine surface texture
Colour gradients
Colour concentraion
Self-healing
Opacitiy changes
Smooth
Heating mat coils
Global pattern change
High resolutions
D
E
F
G
H

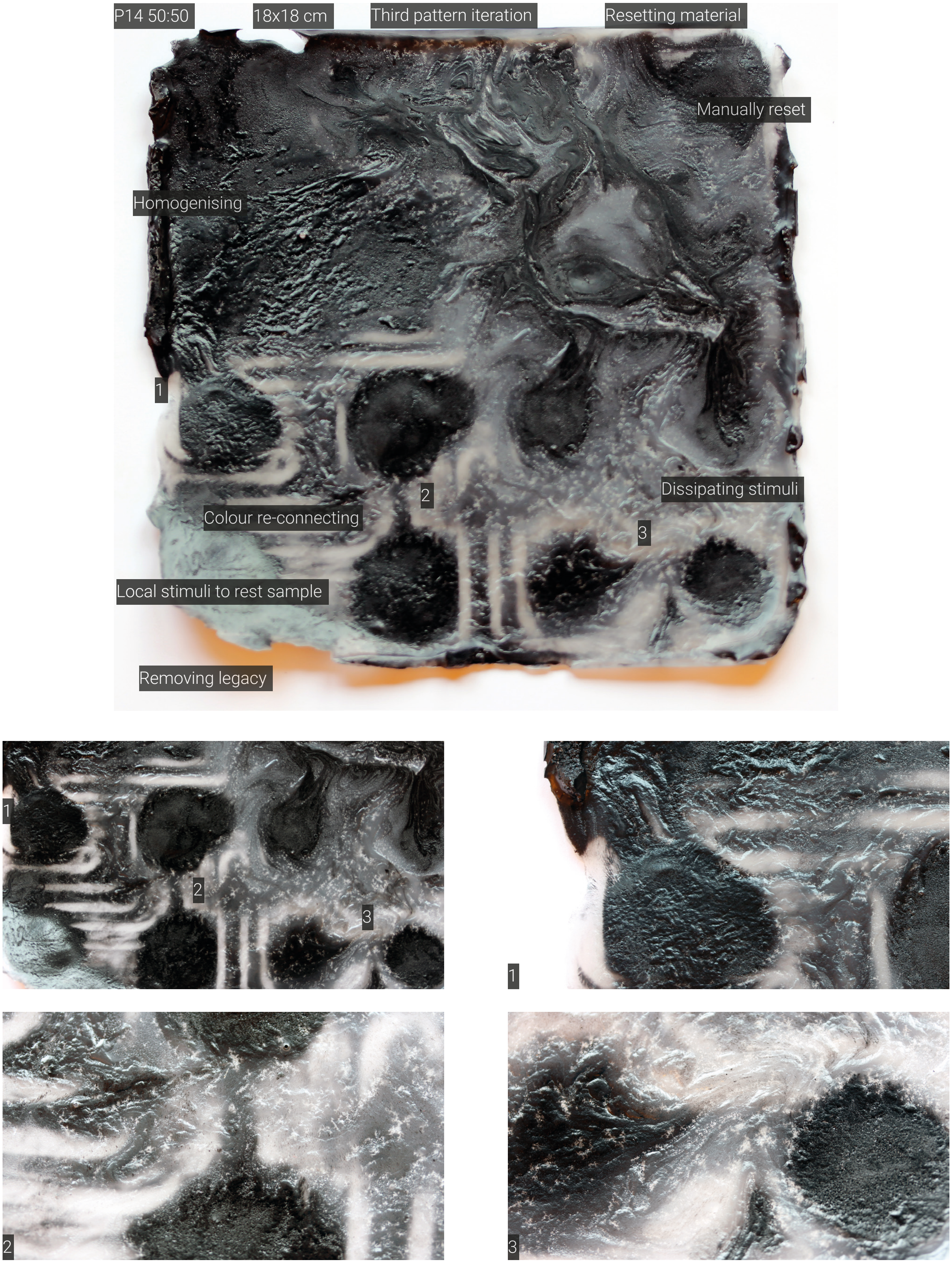
7


P14 50:50
18x18 cm
Second pattern iteration
High resolutions
A
B
C
D
Pattern updates
Legacy patterns
Control area
E
Global pattern update
Pattern legacy
Increased local color concentration
F
G
H
I

8


A
B
C
D
Manually
reset area
E
Previous iteration
Sample reset
Manually reset area
'Low-tech'
Uniform color mixing
Fast
Simple process
F
G

9


P14 50:50
18x18 cm
Third pattern iteration
Resetting material
Manually reset
Homogenising
1
2
Dissipating stimuli
Colour re-connecting
3
Local stimuli to rest sample
Removing legacy
1
2
3
1
2
3

10

This work acts as a proof of concept and demonstrates that multiple material properties can be iteratively updated and at high resolutions when using a two stimuli system combined with state-changing materials. It highlights potential alternatives to totally remanufacturing materials at end of life as the design and fabrication approach enables circular material production i.e. materials that can be updated. However, multiple implications have been highlighted from this research when interacting with materials when pushing updated into remotely via stimuli. These are:

- There are trade-offs over time as certain properties diminish others become increasingly significant. This highlights the need to define time-based hierarchies for various properties when they are desirable and for given applications.
- Due to slow material responses, time lag is created between digital updates and corresponding physical responses. As a result, in-situ and real-time responses are not possible with this set-up, currently. This highlights two challenges: 1) average data values would be required when iteratively updating material properties. 2) the time lag, current set-up and process (placing materials back in the fabricator) lends itself to applications based on iterative updates/fine tuining, for example, medical prosthetics/ splints, track cycling skin suits, fashion/wearables.
- What is the role of material legacy? Does legacy compromise futer interactions? How could legacy help to enhance bespoke design solutions?
- What digital design processes need to be developed/ employed to create reliable interactions and properties being generated? How is feedback achieved without limiting material resolutions and the range of responses?

The simplistic digital interface used and lack of material behavior represented is a limitation of this research, but it was not the focus. Combined with what we term as time lag highlights issues of predictability when interacting with materials to elicit their computational abilities. Johns (2014) discusses the need for stochastic digital models when employing a robotics system and stimuli to interact with materials when the have inderminate aspects. Additionally, the role of stochastic models has been discussed within distributed self-assembling materials process (Zykov and Lipson, 2007) as well as biomaterials (Ozkan et al., 2022). This highlights a converging challenge for interacting with non-linear materials in order to maximise a greater range of responses but ensure robust responses that could open up application areas becoming viable.

Future work intends to develop a tangible user interface (TUI) to investigate how various sensor data can be used to interact with and inform material properties. The aim of developing a TUI is to understand how these design implications and system hierarchies impact more tangible/real-world applications that could lead to increasingly bespoke properties unique to user(s). However, this raises the challenge of determining what constitutes a desirable material response for various applications. This becomes increasingly important when material properties become increasingly non-linear and multiple stakeholders become involved.

Understanding this challenge and incorporating more sophisticated digital design processes could lead to increasingly bespoke structures and products that could address issues of waste attributed to linear design and fabrication processes. Importantly, the potential flexibility, continued interactions and high-resolution achieved in these samples is made possible because they have been fabricated by leveraging and instilling material's computational abilities within them.

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REFERENCES

Asvar, Z., Mirzaei, E., Azarpira, N., Geramizadeh, B., Fadaie, M. 2017. Evaluation of electrospinning parameters on the tensile strength and suture retention strength of polycaprolactone nanofibrous scaffolds through surface response methodology. J. Mech. Behav. Biomed. Mater., 75, pp369–378.

Ayres, P. 2011. Free-from Metal Inflation & the Persistent Model. In: GLYNN, R. & SHEIL, B. (eds.) FABRICATE 2011: Making Digital Architecture. UCL.

Ayres, P. 2012. Microstructure, Macrostructure and the Steering of Material Proclivities, Wiley

Ayres, P., Stoy, K., Stasiuk, D. & Gibbons, H. 2014. Multi-scalar Shape Change in Pneumatically Steered Tensgrities: A Cross-disciplinary Interest in Using Material-scale Mechanisms for Driving Spatial Transformations. In: Gramazio, F., Kohler, M. & Langenberg, S. (ed.) FABRICATE 2014: Negotiating Design & Making. London: UCL Press.

Blaney, A. 2020. Designing Parametric Matter: Exploring adaptive self-assembly through tuneable environments. PhD, Lancaster University.

Blaney, A. 2021. Material Units-Uploading information into matter via stimuli and the challenges of determining feedback. In: Stojakovic, V. & Tepavcevic, B. (ed.) owards a new, configurable architecture - Proceedings of the 39th eCAADe Conference. University of Novi Sad, Novi Sad, Serbia.

Blaney, A., Alexander, J., Dunn, N. & Richards, D. 2019. Designing Parametric Matter. IASDR 2019: Design Revolutions. International Association of Societies of Design Research Conference 2019. . Manchester, United Kingdom.

Blaney, A., Richards, D., Gradinar, A. & Michael, S. 2021. Prototyping Circular Materials Based on Reprogrammable Matter. IASDR 2021: [_] WITH DESIGN: REINVENTING DESIGN MODES. Poly U Design, School of Design, Hong Kong Polytechnic University.

Bowers, J. The logic of annotated portfolios: communicating the value of'research through design'. Designing Interactive Systems Conference, 2012 Newcastle, UK. ACM, pp.68-77.

Burry, M. 2016. Antoni Gaudí and Frei Otto Essential Precursors to the Parametricism Manifesto. Architectural Design, 86, 30-35.

Dickey, R. 2017. Soft Systems: Rethinking Indeterminacy in Architecture as Opportunity Driven Research. In: P. Janssen, P. L., A. Raonic & M. A. Schnabel (ed.) Protocols, Flows, and Glitches - Proceedings of the 22nd CAADRIA Conference Suzhou, China.

Frayling, C. 1993. Research in Art and Design. Royal College of Art Research Papers, 1, pp.1-5.

Gaver, W. What should we expect from research through design? In: Konstan, J., A., ed. SIGCHI conference on human factors in computing systems May 2012 Austin, Texas, USA. ACM, pp.937-946.

Ghoseiri, K. & Safari, M. R. 2014. Prevalence of heat andperspiration discomfort inside prostheses: Literature review. Journal of rehabilitation research and development, 51, pp. 855-868.

Gilpin, K. & Rus, D. A distributed algorithm for 2D shape duplication with smart pebble robots. IEEE International Conference on Robotics and Automation May 2012 Minnesota, USA. pp. 3285-3292.

Goldman, M. & Myers, C. Freezing the Field: Robotic Extrusion Techniques Using Magnetic Fields. ACADIA 2017: DISCIPLINES & DISRUPTION, 2017 Cambridge, USA. pp.260-265.

Ishii, H., Lakatos, D., Bonanni, L. & Labrune, J. B. 2012. Radical atoms: beyond tangible bits, toward transformable materials. Interactions, 19, pp.83-51.

Johns, R. 2014. Augmented Materiality: Modelling with Material Indeterminacy. In: Gramazio, F., Kohler, M. & Langenberg, S. (ed.) FABRCIATE 2014:. London: UCL Press.

Otto, F. 2003. Occupying and connecting – Thoughts on Territories and Spheres of Influence with Particular Reference to Human Settlement, Stuttgart/London, Axel Menges.

Otto, F. & Rasch, B. 1995. Finding Form: towards an architecture of the minimal, Stuttgard, Axel Menges.

Ozkan, D., Morrow, R., Zhang, M. & Dade-Robertson, M. 2022. Are Mushrooms Parametric? Biomimetics, 7, pp.60 - 76.

Papadopoulou, A., Laucks, J. & Tibbits, S. 2017. From self-assemblies to evolutionary structures. Architectural Design, 87, pp28-37.

Patricio, T., Bartolo, P. 2013. Thermal stability of PCL/PLA blends produced by physical blending process. Procedia Eng., 59, pp292–297

Rezaei, V., Mirzaei, E., Taghizadeh, S.-M., Berenjian, A., Ebrahiminezhad, A. 2021. Nano Iron

Tibbits, S. 2016. Self-Assembly Lab: Experiments in Programming Matter, Routledge.

Toffoli, T. & Margolus, N. 1991. Programmable matter: concepts and realization. Physica. D, Nonlinear phenomena, 47, pp. 263-272.

Tolley, M. T. & Lipson, H. Fluidic Manipulation for Scalable Stochastic 3D Assembly of Modular Robots. IEEE international conference on robotics and automation, May 2010 Anchorage, Alaska, United States. IEEE, pp.2473-2478.

Turner, S., Belsi, A. & McGregor, A. H. 2022. Issues faced by people with amputation (s) during lower limb prosthetic rehabilitation: a thematic analysis. Prosthetics and Orthotics International, 46, pp. 61-67.

Wang, B., Chan, K. F., Yuan, K., Wang, Q. Q., Xia, X. F., Yang, L. D., Ko, H., Wang, Y. X. J., Sung, J. J. Y., Chiu, P. W. Y. & Zhang, L. 2021. Endoscopy-assisted magnetic navigation of biohybrid soft microrobots with rapid endoluminal delivery and imaging. Science Robotics, 6.

Wu, A., Ou, P., Zeng, L. 2010. Biomedical Applications of Magnetic Nanoparticles, NANO: Brief Reports and Reviews, pp245-270.

Zykov, V. & Lipson, H. Experiment Design for Stochastic Three-Dimensional Reconfiguration of Modular Robots. IEEE/RSJ International Conference on Robots and Systems, Self-Reconfigurable Robotics Workshop, October 2007 San Diego, CA. IEEE.

IMAGE CREDITS

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