Proceedings Paper:
Dade-Robertson, M., Ramirez-Figueroa, C. and Hernan, L. (2017) Bio-materialism: Experiments in biological material computation. In: Proceedings of the 3rd Biennial Research Through Design Conference. 3rd Biennial Research Through Design Conference, 22-24 Mar 2017, Edinburgh, UK. RTD , pp. 292-307.

https://doi.org/10.6084/m9.figshare.4746988

Proceedings of the 3rd Biennial
Research Through Design Conference

Bio-materialism: Experiments in biological material computation

Martyn Dade-Robertson, Carolina Ramirez-Figueroa, and Luis Hernan

Dade-Robertson, M., Ramirez-Figueroa, C., & Hernan, L. 2017. 'Bio-materialism: Experiments in biological material computation'. In: Proceedings of the 3rd Biennial Research Through Design Conference, 22-24 March 2017, Edinburgh, UK, Article 19, pp. 292-307.
DOI: 10.6084/m9.figshare.4746988.

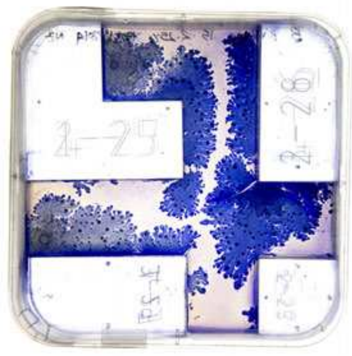

Image credit: Carolina Ramirez-Figueroa.

Bio-materialism: Experiments in biological material computation

Martyn Dade-Robertson, Carolina Ramirez-Figueroa, Luis Hernan

School of Architecture, Newcastle University, United Kingdom
martyn.dade-robertson@newcastle.ac.uk

Keywords: biodesign; materialism; New Materialism; bio-materials; Synthetic Biology; soft technology

Abstract: In his article 'Towards a Novel Material Culture' Menges traces the origins of contemporary computational and fabrication techniques in architecture to 'New Materialism'. Developed by thinkers such as Manuel DeLanda and Jane Bennett, the philosophical school characterizes matter as active and "empowered by its own tendencies and capacities". In architecture, New Materialism has often become associated with biomimetics. However, over the past four years we have been developing a series of projects that take inspiration from the New Materialist paradigm, but that aspire to develop demonstrators and technologies which go beyond biomimicry and make direct use of living systems, designing through the manipulation of living cells.

Introduction

In his article 'Towards a Novel Material Culture' Menges (2015) traces the origins of contemporary computational and fabrication techniques in architecture to the philosophical school of 'New Materialism'. Developed by thinkers such as Manuel DeLanda (2004) and Jane Bennett (2009), New Materialism characterizes matter as active and "empowered by its own tendencies and capacities" (Menges 2015: p.12). In architecture, Menges argues, this has influenced the development of computational form finding methods and 'cyber-physical' fabrication technologies such as robotics and additive manufacture.

Explorations associated with New Materialism in architecture find origin in the material and structural experimentation of Frei Otto, generally identified as the founding father of an engineering method that leverages material computation as a form-finding technique. New Materialism in architecture also seeks, through biomimetics, inspiration from the natural world. There has been, however, a push to move beyond biomimesis towards the integration of living systems in architecture, as is the case in Neri Oxman's silk pavilion (Oxman et al. 2014). These bio-integrated instead of bio-inspired projects imply something beyond the closer coupling of material, computation and fabrication and aim to create systems in which computation, form making, material synthesis and fabrication are combined into dynamic systems which are, in part, alive and encoded in wetware as well as (or perhaps instead of) hardware and software. Michael Hensel describes this aspiration as the 'literal biological paradigm' in architecture. The logical destination for this research would be living architectures which are derived from the manipulation of real biological systems.

The idea of integrating living organisms into architecture and other designed objects is not new. Our rapidly growing understanding and ability to harness the natural world and advancements in fields such as Synthetic Biology have lead to early design propositions and manifestos. Notably, for example, by Armstrong and Spiller (2011) and Cruz and Pike (Cruz and Pike 2008). More generally, a community has grown around bio-art and design, often concerned with the social and ethical consequences of biotechnologies (Myers 2012; Myers 2016). Design propositions for living architectures have been made through, for example, the integration of protocells into a cybernetic systems in Beesley and Armstrong's Hylozoic Ground installation (Armstrong 2011) as well as design speculation through, for example David Benjamin's collaboration with Fernan Federici as part of the Synthetic Aesthetics project (Ginsberg et al. 2014). Much of this work, however, is necessarily speculative.

Over the past four years we have been developing a series of projects that take inspiration from the New Materialist paradigm and the speculations described above, but with the aspiration of developing real demonstrators and technologies, which make use of living systems and are design through the manipulation of living cells. These experiments have been guided by what we consider to be three core tenets of the New Materialist paradigm:

- an emphasis on direct material experimentation and craft;
- a coupling of form making with material performance;
- and a recognition of the inherent computational potential of materials.

Working directly with living organisms, these explorations require thinking at multiple scales, from the construction of individual molecules through to the assembly of building parts. They also highlight the potentials but also challenges of a research engagement with living technologies.

Background

Before describing the experiments in more detail it is worth briefly describing the context in which they were conducted.

Synthetic Biology

SynBio is a broad term referring to a field of engineering which aims to, using the definition of the Royal Academy of Engineering, "design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems" (Voigt 2012: p.6). SynBio often involves the genetic level manipulation of organisms (sometimes referred to as genetic engineering) and has also become associated with initiatives to systematize biological knowledge and to standardise descriptions of gene level biological processes such that they can be engineered to create new systems (relatively) easily and reliably (Endy 2005). This type of SynBio draws on computing science and electrical engineering and conceptualizes individual genes as parts, which can be organized to create genetic circuits capable of responding to a range of inputs by synthesizing proteins and other molecules, which have useful applications. Building such circuits, however, is not trivial and the complexity of biological systems means that their development relies on complex computational modelling to help predict the design outcome and successful implementations are never guaranteed. SynBio is also a contested term and is often associated to more than one design and engineering framework. The definition above, however, is useful in the context of our research as it treats living cells as computational entities composed of hardware (mapped to the physical substrate of the cell) and software (the DNA of the cell and the information held in the pattern of interactions that constitute a cell's metabolism).

While the conceptualisation of biological systems as hierarchical, and divided into discreet and interchangeable units, has the effect of taming an otherwise unruly design space conceptualizing cells as physical computers also risks flattening their complexity. This is paralleled by arguments which are well rehearsed in the recent history of design computation – particularly in the practices described by those in the New Materialism paradigm who argue for a greater recognition of material complexity in design. This argument takes on new relevance in discussions of SynBio.

An additional aspiration for SynBio is to automate as much of the process of design and 'making' as possible. Making in SynBio tends to occur in lab environments through the processes of genetic manipulation, by people with expertise in Molecular Biology. Molecular Biology is both highly specialized and labour intensive. It is suggested, therefore, for SynBio to progress many routine lab processes will need to be automated enabling as much designed and modelling in computation. This raises important epistemological and practical questions when integrating living systems in a design context, as we will discuss below and contrasts with approaches in architectural design which attempt to reconnect craft with computational making.

Bacteria

The projects described in this paper are conducted with bacteria based systems. Bacteria offer a number of practical advantages. Compared to Eukaryotic organisms, they are easier to manipulate at the genetic level with a large variety of well researched tools and protocols. The specific bacteria species we use are also quick, easy and cheap to grow.

Considered as independent cells bacteria constitute relatively simple organisms. However, they also collaborate both with their own species and others – specialising in the creation of biofilms that exhibit city like communications networks, (extracellular) protective structures and enable the metabolism of food. In other words, collectively, they behave much more like multicellular organisms (Shapiro 1998). Bacterial systems also have distinctive morphologies (often this is the way in which colonies are identified) These morphologies change depending on the conditions of growth and other factors. In the context of the specific species used in this exploration, some of these more distinctive morphologies have been studied by Ben-Jacob (1997). Also of interest is the potential of bacteria to synthesize hard material at scales relevant to the built environment. Jonkers (2007) has developed self healing concretes in which bacteria spores are mixed into a concrete aggregate. When cracks occur in the material, mechanical changes trigger a process of biomineralization which binds the concrete back together. Other explorations have shown bricks using a bio-cement derived from bacteria based products (Dosier 2011).

However, morphological and material synthesis mechanisms in bacteria don't, as far as we know, respond to factors traditionally associated with material performance in design. Bacteria are simply subjected to a different scale of forces and entirely different scale of operation. To perform intelligent material synthesis at scales relevant to the built environment, therefore, the bacteria will need to be engineered to perform processes which are not natural to them. As opposed to bio-mimicry, we are taking a biological system and making it do something which it does not have a parallel in the natural environment.

Project Frameworks

Our broad aim is to develop systems of material fabrication and responsive materials based on living bacteria cells. This involves creating new materials which can self assemble, respond meaningfully to environmental inputs and synthesize non-biological, structural materials. Whilst living organisms do this routinely, such systems are very difficult to engineer with traditional engineering methods. To this end we have broken our projects into three themes with the aim of programming living cells to:

- Sense and respond to inputs from their environment (Sensing and Actuation).
- Aggregate in desired patterns or in performance enhancing forms (Morphogenesis).
- Synthesizing structurally relevant extra cellular materials (Material Synthesis).

In all we have four projects, three of which focus on each of these themes and one which attempts to bring two of these themes together.

Sensing and Actuation: Bacteria based Hygromorphs

Bacteria spore based hygromorphs are a new type of hygromorphic material, first described in literature in 2014 (Chen et al. 2014), that use bacteria spores as an active layer fixed to a polyamide passive layer. The system works in a similar way to wood laminated hygromorphs (Reichert, Menges and Correa 2015) but at a smaller scale and with greater sensitivity. Small changes, for example, in ambient humidity can create distortions in the material. Thin strips of polyimide with spores attached to both sides of the film can contract into a concertina shape when dry. Strips arranged in parallel operate like muscles, producing power proportional to the number of spores attached to the material surface. Contraction of the polyimide body can, for instance, lift weight or power engines. While the basic principles of bacterial hygromorphs have been demonstrated, fundamental technologies which use this type of material have yet to be developed. In this context, we have begun to explore the use of bacteria based hygromorphs in conjunction with an undergraduate design studio, integrating lab work with more traditional design based model making and prototype building.

Figure 1. Student manufacturing strips of a hydromorphic material by pipeting bacteria spores on to a plastic polyamide layer. Photo: Luis Hernan.

Morphogenesis: Synthetic Morphogenesis

While multicellular organisms control their morphology through the collective organization of cells, there is no direct equivalent mechanism in bacterial cells. Bacteria, however, do pattern themselves by swarming and signalling to each other when operating in colonies. Species are often identified because of the distinctive morphology of their colonies and complex patterns that are specific to their strain and growing conditions.

We have devised a number of experiments which show distinctive morphologies of bacterial growth by altering the physical and chemical conditions on agar plates, including the level of nutrients, density of the growing medium and the shape of the physical container. These experiments can result in fractal like patterns where colonies branch into areas with high concentrations of nutrients, exhibit directionality where their physical space is constrained and move along channels in response to the surface topography of the media on which they grow and swarm.

Material Synthesis: Bacilla Vitruvius

Biomineralization refers to the process by which living systems induce the formation of inorganic, hard tissue. Abalone, for example, uses this process to generate its shell, which is characterized by its changing properties across its section – hard on the exterior, which maximizes protection from the environment, and the soft on the interior surface where it is in contact with the delicate organism. This variation is achieved by manipulating the orientation and deposition of calcium carbonate crystals, which creates a sophisticated, composite material. The fabrication process produces a structure of significant strength with little expenditure of energy.

Bacteria are also capable of inducing biomineralization. In the case of Calcium Carbonate formation some strains of bacteria change the PH of their environment, sequester from carbon dioxide from the atmosphere and cause it to bind with calcium and produce crystals. In our explorations, we have shown that the distribution and morphology of crystals also differs substantially between different species of bacteria (Dade-Robertson, Ramirez-Figueroa, and Zhang 2015). Our project includes a number of Agar plate experiments in which bacteria have been grown in conditions suitable for biomineralization and extended to include work with students on the calcification of soft materials (such as cotton) using bespoke scaffolds (Dade-Robertson et al. 2013).

Figure 2. Example of a bacteria scaffold made by students to test the growth of bacteria and the deposition of biomaterials. Photo: John Beattie, Alexander Lyon, Markus Ryden and Malcolm Welford.

Synthesis project: Computational Colloids

This is our most ambitions project and involves designing a system at multiple scales, ranging from the development of a novel genetic circuit in bacteria to geotechnical modelling at building scales. Imagine a column of sand saturated with billions of engineered bacteria cells. As a force is applied to the top of the column, bacteria in the sand detect an increase in pressure. The bacteria respond by synthesizing a new biological material to bind the grains together and resist the load.

The project has started with an initial search for pressure sensitive genes, i.e. genes which become more highly regulated or down regulated in response to pressure applied to their cell membrane. This has been coupled with computational models which map gene expression data onto much larger scale geophysical models. We have now identified candidate genes and are working on ways in which we can integrate the two scales by developing microbiological knowledge of the ways in which bacteria distribute themselves in three dimensions using hydrogels as a proxy for soil.

Figure 3. Artists impression of the 'Computational Colloids' system constructing a foundation in response to mechanical changes in the soil. Photo: Carolina Ramirez-Figueroa and Luis Hernan.

Lessons from our practice in bio-materialism

Rather than detail each project individually, we want to use this paper as an opportunity to describe some of the broader lessons we have learned from our experience working directly with biological systems and a type of in-vivo material computation. It is important to recognize that this work often lapses into fundamental science. The early nature of this research means we are not, yet, for example, able to grow demonstrator pavilions from bacteria based materials. We are, instead, looking at the new design possibilities and challenges created by living or partially living material systems through direct experience of working with them. This work is grounded in scientific research but informed by broader speculation. The explorations described here are an attempt to understand the potential and constraints of such materials and the design logics they imply. Our position is that the work being undertaken in areas such as material based computation is complementary to and, to some extent provides a counterpoint to, an emerging paradigm of bio-materialism.

Multiple scales are interconnected

A consequence of New-Materialism has been an expansion in the range of scales we can use in design. Microscopic understanding of material

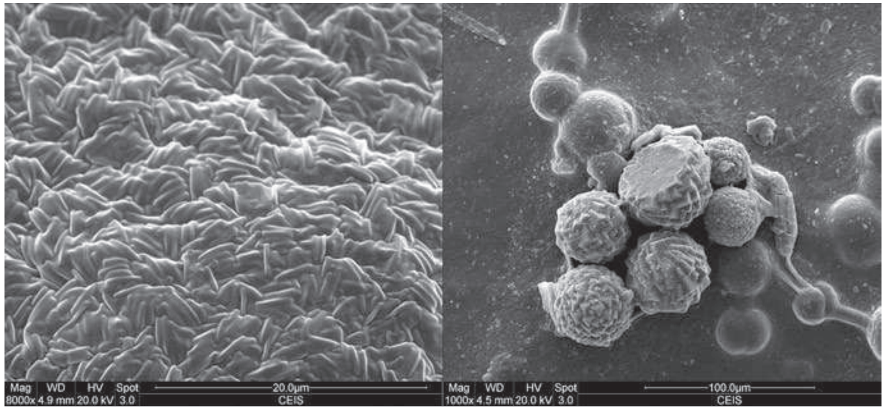

Figure 4. Electron microscope images of Bacillus pasteurii growing in agar. (a) Shows bacteria cells without the presence of calcium. (b) Shows spherical faceted crystals of calcium carbonate induced by the Bacillus pasteurii bacteria. Photo: Martyn Dade-Robertson and Meng Zhang.

behaviour can be utilized through advanced forms of fabrication which are able to distribute materials precisely. As we begin to design with biological materials, the range of scales we design in is further expanded.

In our experiments with biomineralization, for example, we noticed that the morphology of the crystals differs significantly from those we would expect when calcium carbonate form in non-biological contexts (Figure 4). These changes in crystal morphology are caused by extracellular substances and are specific to bacteria species. This process mirrors biomineralization in more complex eukaryotes, where the precise control of crystal morphology creates different materials which are almost chemically identical but which might have radically different mechanical properties. Little is known about how different scales interact in the control of bacterial crystal morphology. Bacteria, for example, are approximately 2 micrometers across, but the crystals they induce are of micrometers across and clusters can be seen by the naked eye. Perhaps a more graphic representation of designing across scales is our Computational Colloids project. The regulatory genes we are searching for will have distinctive sensitivity profiles – i.e. they will tend to have sensitivity to certain ranges of pressure. For instance, the well studied lac gene, which is known to be a pressure sensitive gene, operates optimally at about 30 atms and is part of a regulatory system which helps the cell survive under high pressure (Sato et al. 1996). The gene expression curve for these genes is shown in Figure 2. As part of the project, we have devised a computational modeling program which relates our geotechnical knowledge of pore pressure for soils under load with an editable model for gene expression This allows us to change the gene expression curves and to run simulations which model the effective stress and pore pressure within a 10m3 volume of soil under different loads over time. The software allows us to use these values and map on our levels gene expression, visualized here in as the relative size of each box in a 3D matrix (Figure 5). The images show different patterns resulting from different sensitivities of promoter.

In Synthetic Biology terms, we would use this pressure sensitive promoter as an input 'part' to control another functions in the cell. In this case, to alter the synthesis of biomaterials and potentially bio-cements. If the magnitude of the promoter response is equated to the degree of cementation, the figures are visualizing a process of selective

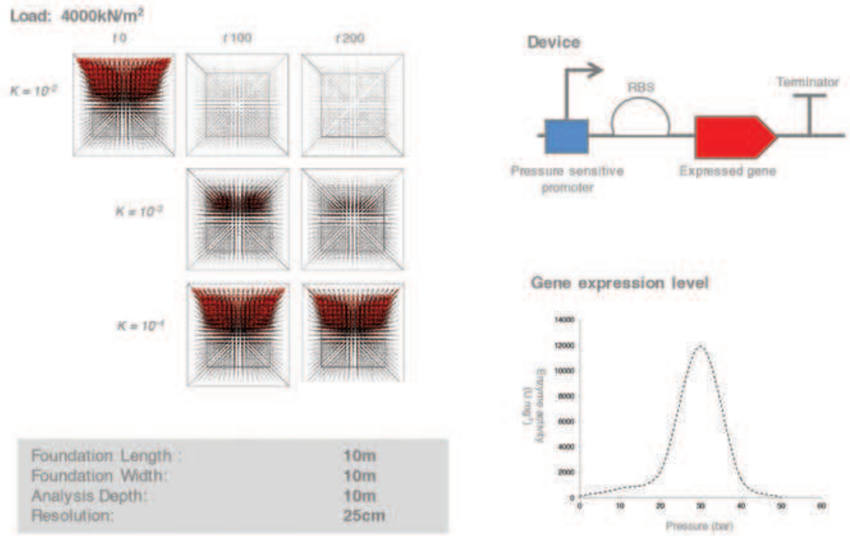

Figure 5. Visualisation of gene expression for bacteria in 10m3 of soils placed under different 4000kN/m2 load. The cubes show the magnitude of expression for a hypothetical pressure sensitive gene. Image: Martyn Dade-Robertson.

cementation where the soil is being sculpted at the scale of meters in response to the magnitude of pressure in the soils and the response profile of the promoter. The promoter profile is defined by differences of a few molecules in the promoter gene and yet, in our model, the consolidation patterns may be many meters across. Macro-morphology is being defined at the molecular scale.

Between Craft, Automation and Mediation

A key tenet of the New-Materialist paradigm in architecture is that innovation can occur from experimenting directly with materials - extending craft traditions in architecture and enabling a closer coupling between fabrication and the ‘mediating artifacts’ of computation. Synthetic Biology allows us to create systems that go beyond abstractions and where design is conducted within the system itself.

Architecture has, however, thrived on the tension between rational abstraction and material reality. In addition, our experience suggests that SynBio may also require innovative ways of mediating between abstractions and material forms and behaviors. In exploring this proposition, however, we will need to question the status of design representations as templates or patterns for material articulation. When designing biological systems, there is likely to be a less direct relationship between design representation and material construction, as the role of the designer shifts from ‘sculptor’ to ‘cultivator’ of materials.

SynBio depends on a wide range of representations and mediating artifacts, in part because the materials which we are dealing with are often manipulated at the molecular scale. We are, therefore, often dealing with the effects of materials – in the case for example of the biomineralization experiments – and interpreting the results through electron microscopy. In the Computational Colloids project we make use of extensive computational modeling and define our genetic systems through shorthand diagrams and symbols such as SBOL Visual (Figure 7

Issues of scale aside, a persistent challenge in our research has been that the craft of scientific research is conducted in highly controlled environments and within tight spatial and legal frameworks. We cannot, for example, experiment with genetically engineered bacteria outside the confines of a Level 2 Containment lab, which often precludes more open design experimentations in environments where we can construct large scale prototypes. There is also a pragmatic resource implication of using specialized facilities. Our Architecture School doesn’t (yet) have direct and unrestricted access to a Level 2 lab and instead we rely on the generosity of collaborators or lab spaces rented out for short periods. In developing the Bacilla Spore Hygromoph project, for example, we only had a two-day access to a lab for a 5 week project. This restricted access means that, in order to follow a material driven approach, we need to have materials which can act as proxies for the biological behavior we are interested in – enabling us to develop prototypes which capture their functionality and their dynamic nature. In the case of the Bacilla Spore Actuator project, shape memory alloys were used as proxies for the actuators. In this

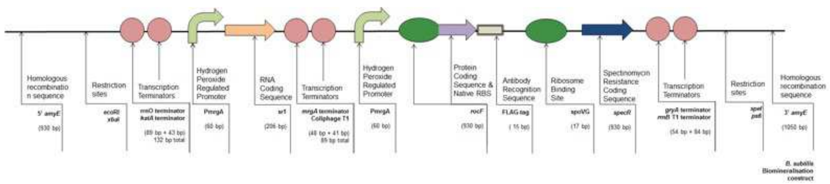

Figure 6. Example of the visual notation for the design of a genetic circuit with transcription terminators shown as red dots, promoter genes as green curved arrows protein coring genes shown as straight arrows and ribosome binding sites a dark green ovals. Diagrams like this are used to define the structure of new genetic sequences which encode for specific behaviors in the organism. Image: Martyn Dade-Robertson.

context, lab experiments were used to inform and tune how the shape memory alloy responded to electrical current, which was used as a proxy for moisture

Many more of these proxies and new types of simulation systems need to be developed and we suggest that the notion of direct material engagement is highly complicated in our work by mediating systems and representations which are an integral part of biological science.

Scaffolding as a technology

Many of the advances in material based computation have been enabled by the more precise deposition or extraction of materials through, for example robotics and 3D printing. The potential for mass customization has been exploited by enabling bespoke parts to be produced as cheaply as mass produced parts. Through the use of biological systems, we aim to move even further – removing the means of production from an external apparatus to the internal logic of the system itself – enabling self-construction and assembly (following the work of for example (Tibbits and Cjeung 2012)). However, to achieve this we have needed to recognize that self-assembly does not operate in isolation, and requires substrates and scaffolds. While these scaffolds and substrates have a different role to, for example, a mold, they never the less play a critical role in the state space of materialization (Dade-Robertson, Ramirez-Figueroa, and Zhang 2015). In nature scaffolds such as soil carry the nutrients in order for a seed to germinate and for the early plant to set down roots and begin to bud. In mammals the amniotic fluid provides a buffer between the embryo and the outside world, as well as allowing cells to assemble in a reduced gravity environment. In our experiments agar, liquid media and other materials play this role. We have, for example, previously reported on the relationship between soft materials and biomineralization in order to calcify 3D structures (Dade-Robertson et al. 2013).

As part of the Synthetic Morphologies project, we also have used hydrogels (based on agar and more recently agarose) which can be used as growing surface (as in the traditional agar plate microbiological experiments) and volumetric substrate. Using both these methods we

Figure 7. Patterns of bacteria forming on agar plates under conditions of low nutrients and in different shaped containers. Photo: Carolina Ramirez-Figueroa.

have begun to experiment with the effects of different amounts of nutrients on the patterning of bacterial colonies. By limiting nutrients the colonies form complex, fractal-like branches. As described above, we have taken these experiments further by grading the nutrients and building bespoke agar plates which channel bacterial growth (Figure 7). It is theoretically possible to extend the logic to use 3D hydrogels. We expect that control of the distribution of nutrients and the shape and size of the hydrogels will have an effect on the distribution and patterning of the material (Dade-Robertson et al. 2016). In the experiments being conducted for the Computational Colloids project, for example, hydrogels are used as a proxy for soils providing both the physical scaffold for the bacteria cells and their sources of food.

Our experience with these scaffolds and substrates is in line with proposals by, for example, Armstrong and Beesley, who have both discussed the idea of soils as a technology. In this, it is clear that shaping the chemical and morphological properties of substrates is itself a significant design challenge (Armstrong 2011).

Conclusion: Soft technologies

While the results of our broad based experiments are tentative, we have in this paper sought to extend the discourse of the New Materialist paradigm in architecture to include living technologies, and in doing so proposed intelligent and responsive material systems which are capable of self-assembly and fabrication. This is not straightforward. While the speculative discourse on living technologies for built environment provides a compelling picture for a new 'literal biological paradigm' in architecture, we have shown that achieving this requires negotiating between radically different scales of design, contrasting design spaces and practices, and a rethinking of the apparatus of production. Our research is still someway short of providing an architectural technology, and has, in its foundational nature, much in common with fundamental science and engineering. However, through the aspiration of developing technologies which shape our material spaces and design processes that are informed by the New Materialist paradigm in architecture, our aspiration is to create innovative ways of working. Bio-materialism blurs the lines between scales of operation and their effects which will require new notions of material and materiality.

References

Armstrong, Rachel. 2011. "How Protocells Can Make 'Stuff' Much More Interesting" Architectural Design, 81:68-77. doi: 10.1002/ad.1214.

Ben-Jacob, Eshel. 1997. "From Snowflake Formation to Growth of

Bacterial Colonies II: Cooperative Formation of Complex Colonial Patterns." Contemporary Physics 38 (3). Taylor & Francis: 205–41. doi:10.1080/001075197182405.

Bennett, J. 2009. Vibrant Matter: A Political Ecology of Things. A John Hope Franklin Center Book. Duke University Press.

Chen, Xi, L Mahadevan, Adam Driks, and Ozgur Sahin. 2014. "Bacillus Spores as Building Blocks for Stimuli-Responsive Materials and Nanogenerators." Nature Nanotechnology 9 (January): 1–9. doi:10.1038/nnano.2013.290.

Cruz, Marcos, and Steve Pike. 2008. "Neoplasmatic Design." Architectural Design 76 (6): 6–7.

Dade-Robertson, Martyn, Javier Rodríguez Corral, Helen Mitrani, Meng Zhang, Anil Wipat, Carolina Ramírez-Figueroa, and Luis Hernan. 2016. "Thinking Soils. A Synthetic Biology Approach to Material-Based Design Computation." In ACADIA 2016: Posthuman Frontiers, 460–69. Ann Arbor, Michigan.

Dade-Robertson, Martyn, Carolina Ramirez-Figueroa, and Meng Zhang. 2015. "Material Ecologies for Synthetic Biology: Biomineralization and the State Space of Design." Computer-Aided Design, no. 0. doi:http://dx.doi.org/10.1016/j.cad.2014.02.012.

Dade-Robertson, Martyn, Meng Zhang, C Ramirez-Figueroa, Luis Hernan, John Beattie, Alexander Lyon, Markus Ryden, Malcolm Welford, and Carolina Figueroa. 2013. "Proto-Materials: Material Practices in Architecture at Molecular and Cellular Scales." In Prototyping Architecture. The Conference Papers, edited by Michael Stacey, 211–23. London: Building Centre Trust, London. doi:13 – 978-0-901919-17-5.

DeLanda, Manuel. 2004. "Material Complexity." Digital Tectonics, 14–21.

Dosier, G. 2011. Methods for Making Construction Material Using Enzyme Producing Bacteria. US20110262640 A, issued 2011.

Endy, Drew. 2005. "Foundations for Engineering Biology." Nature 438 (7067): 449–53. doi:10.1038/nature04342.

Ginsberg, A D, J Calvert, P Schyfter, A Elfick, and D Endy. 2014. Synthetic Aesthetics: Investigating Synthetic Biology's Designs on Nature. MIT Press. https://books.google.co.uk/books?id=vsPrAgAAQBAJ.

Jonkers, Henk M. 2007. "Self Healing Concrete : A Biological Approach," 195–204.

Menges, Achim. 2015. "Fusing the Computational and the Physical: Towards a Novel Material Culture." Architectural Design 85 (5): 8–15. doi:10.1002/ad.1947.

Myers, W. 2012. Bio Design. London: Thames and Hudson.

Myers, W. 2016. Bio Art. London: Thames and Hudson.

Oxman, N, J DuroRoyo, S Keating, B Peters, and E Tsai. 2014. “Towards Robotic Swarm Printing.” Architectural Design 84(3): 108–15. doi:10.1002/ad.1764.

Reichert, S., A Menges, and D. Correa. 2015. “Meteorosensitive Architecture: Biomimetic Building Skins Based on Materiality Embedded and Hygroscopically Enabled Resonsiveness.” Computer-Aided Design 60: 50–69.

Sato, Takako, Yuka Nakamura, Kyoko K. Nakashima, Chiaki Kato, and Koki Horikoshi. 1996. “High Pressure Represses Expression of the malB Operon in Escherichia Coli.” FEMS Microbiology Letters 135 (1): 111–16. doi:10.1016/0378-1097(95)00438-6.

Shapiro, J a. 1998. “Thinking about Bacterial Populations as Multicellular Organisms.” Annual Review of Microbiology 52 (January): 81–104. doi:10.1146/annurev.micro.52.1.81.

Spiller, N, and R Armstrong. 2011. Protocell Architecture: Architectural Design. Architectural Design. John Wiley & Sons. http://books.google.co.uk/books?id=7mA6bwAACAAJ.

Tibbits, S, and K Cjeung. 2012. “Programmable Materials for Architectural Assembly and Automation.” Assembly Automation 32 (3): 216–25.

Voigt, Christopher. 2012. “Synthetic Biology Scope, Applications and Implications.” London: Royal Academy of Engineering. doi:10.1021/sb300001c.