LIVING ARCHITECTURE SYSTEMS GROUP

White Papers 2019

Edited by Philip Beesley, Sascha Hastings & Sarah Bonnemaison

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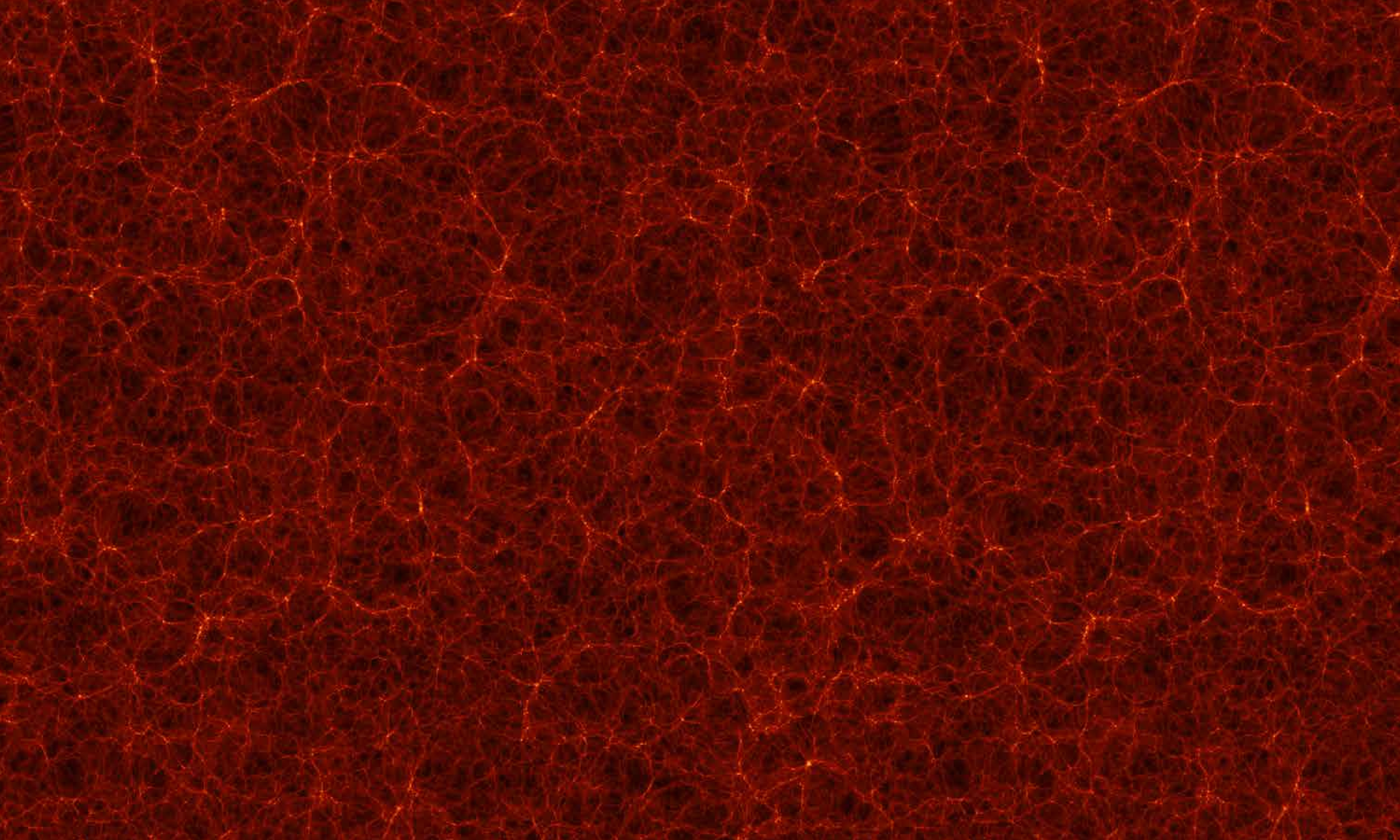

Living Architecture Systems Group White Papers 2019

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Cover Image Modification of a high resolution slice of the sholeMpc box of Bolshoi. Made by Stefan Gottlober (AIP) with IDL. Last accessed February 12, 2019 at http://hipacc.ucsc.edu/Bolshoi/. The Bolshoi simulation is the most accurate cosmological simulation of the large-scale structure of the universe yet made ("boshoi" is the Russian word for "great" or "grand"). The filamentary cellular structures evident within the Bolshoi simulation bear a striking resemblance to the organization that can be seen throughout natural living forms. The Principal Investigators of the Bolshoi project are Anatoly Klypin and Joel Primack.

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Philip Beesley
University of Waterloo, Canada

Can artists, designers and engineers make living systems? Can the layers of new built environments - layers of architecture, sculpture and fashion - come alive? The ingredients that define living systems appear increasingly within the reach of contemporary architecture. Life-like qualities have been sought by artists since the beginning of recorded history, but this quest is being transformed by new ways of understanding the deeply interwoven living world, supported by surging technologies of artificial intelligence, responsive systems and engineered materials, and informed by new arts that permit visualization and conception of exquisitely sensitive complex environments.

Classical paradigms tend to emphasize clarity and unified integrity as self-evident necessities. The premises of classical rhetoric have tended to create polarized divisions between interior and exterior spaces, between human beings and things, and between the realms of technology and nature. The papers of this gathering propose a fundamental renewal of such polarized realms. The new kinds of architecture implied by these studies might appear like a layered forest. The technical systems of this architecture tend to embrace inherently entropic and precarious conditions, far from equilibrium. The kinds of precisions gained from computational processes tend to be combined with physical and empirical methods in this work, lending meticulous attention to craft, material and fabrication alongside abstracted analysis. Extending these mutual exchanges are fresh approaches to physical computation and distributed controls that imply a continuous spectrum between sentience and physical fabrication. This is architecture that learns, plays, explores and is curious. It has the ability to act with intelligence, empathy and resilience.

The Living Architecture Systems Group (LASG) was conceived ten years ago, amidst collaborations extending the work of individual and small-group architectural researchers and creators in Canada, USA and Europe. An international collective group began work together with the support of a 2012 Social Sciences and Humanities Council of Canada (SSHRC) Partnership Development Grant. Funding in this first phase was combined with support from museums and galleries, making it possible to launch a series of immersive interactive environments accompanied by experimental workshops during 2012-16. Funds for a full SSHRC Partnership Grant were achieved in 2016, launching the public phase of the LASG. Multiple collaborators agreed to contribute, and the partnership formally began in April 2016. Five streams - Scaffolds, Synthetic Cognition, Metabolism, Human Experience and Interdisciplinary Methods - were first positioned to organize the group. In 2017, Theory was added, providing a stream enfolding philosophy and history. Overlapping creative, technical and scientific developments within diverse media are continuing with multiple intersections between these widely varying disciplines, inviting further extension of LASG 'stream' organization.

Integrated research and creation is a core of this collective work. Technical performance is converging with aesthetic language. The practice of research-creation supports integrated scholarship within a spectrum that combines art and science. Aesthetics, scientific analysis and innovative technical craft tend to be practiced in overlapping combinations within this approach.

The potential application of living systems to architecture is large, and the LASG's contributions are necessarily limited. Research devoted to the technology and design of living architectural systems distinct from that of LASG contributors appearing within the current volume is evident at Stuttgart's Institute for Computational Design and Construction (ICD), the Bartlett School of Architecture, the national Swiss facilities of ETH Zurich, Media Lab at MIT, the Institute for Advanced Architecture of Catalonia (IAAC), the Master's programs in Emergent Technologies and Design (EmTech) at the Architectural Association, the Spatial Information Architecture Laboratory (SIAL) in Melbourne and new developments at Swinburne University of Technology, new facilities at Tongji in Shanghai, architecture research centres within Harvard GSD, SCI-Arc, Taubman College at University of Michigan, and the University of Southern California, and in interdisciplinary dialogues hosted by other disciplinary centres such as the Wyss Institute at Harvard and the specialized art and bioengineering facility within the University of Western Australia's SymbioticA. Likewise, recurring conferences hosted by specialized knowledge-creation societies such as Academy of Neuroscience for Architecture (ANFA), ACADIA, eCAADe, CAADRIA, SimAUD, ROB|ARCH, Fabricate and CHI, journals such as the International Journal of Architectural Computing (IJAC) and general societies such as the Association of Collegiate Schools of Architecture (ACSA), include dedicated sections on closely related topics. These acknowledgements are incomplete by far, with many others playing important and leading roles. The diversity and energy of these numerous groups testify to the potency of the topic of living systems within contemporary architecture.

Broad themes of research can be seen within the papers presented here. Open boundaries and expanded dimensions run throughout the studies, exploring the scales of new adaptive and responsive architecture, from intimate personal spaces to regional infrastructures. Subtle phenomena and expanded perception frequently appear, exploring dimensions at the edges of human perception. These qualities move from primary, existential qualities of light and dark through interwoven social realms. Immersive sonic environments and precise measurements using innovative sensors of physiology are included. A deep involvement in craft is offered, making matter vibrant and reflecting the unparalleled new abilities of designers to precisely address material performance. Striking qualities are being achieved by applying the principles of biological structures to architectural components. These qualities are underpinned by design ideas that are founded on innovative conceptions of physics. Decay of organized systems may seem inevitable, but new conceptions suggest that living systems can thrive within the seemingly disordered spaces of turbulent, changing environments. Innovative design methods are included that combine meticulous control of computationally derived geometry with material craft.

Specialized studies in theory and craft of artificial intelligence are now being applied to large-scale architectural environments. A synthetic approach to cognition demonstrates new understanding of how interactive machine learning might be implemented within large distributed systems involving multiple viewers and occupants. Software applications support distributed mesh and field-based multi-sensory expression. Stage and dance performance-based interactive works couple actors and audience members with immersive environments. Kinetic architecture documents contain evolving research in dynamic, adaptive construction and mechanisms that transform the fabric of architecture. Integrated robotic construction systems offer efficiency and versatile expressive manipulations of form. Elastic and resilient mechanisms provide transformed kinetic qualities that approach empathetic, emotional gesture. Within the Toronto-based LASG studio, mechanisms are designed in ways that emphasize subtle movements that include vibrating and trembling. Sensors are designed to respond to slight movements and gestures, encouraging sensitive, gentle play. Small movements take minimal energy, while offering 'precarious' reactions that respond to the gentlest of stimulation.

These studies are in turn framed by theory, history and philosophy. Reflections on past and future Living Architecture offer new reflections that place the work of the LASG within traditions including historic conceptions of Organicism, 20th century participatory art and open systems, and radiant geometries related to Aquarian Age conceptions. New, mutual relationships that couple human, animal and mineral realms are invoked. Such hybrid approaches demonstrate an extraordinary efflorescence of hybrid architectural constructions that cross traditional boundaries between nature, technology and urban realms. Precisions are emerging that offer highly developed technical craft and nuanced aesthetic language. Every study within this gathering is interdisciplinary. The sheer diversity of these studies suggest that the topic of Living Architecture is volatile, testing the limits of classical disciplines.

The scales engaged by researchers and creators contributing to the current White Papers 2019 volume span from microscopic dimensions to urban and regional development. Urban and regional studies within this volume include a bioregional network being organized in Appalachian states by Eric Mathis, conceptions of adaptive, regenerative infrastructures of the future by Douglas MacLeod of Athabaska University, transformations of high building layers by Sheida Shahi of Waterloo, and visionary urban fabric by Terreform ONE, New York. The language and practice of complex spatial modeling coupled to material qualities is being expanded by practices including CITA at the Royal Danish Academy of Arts and the Sabin Lab, associated with Cornell. Concentrations in biologically-inspired design and biomaterials are emerging, including new contributions from Petra Gruber's Akron, Ohio-based laboratory, Dana Cupkova's Epiphyte Lab at Carnegie Mellon University, and material-based research extending Manuel Kretzer's Europe-wide materiability network. Expressive kinetic constructions based in next-generation performance have been documented by Vera Parlac of the Laboratory for Integrative Design (LID) at Calgary. LASG collaborator Iris van Herpen has fostered widely celebrated collaborations within couture, extending vivid imagery and formal expressions of material craft. Collaborations with the Delft University of Technology are now extending both Van Herpen's experimental couture and the Toronto-based environments of the LASG.

New systems of complex-systems dynamic visualizations are in development within a research cluster led by Katy Börner of Indiana University (IU). Börner and IU colleagues including Andreas Bueckle have conceived of 'macroscopes' complementing traditional microscopes, reinforcing the value of LASG installations as large-scale architectural testbeds supporting collection of unique, enriched data. Techniques of dynamic digital visualization and information-gathering offer valuable methods for effective design of interdependent relationships. Maya Przybylski proposes general terms of data quality and relative positioning of frames of reference. Specialized craft is demonstrated in Codrin Talaba's augmented reality study, and is extended by the contemplative poetics of Michael Awad's continuous-scan collaborative work.

New understanding is emerging of how interactive machine learning might be implemented and verified within large distributed systems involving crowds, led by Dana Kulić of Waterloo and Monash. Software supporting distributed mesh-based multi-sensory expression and control is in progress, with multiple contributions that include York University and OCADU's Artificial Nature collective. Sha Xin Wei and the Synthesis Center at Arizona State University have led stage and dance performance-based interactive works coupling immersive environments with actors and audience members. Nima Navab and Desiree Foerster propose subtle phenomena within aerial and fluid realms as a design medium. Granular synthesis controls for the architectural medium of sound are offered by Amirbahador Rostami. Immersive sound performances with Amsterdam-based partner 4DSOUND have been staged in Toronto, Bloomington and Berlin, with surging progress in control and visualization of distributed sound.

Providing a broad context of philosophy and theory, Sarah Bonnemaison of Dalhousie is developing reflections that place the work of the LASG within renewed conceptions of long architectural tradition of Organicism. Michael Stacey provides a fundamental history of adaptive architecture, focusing on British and European traditions. Mark-David Hosale's 'worldmaking' extends related conceptions into vividly imagined future realms. Adam Francey contributes precisions of perceived agency, projected into machinic environments. Poignant reflections by Alexander Webb of the European Graduate School emphasize how increasingly intimate machine-human relationships are fraught with risk.

The White Papers 2019 represents a portion of an increasingly robust and involved community of research located within multiple international centres. Contributions made at the LASG 2019 Symposium in Toronto are published in a parallel volume of Proceedings. Demonstrations at the 2019 Symposium also include large-scale environments developed by a central cluster of architecture and engineering collaborators led by the author, focusing their work within a warehouse design and fabrication studio in Toronto, associated with the University of Waterloo. This location has become the headquarters of the LASG, providing a locus for workshops, testbeds and prototypes. Built works between 2016 and 2019 by members within the Toronto studio include permanent installations of testbed environments located at Indiana University in Bloomington, the China Academy of Art at Hangzhou, and Shangduli, Shanghai, together with recent temporary environments at Toronto's Royal Ontario Museum, the Daejeon Biennale (Korea), MAK Vienna, Futurium Berlin and the Vitra Design Museum Basel.

Numerous participatory workshops have accompanied these built projects. Expert workshops support ongoing research within a continually evolving collaborative partnership that currently combines groups from Canada, USA and Europe. Public workshops and summer camps include offerings for students within Grades Six to Eight science classes, high school students entering University, and graduate and undergraduate design students. Research and design workshops for experts are now in development.

The experimental sculpture environments created by the Living Architecture Systems Group are now being extended to permit participatory design and open-ended creative exploration, led by Rob Gorbet of Waterloo's Knowledge Integration, Lucinda Presley of ICEE Success, Katy Börner at Indiana, and multiple partners. A developing LASG STEAM (Science, Technology, Engineering, Art and Math) curriculum seeks to support wide and inclusive participation and equip emerging generations of designers with skills for working with complex, deeply interconnected environments. Kits for these workshops and classes contain electronics and sculpture building components. The kit components closely relate to the arrays of intelligent controls and lightweight custom fabrications within LASG installations, permitting individual exploration. Kits contain modular components and simple electronic controls designed for multiplication in arrays and chains, creating substantial networks. Construction kits that include digital fabrication patterns and prefabricated parts allow building of constructions similar to the deeply layered environments seen in recent LASG testbeds. Specialized modules permit connection and extension of systems contained within these existing sculpture environments and invite exploration of systems that could be developed in the near future.

The LASG kits are designed to encourage exploration of evolving, adaptive, responsive architectural spaces. Kits for young students include very simple, low-cost components and easily-found domestic materials that invite play and exploration at home. Clip-together modular construction elements are designed for laser cutting and 3D printing using machines commonly available in maker-spaces and schools, allowing new communities to share and expand the systems while keeping costs minimal. New generations of these materials will offer multiple components easily coupled together by experts and inexperienced users alike, creating constantly adapting interactive prototype systems accompanied by vivid, evocative visualizations. Complementing the group's contributions to precise knowledge, playful embodied interaction and mutual relationships lie at the heart of this community-based work.

This White Papers 2019 volume offers readers a sense of the variety and depth of research that is being conducted by Living Architecture Systems Group members. The adaptive and resilient qualities within this new experimental architecture can ultimately contribute to a more inclusive and empathetic built environment.

Philip Beesley (Canadian, 1956) is a multidisciplinary artist and architect. Beesley's research is widely cited for its pioneering contributions to the rapidly emerging field of responsive interactive architecture. He directs Living Architecture Systems Group (LASG), an international consortium of researchers, creators and industry partners. LASG explores questions such as whether architecture can integrate living functions and future buildings could think and care. LASG's immersive installations integrate expertise in architecture, environmental design, visual art, digital media, engineering, machine learning, cognitive psychology, synthetic biology and knowledge integration. Collaborations with LASG artists, scientists and engineers has led to a diverse array of projects, from haute couture collections to complex electronic systems that can sense, react and learn.

Beesley is a professor at the School of Architecture at the University of Waterloo and Professor of Digital Design and Architecture & Urbanism at the European Graduate School. He represented Canada at the 2010 Venice Biennale of Architecture. He has authored and edited numerous books and proceedings, and has been featured in Canadian and international media, including Vogue, WIRED, Artificial Life (MIT), LEONARDO, CBC, and a series of TED talks.

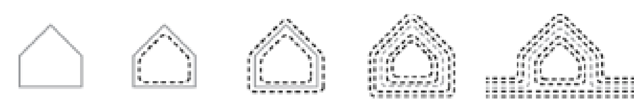


Image LASG research outline diagram showing twenty-year progression towards fully interconnected environments

Living Architecture Systems Group Interviews

Sarah Bonnemaison, *Dalhousie University*

During my sabbatical in 2016-17 I travelled to visit the studio and laboratories of core members of the LASG to learn about what they do and why they do it. I was not an interviewer looking in from the outside; I was an active participant with an agenda.

My agenda was to engage in conversations about living systems and how, as designers, we contribute to this endeavor. As I performed the interviews, I realized that sending ahead an essay about the theoretical issues I wanted to discuss, such as theories of the organic, enriched our conversations. I approached the interviews either from a scientific point of view or from a philosophical point of view. An essay on organicism in the sciences by Scott Gilbert and Sahotra Sarkar entitled "Embracing Complexity: Organicism for the 21st Century,"[1] informed interviews with Martyn Dade-Robinson, Rob Gorbet, Dana Kulić and Alan Macy. Mari Hvattum's essay, "'Unfolding from Within': Modern Architecture and the Dream of Organic Totality,"[2] informed interviews with Philip Beesley, Colin Ellard, Carole Collet, Michael Stacey, Rachel Armstrong, Andreas Bueckle and myself (the latter conducted by Luke Kimmerer). Some of these essays appear in this edition of *White Papers*; the others will be published in a future volume.

Through these conversations I understood better the complexity of mimesis in bio-design and became even more convinced that the aesthetic philosophy of organicism that grew out of the Renaissance and flourished in the 19th century is even more relevant than ever.[3] These interviews are a document of this search process that recalls a Socratic approach to learning and discovery.

1 Gilbert, Scott, and Sahotra Sarkar. "Embracing Complexity: Organicism for the 21st Century." Developmental Dynamics 219, no. 1 (2000): 1–9.

2 Hvattum, Mari. "'Unfolding from Within': Modern Architecture and the Dream of Organic Totality." The Journal of Architecture 11, no. 4, (2006): 497-509.

3 van Eck, Caroline. "Organicism Revisited. The Desire for the Animation of the Inanimate Matter in the 19th Century." Archithese 43, no. 4 (2013): 52-58
University of Pennsylvania

Additional Reference

van Eck, Caroline. Organicism in Nineteenth Century Architecture, an Enquiry into Its Theoretical and Philosophical Background. Amsterdam: Architectura et Natura Press, 1994.

Sarah Bonnemaison is a professor at Dalhousie University in the Faculty of Architecture and Planning. Her ongoing research interest is in architecture and its relation to nature, notably with the award-winning book, *Architecture and Nature, Creating the American Landscape*, (with Christine Macy). She is currently writing about the resurgence of organicism in architectural theory and practice. Her design practice in tensile structures has now evolved into creating exhibitions about topics such as the transformation of food in the modernist kitchen and the resurgence of organicism. The exhibition, along with the catalogue, are conceived as a research tool that grows in each place it lands.

On Organicism *with Sarah Bonnemaison*

Luke Kimmerer, *University of Waterloo*

Luke Kimmerer

Can you tell me what organicism as an architectural theory is? And what does it reject? Another part of this question refers specifically to the 1993 book *Organicism in 19th Century Architecture* by Caroline van Eck. In this van Eck illustrates a thread of history where the desire for elegance and truth in architecture is understood as having the capacity to evolve with the cultural and social landscape. What are the fundamentals that allow this persistent evolution?

Sarah Bonnemaison

It is this *persistence* that got me interested in organicism. Architects have been learning from nature, copying nature, or finding inspiration in nature for a very long time as we see the work of Philip Beesley among others today.

It seems that whenever there is a sea change in society such as in the 19th century with industrialization, and all the machines replacing what craftsmen used to do by hand – people get stressed and say "let's turn to nature as a model" because that seems infinite and fundamental. Maybe with all the changes that are happening today with the digital world, the same kind of phenomenon is once again looking at nature as a model. It is actually "funny" how big digital companies call their creations: "raspberry" for a telephone, or "apple" for a computer. Why are they using a natural terminology to name machines? I think because it makes these machines softer and friendlier.

As architects, we want to be right at the forefront of both ideas and technical development. But a large part of what we do is crafting materials. We want to do it well so we learn from the past. The other aspect of what we do is promoting a better way of dwelling together. This attitude distinguishes architects from builders. Like craftsmen builders repeat and improve, but they are not interested in the idea of living. The desire for a better co-existence introduces Organicism, which originally came from rhetoric - the art of building a convincing argument by using techniques drawn from nature.

In our relationship to nature, we partly want to learn from it. We have an insatiable curiosity to understand how things work, why the planets turn that way, why the folds of the earth have these colors? And we partly are fascinated with the creation and the adaptation of nature.

As creators and inventors, we draw from nature because nature appears as a model of perfection. There are two different sides to organicism; one is more analytical and driven by curiosity and the other one is more - you could say - rhetorical, creative, artistic, and inventive.

Does van Eck not use the words "invention" and "interpretation"? Are they not also what you are trying to illustrate?

Yes. In this discussion, whenever you want to create something convincing, you are going to use materials that are already available to you. Organicism suggests that in order to invent something new, you are going to look at nature in order to be creative, and to come up with new ideas.

This suggests that nature is the ultimate persuader. It's hard to argue against nature because it is the truth. It is inherently the strongest "thing".

Early on the highly debated question was "what is the difference between nature and God or spirituality?" Even though the people knew that nature was the ultimate truth, what they wanted to do was to approach God. But they couldn't copy God because God was a mystery. So, the next best thing was nature, because nature had been created by God – that was the logic. When they built a church, nature inspired both the structure and the decorations. Believers visiting the church felt spiritually elevated.

I want to talk about the 19th century. When organicism became secular and the focus turned to the natural sciences; and the Cuvier versus Saint-Hillaire debate was perhaps the turning point. Can you expand on it?

What did you get from it? Did you feel like it was a big sea-change from before to after?

Absolutely! To me this is really a question of my own spirituality, which has admittedly changed during my pursuit of an architectural education. That said, I am hesitant to think of things as having a function before they arise.

That's exactly what the debate was about! One person thought that there was an idea before the form of an animal was created. The other would say no, the form of an animal came because it was trying to overcome a problem. The more modern perspective is the second one. They would say, well, "the shape of the claw of a lobsters came about because they were trying to grab something" – there is no idea behind it, no plan, in other words: no God.

Nowadays with DNA and chromosomes, it gets more complicated because before an animal is born, there are all those languages in the DNA inside the cells. So, the plan for development is already "out there." As the animal grows, the environment has an effect on it. It reacts to the environment in a certain way according to its DNA. What is happening in nature actually encompasses both schools of thought.

I have been thinking about neurophysiology since last fall. When I read Maturana and Varela [*Autopoeisis* and *Cognition*], the idea that interactions, physical interactions, and one's neural system are constantly in a state of change; and one "circuit" affects its neighbours; and the neighbours inherently affect their neighbours, so there is always flux and influence. We, as a unity, engage in the same recurring interactions. Naturally the synapses that occur form a bit of a "memory," which is almost evolutionary. As living organisms, we reproduce and that memory is carried forward.

Or not! Depending…

Or not. Yes! That raises the question of persistence. It would be curious to observe whether mechanical movements of my arm, or mental activities that I engage in have any effect on my offspring.

Well apparently it does. It is evident in the fact that now we are using the mouse pad a lot. This action is different from grabbing something, which we have done forever. But now it's done with just one finger. Apparently it also changes how our brain is structured. Some of the younger students that I am seeing right now cannot tie their shoe laces anymore. It's wild!

Even in my generation, I cannot seem to type on a keyboard properly. Everybody aged 50 and over keeps asking me, "why are you typing with your one finger?" Well that is the only way I know how to do it; everything that I use only needs one or two fingers. But I can do it quickly.

Yes. And you get very good at it too. Probably your one finger is as good as all your fingers.

Yes. Absolutely! I take my given form and I learn to use it to the best of my ability.

Back to organicism, I am seeking specific examples to illustrate the difference between mechanical and organic forms. For example, I would use the *Urpflanze*, the archetypal plant for organic form that would directly illustrate the idea of growing from within which is one of the key ideas of organicism. And then I would juxtapose a Lawrence Harris painting of the Northern landscape with a mountain or snow drifts. The mechanical form of nature does its thing in that sense, but it wasn't living. And I know you feel that the Northern transept at the Notre Dame illustrates aspects of humanist and transcendence. How could a reader – somebody who isn't well informed on organicism, or organic form versus mechanical form – best understand these two images?

Well, in architecture, most people know how nature is represented in stone decorations, for examples, in capitals. You see flowers or plants cut out in stone and you think, “ok, that is talking about nature.” What more difficult to illustrate are the internal forces in the building that give it its form. Calatrava understood these forces and represented them well in his architecture. One can imagine that the form is the result of the compressive and tensile forces that are flowing through the material.

By contrast, you have the mechanical activity that is based on repetition. This is the mountain being shaped by the water or the snow drift shaped by the wind. This does not come from within, it comes from the outside. The main thing, again, is to go back to “what is the idea that is being expressed by the form that you see?”

So is the word “organicism” the most appropriate label for what the LASG is doing and the type of philosophy that they are trying to work within or under? I understand “organicism” in the sense of a microcosm and building the space within it. As a composite to its form, organic matters exist almost like organs in a body. I agree that LASG is working towards a philosophy that is certainly in line with the persistence that organicism has. But whether organicism as a word has to also represent that composition.

I have shared with you a list of words that in a way I think the LASG addresses in some aspects of their works. Those specifically have come up in conversations between Philip and me because he has got a certain rhetoric, history and poetics that yield that type of conversation. Regarding the word “organicism” and the work of the LASG, do you think you would approach it with more flexibility?

I think the point of using the word, and why I was excited to use it, is not so much to put a label, but more to give it a historical context. Simply to say that the work we are trying to do at LASG has a history in architectural history. The umbrella term of organicism is multifaceted and complex. When you look at it deeply, you understand that a great deal of the mechanism embedded in it is very similar to what is going on now.

For example when you say, what about “abiogenesis,” “emergentism,” or “synthetic,” all those words are like subsets of “organicism.” In the 19th century, architects like Semper, who developed a theory of construction as layers (as opposed to mass), were very excited to have conversations with Naturalists. Semper was excited to get into the details of the natural world from a scientific point of view, and then apply it to architectural theory. It is exactly the same thing Philip is doing now when he has conversations with scientists.

He gets excited about pluripotent cells because he feels that his works can be nourished by that scientific idea. Our creative process, as artists and architects, is really the same. Science has evolved so of course there is a difference. Now we are not looking at bone structure like we did when we were reading D’Arcy Thompson. We are looking at nature at a much smaller scale: cells, or neural science as well as larger scale, the cosmos and the flows of big data constantly “listening” to nature.

However we are really just learning from it. We are not scientists. We are not here to solve cancer or the evolution theory. We are just learning about what scientists are thinking and the methods they are using.

The other important issue is aesthetic and its reception. Ultimately, “organicism,” or Alberti’s favorite word *concinnitas* – on which I am writing an essay – is another rhetorical term that refers to art modeled after nature that is skilful and purposeful. Both terms aim at how we create art or architecture from our observation of nature. In other words, organicism contributes to the philosophy of art. When you create with the mindset of drawing inspiration from nature, the result reflects what is interesting to you at the time. To me it as simple as that.

We can use other words than “organicism.” But the good thing about that one word is that it encompasses two ideas. The idea of understanding from nature and of wanting to create. Whatever we create, we are trying to make beautiful and communicative ideas that will make an impact on the viewer or the user. That is why, for example, we use the sentence “God is in the details” – that’s absolutely “organicism.” It means to be able to make things and enjoy them in beautiful ways, intelligent ways, efficient ways and meaningful ways. We believe it to be something beautiful and eventually spiritually uplifting.

Another aspect I like about “organicism” is that it is also very humble in some ways. We are going to make something here. We’re going to put two pieces of plastic together, and a little bit of digital whatever. We’re going to mix it all up, and then hope for the best. That is very different from the purely analytical mindset of scientists who are trying to figure out how the world works. We have words like “growth,” “ecological design,” and “responsive architecture,” which are more on the side of design. I think that’s what we have to keep in mind throughout this whole thing. What LASG is doing is close to ecological design and responsive architecture. It is again all about new design can work with nature.

Our last question before we get into the lengthier ones. Something in my own work as of late has been a prevalent thing. I call this my proposition: "the means to which an end is achieved must be understood in a manner in which an end desires to emulate."

If we are in pursuit of an organic design, do we also have to mimic organic process? Is that fundamentally true? Or can something organic be achieved through a more scattered?

Intuitive way, you mean?

Intuitive? Sure!

A conversation I recently had with someone: a craftsperson or a wood worker is almost one with the wood. They feel it. They work with their hands. You could argue that it is a very natural thing to do, to engage your own body with the material, with the process versus automation, leaving it to prescribed logics that have been developed by the scientists. But we're still able to achieve somewhat organic things through automation sometimes.

Because somebody still writes the program.

I guess this might extend to the next question about craft and what it is.

Obviously the divide is not simple. On one hand if you are working with a little tool, it will be more organic. If you're using the big machine then it is repetitive and not going to be organic. That's way too simple.

What craftspeople will tell you is that they have been using and adapting tools for a long time. Now they are using computer-driven machines as another tool, but to them it is no different from the tool that they made 200 years ago. The machine is still made by the human being, right? It is not self-replicating like cells, you know, like an organic body.

Right. We don't necessary think about design and outputs as being part of that natural world, but inherently we use nature. That just seems fundamentally an act of fiction.

Doesn't Caroline Van Eck call it interpretation? That means to interpret things in ways we understand nature.

Yes, she calls it an interpretation absolutely.

But you think it is an artifice?

In some ways, yes. In my opinion, the definition of nature has to include us and our products. I think we see that in Hannah Arendt, and perhaps more recently as well. But the two definitions that Burnet proposes about nature, I think draw the line somewhere around us. There is nature, there is us, and there are products that mimic nature in ornaments and in forms. And that changes throughout history. But there seems to be a consistent divide where architecture is not necessarily considered living, as part of the living system.

Perhaps that is just my confusion. I think in a way all architecture is part of a living system. City and social system function as living systems. But there seems to be a conversation about fictionalizing the act of doing architecture as being a fiction of nature. Is that a false statement? Is there a misconception on my part?

I would not say false. A lot of people feel like you. But if you want to use nature as a metaphor such as the city has veins, etc. you could look at the 60s and 70s when urbanists used nature to talk about something larger like cities. In some respects, it failed a little bit due to scales. The metaphors need to change as one changes scales. So for example when Philip Beesley designs a detail he calls a frond, he can say, "I'm learning about how to make this detail by learning about this particular natural phenomenal I observe in fronds." And he designs it as an interpretation of natural fronds. They are very small, and bundled together they create a group. At this point you need a new metaphor for your next design move. Maybe you look at a groups of ants or bees. Is it more about communication, data going back and forth than about the flexibility of the fronds?

As you are going up a level of complexity, and this is the idea of organicism again, you have to change your way of looking at it. If you rely on the same idea from the very small to the very big, you are going to end up with something that feels fake. Just like you say, it feels very much artificial and does not feel correct. You have to be very careful of how you use nature to design so that the scales correspond to the ideas.

Scientist who rely on organicism when they analyze a body and the nervous system do just that. When you look at the cells you have some kinds of ideas. And when you look at a group of cells you have to look at different ideas. Then you go to the brain and so on. They are very clear about it; you need levels. Each time you have to change the way you conceive of it. All to say is that you're absolutely right. We should feel that the human is part of the whole thing. It is so important. I wish we really believed in that.

Before the 18th century, humans were part of nature. In the Vitruvian Man, Leonardo Di Vinci represented nature. He was not representing just the human but the natural creation of it all. After the 18th century, people started saying, "Oh nature, we are not that!" That started the divide; there was a living and there was a dead. More recently in the 19th century, there was a divide between what was mechanical, innate, and what was living. And I have the feelings that now with the digital world, we are trying to put it back together with the whole idea of ecology and natural systems. Everything is linked; it is not about what is dividing.

To build on your comment about scale, and you spoke about being careful in how we should apply nature, you were saying that we could in fact misrepresent nature in design. How would you speak to biomimicry in that sense?

When we say "let's make a plane like a bird," you cannot just mimic the bird shape for the plane and hope it is going to fly. They tried it and it did not work. You have to first understand the dynamics of wind and air flow in order to make it work. And how a bird gets lifted in order to design your plane. So, you have to go deeper in what you are learning about nature, especially when you get to different scales, different materials and so on.

I had a very good conversation with Dana Kulić about the idea scales. For example, there are many different layers in Philip's work. Philip and Dana had huge discussions to decide whether all the information should be concentrated in one spot, or should each small element have a little bit of the intelligence. And they went back and forth, pros and cons, for a long time. Ultimately, they decided to have the learning happening in many different places. Because philosophically they wanted to show that there was more brain power in many of us together than in just one person. It was really a political stance. They tried to demonstrate

how a machine with very little intelligence was capable to learn a lot more when there were many of them.

What was interesting is that Philip and Dana are looking at sciences and trying to say something with the installation. They are trying to give us an impression that these little things are responding, how amazing it is that they are learning so fast, responding so well. The impression slips into your unconscious while you are inside the installation through a sort of vibration.

I think those things are very interesting and they are very experimental because they try to offer some suggestions about larger ideas. It is not only robotic like "Oh this little thing is so cool!" It is able to move up and down now, but five minutes ago it couldn't do it. The whole experience represents something bigger and more uplifting because it makes you feel something positive about what you are seeing.

Of course. And I think we need to recognize the importance of Dana's work in being able to engage with cause and effect on a more observable level. You called Philip and Dana's decision a political gesture. We can say that the sculpture is a product of invention. A gesture is being prescribed both in the form and in many components, in the way it actuates, in the way it behaves, and in codes.

As a visitor underneath a sensor engages with it, they feel the movement of their arms versus that of the whole sculpture on a larger scale. I have my eyes on one piece and I can see it moves. But in my periphery I can also see the rest of the sculpture doing something else. If I am able to look at a computer screen while a visitor is interacting with the sculpture, I could see how one action could cause patterns throughout the sculpture that was perhaps not as identifiable when I engaged with it physically.

When I am immersed in one of Philip's works or any beautiful installation or architecture, its beauty excites me. I am uplifted because of the beautiful and amazing experience. I find that Philip's work can get to your subconscious. It is a bit like when you are looking at a field of high grass and the wind blows through it. That kind of vibration caresses your brain. This differs from my experience of looking at a painting on the wall which could be more intellectual. My mind is at work to comprehend the implied space and the content.

However, when you are submerged in an installation or an architectural environment, it is all around you. As a result it touches all your senses as you move in it and gets more into your unconscious. When you describe your experience of looking at the screen and your analysis of the action and the reaction, you go from a sensual experience to an intellectual one. I cannot imagine the screen makes you feel good, but it is satisfying to understand how it works. It gives you an objective distance.

But in terms of a logic loop and how our subconscious works, the screen being a reductive tool allows you to learn how you interact. You can go back and say, "I am going to do this. I am going to have a conversation with this sculpture because I know how it works, and how to trigger its behaviours."

Like a learning tool in a way…

It is a language tool I would say.

To communicate with the sculpture?

Exactly, in the context of information and living system, I think it is very key. In some ways, the interface does not let you engage materialistically with the sculpture.

But that is the point, you can step out. You learn about it and then you can go back in. In a way, it refers back to what we were discussing at the beginning about the whole idea of organicism. First, you learn something and then you apply it to represent what you understand. Afterward the creative part is to go back into the sculpture and to play with it. Then you can go out again and be more in your head, and reflect on what you learn from the responses. As you go back and forth, this brings the environment and your experience close to each other.

Regarding the domain of things available to create our build environment, what does that look like a hundred years from now? What are the goals of the LASG beyond this SSHRC grant? What is the new medium coming out of the work today? More generally, how might the toolbox of the architect look in the future? I have been thinking about the gentlemen from 4DSOUND. Sound has a designable medium as opposed to designing a space with some acoustic treatment on the surface that already exists. More explicitly, you cannot control sound in a space but you can give it shape, and movement per se. How is that going to enable designers going forward? We can speak to computer science, the idea of a building with a network of information that is not of the people moving through it but of its strata. So what are the tools? And what is this next generation of architecture as we think about living architecture? What does it look like to you?

It seems like sensors are key. The way Philip works is by taking some ideas which have their own organic growth. With each generation, he changes them a little bit. When sensors came along for him, and for all architects, they have totally opened up this idea of a learning architecture because the technology is so quick and so human-like. When I talked with Alan Macy (Biopac) about sensors, we noticed that they were really progressing. But the main question is what to do with the information you get from a sensor?

So then, what do you create? What do we want to do with it? We have this technology that always changes, that is becoming more available to us as it is getting cheaper, more compact and even wireless now. We have institutions like universities supporting us to do research. But the question "what do we want to do with it?" stays completely whole. We know that we are driving the bus. It is great, but can we get off the road? That is why ethics and philosophy are really important in these cases. Because if not, you can get into hot water.

Certain political actions have taken place because of this mega data and power. People buy it and they do not do the best thing with it. So I think we have to be very careful. I am not saying we should refuse. We just should be really aware of what we are doing, how we do it, and what it means.

If you design a space on a 16 x 16 grid and you give some treatment to the walls or the columns, you can hypothesize "well I suspect that people will react this way." And now you introduce the idea of sensors, you can be more specific on the feedback we get from how people interact with the spaces. You can make stronger predictions, and you can be more deliberate in the way you design.

In a way, that seems a little bit controlling. Having people engage with an architecture - the mysteriousness. I cannot recall exactly the title of an article – maybe one by Dianne Kanne – but it talks about the mysteriousness of nature. And having people engage with an architecture that is mysterious can be something that is exciting and engaging.

I see where you are going. If I understand you correctly, you think it is important to keep the uncanny and the poetry in things and not wanting to control everything. Is that what you are thinking?

A little bit, yes.

Then, of course I would agree with you. On a more mundane level, I think that we should always understand that humans are very different from each other. The more technology and architecture can help us control elements and our environment individually, the better our individual experience is. For example, if someone has decided that the whole room should be at a certain temperature during winter and we each want a different temperature, the majority of us will suffer in that environment. Therefore, it is fundamental to be able to set the temperature in parallel with people being able to open their windows. They are now able to control their environment. If your office is too hot, then you can open your window. So it is really a philosophical attitude to saying “not everybody is the same and we need to be able to connect with the environment outside” and so on.

I see the opposite is happening now. A lot of the new buildings being built are hyper controlled. Somebody has decided on everything: the colours, the windows etc. Most people are really just suffering in there - they are not happy and they get sick. They actually develop *building sickness* because we are not meant to live in a machine.

I am giving a very simple answer but I think it is fundamental. We still need to have control over our environment, but it should not require a million computers between us and opening the window. For example, on trains in France they have decided that each passenger can heat their seat according to how they feel that day as opposed to heating the whole train. If the seat is not occupied, it will not be heated so they also save a lot of money there. The overall focus is saving energy but it also addresses individual needs.

Alan Macy’s work goes in this direction because he works closely with the body. He knows that each body reacts to everything differently – physically and emotionally. He then writes programs and builds the hardware to create those little devices that help you to cope. For example, he makes pacemakers to make your heart beat better, but not without an awareness that the technology has to adapt to each body since each one is different.

So subjectivity and the individual scale are being the drivers.

Yes. His whole thing is how you go from analogue to digital. Think about how your heart is beating; it is not beating like a machine. Your heart is beating differently from my heart. So how would you take this analogue information and design a machine that works with digital information with the aim of helping one’s heart beat better? It sounds simple but actually it is very complicated to go from analogue to digital on an organic, living body.

In this case, it is the individual versus the machine. But with our intelligence and computer programming, we can really adapt to the organic.

In closing, I want to ask you a question generally about Stream 6 (Theory) and how that fits into the LASG. I guess the role of philosophy is research collaboration. Can you share what you are trying to do? Why is it important to the group?

When I spoke with Philip at the beginning, my hope was to communicate better between each other. In trying to share the visions of the work we do, I began to read about the relation between architecture and nature. I asked, “why is it that it is interesting?” and gave myself time to reflect on it. The next thing I thought was to engage with different people in the group. So I started to interview other LASG members. The conversations are seeding ideas so that people have time to think and reflect on their work before our gathering in March, which will be the next step.

The challenge is that everybody is very much into their own work in a very narrow way. They go very deep and they are very good at what they are doing. So I think my job, and maybe your job as well, is to pull them out and ask, “ok let’s look at this. Why are we doing this? How are we communicating between each other? What idea am I taking from this? What does it do?” I think that is basically it.

I think that sums that up very nicely.

Good. I am glad.

Luke Kimmerer is a graduate researcher from the School of Architecture at the University of Waterloo. For the Living Architecture Systems Group (LASG), Luke coordinates activities that contribute to research development, publications, and event planning. His research interests lie at the intersection of process philosophy, network science, and data visualization. Luke is funded by a Mitacs Accelerate grant and SSHRC.

Between Engineering and Art *with Rob Gorbet*

Sarah Bonnemaison

Can you tell me a bit about your research process, what your hopes are, and what you would like to grow from your research?

Rob Gorbet

I consider myself to be first and foremost a collaborative researcher, rather than a strong, independent research leader. I help other people drive their projects. I sometimes find myself in a strange situation as a stream leader. I think there are stream leaders in LASG who have a very clear idea of where they want to go, and they're going to drive that project. My stream is specifically about education and the interdisciplinary work. It is more of a meta stream than the actual making of Living Architecture. I'm very interested in the projects that can bring LASG into the mainstream in terms of language and understanding and awareness,

and bringing it into the educational domain mainly as a way of helping people think differently about creativity and problem solving.

One of my main collaborations through LASG has been with Lucinda Presley, who is an educational designer and consultant from the United States. One of the big things in STEAM, K12 education and 21st century competencies is teaching creative thinking and problem solving. We know that it helps to have a context in which the answers are unknown; the more our context is understood by the students, the more they fall back on prescribed answers to problems. The definition of creative thinking is to be able to be in a familiar context and yet think about different things. That can be difficult for student novices.

The advantage of the work that we're doing at LASG is that it's multidisciplinary. Not only can we provide a context for students to exercise their imaginations in ways that they haven't really thought about before, but we can also tailor the workshop in a particular classroom to whatever standards for art and sciences the teachers are trying to target. For example, we can talk about electricity and actuators and electronics and movement; or we can talk about biology and mechanisms or chemistry. The fact that we can tailor a presentation to the specific learning the teacher needs in that classroom makes it a very powerful tool.

We've also incorporated a number of other partners including TDI - the Toolbox Dialogue Initiative - who are interested in the sort of overarching dialogue on how disparate groups work together.

Do you ever go into art classes?

We haven't been specifically in art classes. But we did a school in Waterloo where the art and science teachers came together into the science class, and we worked with both curriculum standards.

Lucinda has an Art History background and teaches Art History in Texas. One of our goals is to incorporate the idea of form, space, line and balance and some basic art concepts to say that art doesn't have to be a painting. Art can have electronics in it, and it can be interactive. So that project appeals to me on many different levels.

That's very appealing. This might be good time for you to share how you fell in love with interactive arts.

I come from an engineering background. I am an electrical engineer. I studied in electrical and computer engineering at Waterloo University. I did my Masters and PhD at Waterloo as well; and then I did a post-doctoral fellowship at the University of Toronto.

I got hired at Waterloo in 2000 as an Engineering faculty member. Along the way I had some small experiences and connections with art and culture.

From the age of 12 to 14, I lived in Paris. My family drove me around and we saw lots of museums, churches, and other cultural things. I think that appreciation for culture and even diversity was probably a dormant influence. I studied four different languages when I was there. In addition to French, I also studied German in Grade Six, Seven and Eight. In Grade Seven they added a dead language, so I started taking Latin. Then in Grade Eight, I started taking Russian. So by the time I was 14, I was an Anglophone bilingual in French, studying in French, studying through my third year of German, my second year of Latin, and my first year in Russian.

But all this to say, when you were young, you were already able to think in different modes.

That's right. In hindsight I think it had a bigger influence than I knew at the time. Others might think differently, but as an academic I don't think I fit the traditional model. I am much more interested in teaching than research. I don't drive my own research agenda; and that would be how I first got introduced to the art world as a contributor.

In 2000, Ernest Daetwyler, a Swiss artist living in Kitchener, was trying to design a sculpture for a festival in Switzerland. The sculpture consisted of two big satellite dishes that would rotate and communicate across a canal by blowing soap bubbles at each other. Daetwyler had taken off the receiver part of the satellite dish and built this extension with a half-moon shaped dish and a disc that rotated through the soap, and fans that would blow soap bubbles. But his motors kept burning out and he needed help. He exhausted all of his personal connections before he called the University and somehow ended up at the Dean's office. The Dean said, "Oh we've got this new guy Gorbet. Let's ask him if he would help!"

So I did! I sat down with Ernest and in a half a day I did the calculations and found some motors with the right gear ratios and voltages. That was where I first got this feeling that what for me was an average problem to solve, was magic for him. It allowed him to bring his creation to life.

After that my brother, Matt Gorbet and sister-in-law, Susan moved back from California to Toronto to have a family in 2001. They came out to visit me here during CAFKA (the Contemporary Art Forum Kitchener and Area). The idea of CAFKA is bringing art outside of the rarified space of the gallery into the street and public spaces. We went to visit CAFKA over at the Kitchener City Hall.

In 2002, they had a call for proposals on the theme of "Power to the People." Matt, Susan and I put in a proposal called *P2P.* The piece was about questioning the role of central oversight in communications and the extent to which that was important in a society. It was during the rise of Napster and file sharing, and the accepted practice was centralized.

But were you questioning the practice?

Yes. But I think the practice was centralized simply because of mass communication networks. This was the beginnings of the Internet. Mass communication in the way that we know it now didn't yet exist. The proposal was grids of light bulbs and switches that looked like a marquee, which is a canonical icon of communication. And you could put whatever message you wanted up.

P2P literally means "bringing electrical power to the people" but also kind of this power of communication and those questions of centralized oversight. The jury loved the piece, but they didn't want it to be indoors, which the original design was. They wanted to be outdoors and to be twice as big. That meant it had to be waterproof without changing the way that it looked. We wanted to use standard household switches that would be inviting to people.

Would you say that the piece was the first one where you really tangoed with the interactive part?

Yes.

So in a way, that was sort of your first kiss.

Certainly! It was the first work that I was directly involved in the creative side, and the creation. It also exposed me to another part of interactive art. My experience with Daetwyler taught me how amazing it was to collaborate with somebody and contribute to the project something that no one else could bring. *P2P* taught me how impactful a well-designed interactive art experience can be on the visitor.

Interactive art doesn't really exist unless somebody is using it. We would stand across the street from where the piece was installed and just watch people use it. We talked about people as the medium. In the same way that a sculptor understands clay or a painter understands paint, an interactive art designer needs to understand people.

Over the last decade we've learned about making interactive art, and things that psychologically and socially empower people to use the piece without instruction. The piece was up for ten days; and there were people who fell in love with the piece. They brought people to it and also protected it from being tagged. One night there was a group of punks hanging around the piece. Matt and I crossed the street and started engaging them. They all said we basically gave them what they wanted - an opportunity for them to express themselves. So why would they tag it when they could put the tag up on City Hall? *P2P* was where I first saw the impact on the individual.

Fast forward a couple of years. In 2005 Matt, Susan and I got a commission for piece called *Solar Collector*. It is an architectural scale interactive outdoor sculpture. That's how Philip found me – from an article about the commission. At the time, I was doing research on shape memory alloys: novel engineering materials that the automotive industry was interested in harnessing. I was literally making better door locks for cars by figuring out how to make more them behave more predictably when it's very cold out. I had a big grant from General Motors and five grad students in a lab. On the one hand, there I was making better door locks; on the other hand, there I was making interactive art.

You can tell which one shifted the balance. So I spent a lot of time working with Phillip. The first piece that we did together was *Implant Matrix*, predating the Hylozoic Series. The first Hylozoic piece was *Hylozoic Soil* at the Montreal Museum of Fine Arts in 2006. That was the first big piece that I did all the hardware design for.

So we understand now some of the roots of my interest in interactive art. In 2004 *P2P* got an award. I was at the Award reception with Matt and Susan when Bruce Taylor, the Chair of Fine Arts at Waterloo approached me and said we should really do a course together. So we designed this course, and he went to my Chair to get me permission to start this tech art course. We put ten upper year engineering students and ten upper year sculpture students in a class together. Bruce, who is a sculptor, co-taught the class with me. We were both at every lecture. Some of the most interesting content in the course was unscripted dialogue between Bruce and me at the front of the room.

And that's a creative part, isn't it?

Yes. The way my perspective as an engineer/artist and his perspective as an artist came together was fantastic!

The course also gave me a whole lot of tech art projects to work on. They weren't mine, but I could help debug and help them come to life. In the process I started to get fascinated by the dynamic between the artist and the engineer. I started doing research on Billy Klüver, who in the 1960s was an engineer at Bell Labs. He knew people like Andy Warhol and Robert Rauschenberg. He started EAT, Engineering Art Technology, which was like a matchmaking service for artists and engineers in New York City. They had culminated in this show called 9 Evenings at the Armory where they brought together artists and technology people to create these interactive experiences. It was an enormous critical failure because it was like nothing that anybody had ever seen before. People were playing tennis and sound was moving around the room, but they were inventing the systems for doing distributed sound in space. So many of the things that we know now were invented as ways of helping artists achieve their visions that didn't exist.

Why was EAT a critical failure?

I just think the majority of people didn't get it; they thought they were doing really weird stuff. "This isn't art." "What is this stuff?" But it's like when the Impressionists started out. The critics said, "Well, that's not art!" because it didn't follow the rules.

I started reading about Billy Klüver and we started teaching the history of technology and art in the course. That was when we wrote a paper asking, "What can we do as academics when we're trying to build educational contexts to bridge across really disparate disciplines?"

A lot of people will argue that art and engineering are not that far apart; and in some ways they're not. They're both very creative acts with creativity at the core. However the context in which you're doing it can be very different. We talked explicitly in the course about navigating the stake and the expectations of the participants. For the engineers this was just another project course. But for the artists, they were building a piece that could be the most important work in their portfolio. They needed it to work, to look good, and to last beyond the collaboration.

It's very interesting. I had asked you earlier what inspired you the most. It sounds to me that Klüver might have been your model.

He was sort of a pioneer. I never really thought about him as an inspiration but more like a reference. There are other people too, but Billy Klüver is probably the closest. For example, I'm fascinated by Sol LeWitt's *Wall Drawings*.

If you don't know that series, the idea is that Sol LeWitt never actually executed any of these drawings. They're more like instructions on a one foot grid: "Put dots at the corners and draw blue lines, half of them wavy half of them straight." When different people execute, it's a different vision. The idea is of disconnecting the creation from the execution, and in the process of doing that allowing other people into the process. If you're going to sell a Sol LeWitt, what are you selling? Is it the execution? Or is it the instruction? What's valuable about a Sol LeWitt? Is it the napkin on which he wrote the instruction? I find that fascinating.

How does that connect with your interest in people participating and engaging with the work?

It's a different kind of participation. These instructions come from the artist, but there is a group of people executing. I wonder whether in history there is an example of mass public execution of one of these *Wall Drawings*. Or whether it's always the gallery that gets a gallery guest or some volunteers to do it.

In pictures I've seen, it looks like there were a number of people.

It's often a number of people but usually it's in a gallery. I don't think it's the general public. I wonder whether any of his pieces have ever been executed *en masse* as a general public thing.

Did he say it should only be executed in galleries? Was that one of his instructions?

I don't think so. Not that I know of.

It questions authorship, doesn't it?

Yes. For example, Bill Reid, who was a great Canadian sculptor, had Parkinson's at the end of his life and couldn't carve. He had an army of apprentices to make Bill Reid sculptures and the artists were never credited. There's a long history and lots of examples of this sort of apprenticeship model. LeWitt is a little bit different in that it's different people executing every time. It's not like he's cranking it out in a studio. It's not really the apprenticeship model because you don't have the same person learning and building a craft. I think this apprenticeship model and craft is seen a lot in architecture as well.

That's what I was going to say too. You cannot possibly be an artist in architecture because you need all those people to do the studio work.

That's right. This is where I think that Philip is not an artist, he's an architect! I've seen it most concretely in my work with Philip when we visit any city in the world and we can drum up an army of 15 to 20 volunteers to help us with installation. I think that is owed to this culture of apprenticeship putting in time and working with the master.

I think that whole thing about people's involvement and what they contribute could be really interesting to tease out more. It is like being behind the scenes and it's really fascinating.

I think that there's a balance to hit. It has to come together as a unit, and the design needs to be flexible enough to accommodate the different ways that people are putting things together, so that people don't get frustrated by the rigidity of things. Instead of having to be there for days and become an expert, multiple people can contribute for brief periods of time.

The learning curve has to be short.

In order for that to happen, the whole that comes together from the collective needs to accommodate variability.

You know I'm really interested in organicism. The philosophy has two elements that I think are relevant. The first one is that you create something that has unity. It's not about doing networks that are spreading or reproducing throughout the world. It's about creating a thing at the end of the day.

The second one is learning from nature. Different systems work at different levels of complexity and they're all interdependent. Each one is embedded one into the other. Because the organicism is a way of inventing and creating it, it's not about interpreting what exists but about creating something new.

Your contribution to Philip's work is to create clarity on how those different networks work. Maybe some of them are friendlier to have people come in and do things, while others are to be left alone. Some of them have to be preconceived, so that unity can happen.

I get excited about people collaborating and making a thing together. Often large collaborative works get pieced together from bits, like a community mosaic. And it's wonderful that people have come together and they've created something; but it doesn't have integrity.

Yes, it doesn't have unity.

I definitely think that integrity or unity is important. It's what is going to distinguish and allow the message to rise.

Yes, when the viewer interacts with the piece, the unity will help them get it. If not, then all they get is a mirror of that community, which is fine. The community expresses itself. But if we want another message or something that connects to art, it is a bigger task.

This idea of layers is very interesting. Earlier I was talking about the importance of interface design in interactivity. Too often you see particularly with interactive art, the experience for the visitor is that they come into the gallery or the museum or the space, they push some buttons and some stuff happens; or they wave their hands and stuff happens. The goal becomes for them to try to figure out how to play the piece. And they figure it out and then they move on. They never make it to the point that the artist was trying to make. So I think of it in layers. The artist has this conceptual layer: a message that they want to send, or an experience, or an emotion they want to transmit. But then there are other layers: the

technology layer and the interface layer. And those can be too thick, making the conceptual layer, the whole point of the piece, inaccessible to the vision.

I've had people in the technology art world, artists, come to me and ask, "Is it possible to make good technology art?" Because they've seen these pieces that are all about pushing the button and learning how to play the piece. And I think, "Absolutely, it is!" But it takes good careful interface design.

It's the hardest task because you're inventing and creating something new. It's not like you know if people are interacting with something they already know. Part of it is going to be new and that's the excitement. But the question is, how fast can you bring them to that new part so that they can really groove on the higher level?

I guess that's one way to think about it. But a really well thought out design, unless it was absolutely not possible based on what you wanted to do, will actually have people interact with it in ways that they already understand in order for the interaction to not be the focus. *P2P* is a great example. When we had to move the piece outside, the easy thing would have been to move to waterproof switches. But waterproof switches are very industrial and they're not inviting; they're intimidating. People would be looking at this big thing and asking, "Am I allowed to touch it?" So it absolutely had to be the normal everyday wall switch, which is not waterproof. That meant that I had to redesign the entire electronics so that it wasn't high voltage, because they could electrocute themselves if it rained. It was critical that the interface be simple and obvious. By knowing the psychology, how do people interact and affordances... you know the term "affordances"?

Not really...

It comes from a designer Donald Norman. He wrote a book called *The Design of Everyday Things* where he talks about several different dimensions that are characteristics of good design; one of them is affordances. The idea is that the thing should communicate to you how you're supposed to use it without instructions. If you have to put a sign on it then it's failed.

Do you feel like you're contributing that to Philip's work?

I don't think so. We have never really talked about the physical design on that level. Right now the kinds of interaction that people have with our sculptures is just that they walk around. Hence, the question becomes, you know, the placement of the sensors in order for them to have an experience that makes sense to them. Also in our work, we're trying also to accomplish this sense of mystery. We don't want people to understand how it works.

But you want them to experience it. You don't want them to just walk in, take a peek, and then walk out.

That's right. But I would rather they not know where the sensors are. Otherwise it becomes a game of, "Oh, there's a sensor!"

I think it's about being clear. But again with that unity, what are the goals? Is the goal about mystery? Is it to bring people in and experience it? So that they have enough time to feel embedded in this mystery.

That's right.

Earlier you were asking what our motivations were. There was one memorable experience that launched a whole sort of range of inquiry for us. At the 2010 Venice Biennale, we exhibited a series of columns that were hooked together with the sensors at the bottom. On these columns, there were 12 fronds that would raise up in sequence as you walked past the sensor. The sensors were not really hidden, but the intent was that they'd be far enough disconnected from the movement that they weren't obvious.

I was watching this one elderly Italian gentleman. He was leaning on his cane and he was walking through this thing and he stopped. He knew that they moved and he had understood enough about it that he knew that they moved in response to people being in the space. So he was waving, clapping, trying to figure it out, but it just would not move for him. Because he wasn't triggering a sensor.

Because he wasn't moving around.

That's right. And he got frustrated. As he turned to walk away his foot brushed in front of the sensor and one little frond moved. He turned back and he wagged his finger at it. It was just like they were anthropomorphizing the sculpture - it was the coolest thing!

People talk about it as having emotion. They talk about it as being scared or angry. Dana Kulić has launched a whole thread of investigation on how people

detect and discern emotion in movement. What could we do to intentionally convey certain emotions in this sculpture? Could we do anything or is the interpretive part of that movement so varied across people that there's no way you could communicate in a uniform way?

I've been speaking with Adam Francey, an electrical engineer, who has developed sensors to pick up emotions on people's faces in a very elegant way. It doesn't go inside; it is like little things that stick on the body. I thought it would be very interesting if he would bring his gear and do some testing on people. Francey can then help us to interpret the data of what people feel and so on.

That's very interesting to me. One of the objectives of the Toolbox project is to look at the difference in people's experience of a sculpture and if they've had a dialogue about it first. Depending on how much background they've got and whether they understand the conceptual basis for it, do they experience it differently? Part of that might be how they react to it emotionally as well.

Then it would help you to get data that is raw and unfiltered, instead of a series of questions.

Maybe. But part of the goal is that we can start taking advantage of the existing test beds in Salt Lake City.

We know that sound, music and color influence emotional state. One of Colin Ellard's early studies was, "Why a walk in the woods is calming?" In his lab he got a virtual reality simulator where he designed an environment that you could walk around in. He would measure your heart rate, skin conductance and all the autonomous nervous system signals. He did a controlled experiment where he gave people the same stress test ahead of time. For example, counting backwards by seven from a thousand while listening to heavy metal music. Then he put them into the simulator and charted their relaxation curve with and without the wind turned on. With the wind turned on, they relaxed faster, statistically speaking.

So it's not windy like a storm.

No. It was just a breeze. The speculation is that visual noise such as the leaves moving and the branches moving can unwind your mental state. The same way that some people fall asleep listening to white noise on the radio. There's this visual noise in the periphery that fascinates me. So there's the idea that movement also, and why not, can influence our emotional state.

I totally agree. But it's not just anything moving because when you're on a busy road, a movement of the car is unnerving.

That's right. But the movement of a busy car is not noise. If you think about the musical equivalence of the movement of a busy car, it's very rhythmic and it's very fast. Whereas the leaves, they are much like the static on the TV screen.

So it's a quality.

I would speculate that if we were to translate the car that is going by into musical sound, it wouldn't sound like white noise. It would sound like some kind of rhythmic something.

Yes, it feels more aggressive. Do you think the kind of movement you and Philip are trying to generate is more like the leaves moving?

It depends what we want to try to accomplish. If we want to calm people, I would argue probably that's what we should be aiming for. I'm not sure that we want to calm people. I mean I'm much more interested in trying to figure out how we could convey a range of emotions. Maybe one day we can read somebody's mood and temper or modify it.

We met some Health PhD students at the Eurpoean Graduate School in Switzerland. I think they would be really interested in researching this for mental health and therapeutic potentials. Some of them could participate in those experiments then try to interpret the results. The work I've done on responsive environments is really aimed towards making more healthy environments. I had this sort of pragmatic aspect despite my love for the art. But as an architect I feel it's a possibility.

As an engineer I feel that too. I love doing the work that we do with Philip. These big pieces that ask big questions take a lot of work to put up and then watching tens of thousands of people go through.

In 2010 I left Engineering and moved to a new program called Knowledge Integration. I had some new courses to teach and I became the Chair of my program. There are a couple of different threads that we're pursuing. One is working with TDI to test people's reactions to the sculpture, with Lucinda thinking about going into the classrooms. And it's tricky to figure out how to do it right. Because we've done a few, five or six different interventions in three or four different schools. And it's tricky to learn from the students. Because we're extensively measuring things like their ability to think creatively and solve problems - which is difficult to measure right without a very large sample population. It's hard to draw any conclusions about the impact of our work. Was it the workshop that we did? Or was this particular group of twelve kids just more creative? Was it something that the teacher did two weeks prior in class that primed them to be better at doing this? Or is it the fact that it's Waterloo Canada versus Salt Lake City versus Texas?

The way to deal with variables like that is to have very tightly controlled situations, which we can't in the schools, or to have very large sample populations where all of the variability averages out. And we don't have either of those things. For me it's very frustrating.

Do you think maybe the question needs to be refined?

I do. But I also think that no matter what you ask, it's going to be very difficult in that context to do anything more than anecdotal. You have no control group. Maybe with a better study design...

But could it be helpful to maybe have a small group and over a longer time?

It could be, and it'll tell you different things.

It seems from what you're saying that it's self-evident in a way that they are going to feel creative. That's why I am thinking a question needs to be asked there.

Yes. There's something else that I'm very excited about. Trevor Haldenby has proposed to do science fiction prototyping. He would get people to interview LASG members and write some speculative fiction about the future of architecture. It serves two purposes. One as a way to help us as a group reflect on what we're doing, so there's an internal kind of reflection that happens that is a process.

So fiction is actually writing stories?

Yes. There’s a guy at Intel who started this idea of science fiction prototyping using narrative and storytelling and allowing the brain to go outside the realm of the possible to think about what could be.

It’s a huge tradition in architecture - think about utopia! By definition architects draw something that will happen the future. It really started big during the French Revolution in the 18th century when they wanted to try to imagine another world. So architects and urban designers would draw up these amazing cities and buildings. And they used them as sort of motivation for what we could do. To have people dream of the future.

So, we’re connecting to the origin of smart cities charettes.

I think that’s one of the big things that distinguishes architects from being just builders—being able to imagine something that doesn’t exist.

Yeah, that’s a really interesting way of putting it. And then the other goal of that is to actually produce a story that uses the language of living architecture and might then be out in the public to help disseminate and make that connection to our work.

Formally trained as an electrical engineer, Rob Gorbet is an interdisciplinarian, a mechatronics specialist, an award-winning teacher and a technology artist. Rob’s teaching has included courses on the profession of engineering, microcontrollers, robotics, control systems, technology art and museum exhibit design. His engineering research involves the design of actuators made of Shape Memory Alloys (SMA), for everything from car door locks to subtle next-generation actuation systems for responsive architectural environments.

Rob is a key member of Gorbet Design, a design firm and consultancy specializing in public interactive artwork and experiences, and also collaborates with other designers, artists and architects. As a Professional Engineer and Associate Professor, Rob Gorbet chairs an innovative integrative curriculum development and technical research program in computation and mechatronics at the Department of Knowledge Integration, University of Waterloo. An award winning teacher and artist, Gorbet’s unique interdisciplinary expertise includes knowledge integration, mechatronics and complex interactive systems. Gorbet leads the Interdisciplinary Methods research stream in developing conceptual paradigms, curriculum models and design methods.

A Reflection on Complexity *with Dana Kulić*

Sarah Bonnemaison

Organicism is very interesting. On the one hand, it is a philosophy of aesthetics that describes a way to learn from nature, to invent and create beautiful objects. Organicism also covers another trend of thoughts in the sciences that is still relevant today. It is a way of thinking about systems that builds one system on the next in increasing complexity. You work with Philip Beesley to build beautiful things, yet you have your own method of working, so I am interested to know how you think it relates to organicism.

Dana Kulić

Actually when I was reading the text about organicism and embryology, I thought it was interesting because it very much connects to some of the discussions that have been going on in robotics, and also in other research on autonomous agents and systems. When we are developing a control algorithm for controlling and directing many robots, should that system be centralized so there is one central master agent that is directing the activities of all of the agents, or should the system be decentralized so that each agent has their own control algorithm and some methods of communication, so that through those individual actions and the communications, a group behaviour emerges automatically? Researchers who have been proponents of this kind of distributed method have been very much inspired by biology. A few notable inspirations are ants and bees. These are very simple insects. Each individual has a small brain with limited capability, yet through communications between the agents the group can generate very complex behaviour, and very complex structure building can emerge.

And of course, learning from nature can take place at different levels of abstraction. We can think of learning from nature right at the neural level. Some researchers are trying to replicate exactly the brain's computational structure at that neuron level, creating computational models of the brain. There is a very famous researcher here at Waterloo, Chris Eliasmith, who is developing and testing such models. Other researchers are taking the inspiration from nature at a higher level, at a more functional level. Artificial agents and robots don't have the same neuronal structure as the biological system but we wish to implement the same or similar functionality. Instead of having neurons, robots have some programed behaviours that are implemented in silicon. There aren't neuron per se, but still, the kind of behaviours and the kind of communications are designed to emulate what we observe in the natural system.

In your work, are you trying to analyze something in nature and trying to copy it? How do you work?

So this question of centralized versus distributed is actually something we have been investigating in our collaboration with Philip. When you observe these systems, one of these installations, you can conceive of it as being a single entity. But because it is spatially distributed and consists of many different elements, you can also conceive of it as a group of agents, as a group of individuals that are grouped together in a kind of a forest. Both of these are computationally possible. When we are thinking about how do we design an algorithm that will control the behaviours of this system, we can design a centralized algorithm where you have a single algorithm that observes all of the sensors of the system. Based on that observation the centralized algorithm generates actions of the system, acting like a single entity. On the other hand, you can also conceive of the system as a group of agents, then you have a separate controller that only uses the sensor data of that single agent; it only controls the action of that single agent. And then you have some communications between the agents to create coordinated behaviours. It is something that we are very much investigating within the context of the work of LASG.

I spoke with Philip recently about the one that he is building right now, *Amatria*. He said it is more centralized.

Yes. But there are different ways of thinking about centralization. You can think about centralization at the implementation level, and centralization at the functional level. When you have a centralized system, one advantage is that the single agent has access to all the information. It can make the best decision because all of the information is available. It can make a globally optimized decision. On the other hand, having a centralized agent introduces a big potential failure mode. Because if the central agent fails, the whole thing is dead. When you think about it in terms of an exhibit, it is a big risk because you don't want to have a case where all of a sudden, you have the room full of visitors and the system is just not working.

Yes, it's like having only one plug.

Exactly. Now on the other hand, when you have a decentralized system, the advantage is that if any one of the agents, or units fails, it is almost imperceptible to the observers because everything else continues to operate. Two or three actors might not be operating, but you don't notice. Because the other agents are continuing to operate, it might appear that the failed agents are just in idle mode right now. But on the other hand, you have these additional costs because no one agent has all the information, so you have additional communication architecture that you require. You need to have these individuals communicating with each other – and that's a cost.

And also visually. There are a lot of little wires. Like a lot of guts – so to speak.

Exactly. And then maybe the decisions you make are not optimal because no agent has all the information. Every agent is just making a decision for itself locally but there is no guarantee that this local decision making will lead to a globally optimal decision. I should mention that part of the wiring is also to provide power.

With the system that we've been investigating, because no design is a clear winner – both designs have strengths and weaknesses – we are hedging our bets. We have the capability to implement both centralized and decentralized systems. We have a centralized system, and all of the wiring that supports all the data coming to a central server where it's been processed, and all of the command messages come out from that server. But then in each node, we also have local capability. So if the local system is disconnected from the central system, it can still operate autonomously. It doesn't just hang there doing nothing. The current system is kind of a hybrid.

Another advantage of having a central system, particularly with the new Indiana University installation *(Amatria)*, is the collaboration between the information science researchers who want to be able to visualize all the information that is happening in the system. This kind of data logging is facilitated if you have a central server where all the data is coming in, and then you can log it from there. That's also part of the reason in the Indiana system we have a centralized architecture, but the design of the architecture is actually flexible. We can have a decentralized system where the only centralized part is the data logging. The actual interactive behaviours and online interaction are decentralized. That is possible with the architecture that we're building.

Could you find the parallel like that in nature in this hybrid system? For example, the bees – if the Mother Bee dies, the whole thing is over.

The tendency is more towards decentralized systems, because decentralized systems tend to be more resilient. In nature, organisms are optimized for being resilient. Whereas since we're designing artificial systems, usually what we do is that we control environments very carefully, so the need for resilience is lessened.

Maybe a good example are organisms that live in protected environments. They lose their defensive capabilities because they are not required. Then when you have invaders, usually introduced by human visitors, that ends up in a bad outcome for those organisms.

Actually, I think humans are sort of like that. We are not as skilled as we used to be at defending ourselves because we are so protected. We could argue there are different levels. One is about the network, and your data collecting is about memory.

Exactly. The third advantage of a centralized system is ease of maintenance. For example, if we want to update our software implementation in the algorithm, having a centralized system would allow us to upload the software to the all of the nodes simultaneously. This is much easier in a centralized system.

I think your hybrid system sounds very interesting. How would you compare this with the article that you just read?

I'm very much on the side of the organicists in the debate. The kind of behaviours that can emerge from individuals collaborating is something that cannot be observed from the behaviour of a single individual. We see that also in some of the experiments that we have done with distributed systems. We implemented this version of a learning agent. Comparing our current robotic system to nature, one of the things that robotic systems and artificial systems lack is the ability to evolve, to improve, to repair, and to regain functionality over time. If you think about each individual bee, each individual ant, they get injured during their activities and they recover. They might learn where the new interesting food source is. Not just learn that for themselves, but also convey that to the rest of their group.

What we've been working on is this idea of imbuing each agent with a learning mechanism, so it can learn over time. We have each agent learning, and then we have some communication between the agents. So how does that impact what they learn, and how does the behaviour of the system as a whole evolve?

It turns out this communication is very important. If you don't have communication versus having some kind of communications, the evolution of the whole system looks very different. This is something very much on the side of the organicists. In our simple experiment, you get behaviours when you have communications among the individuals. You get behaviours that you would not observe, if you just have individuals that do not communicate with each other.

So, what happens when they don't communicate? Do they just keep the information for themselves? They keep on making the same mistake?

Just to give you an example, imagine one of Philip's installations. You have a person walk into the space. Each system in the installation is a learning agent, and it's been learning the relationships between its inputs and its outputs. What it learns when there is no visitor in the scene is the very simple relationship. If I turn the light on, my light sensors will be brighter. If I move my shape memory alloy, I will see a change in movement in the accelerometer. And no matter what I do, the infrared sensor which is sensing the presence of occupants will not change in value. Now a person walks in, and all of a sudden all of those models become violated. Because now the person is modifying the values of the proximity sensor. Now they move closer and further from the system. And if they touch the sculpture, they are changing the readings on the accelerometer, which wasn't happening before.

To learning agents, this is now a huge opportunity to learn. It starts generating actions to try to understand the new state of the environment when the visitor is present. If you have no communications between the agents, then only the agent that is nearby the person is involved. Because to all of the other agents, everything looks the same. When you have communications between agents, now the agents that start learning start communicating to their nearby agents. The neighbours are then also receiving new information, so they also start generating new behaviours. And now the visitor's interest might be also attracted not to this agent but to the nearby agent that is also activated. As a result, you have emergent behaviours between the agents and the visitors. Because the visitors might draw their attention to the nearby agent, might walk over there. So what you learn is different, how these systems behave is different, the entire evolution is very different when you have communication versus no communication.

It's something that we experiment with to find out what the best architecture is. We've experimented with spatial neighbours, functional neighbours, or just random neighbours. What we found with some preliminary experiments was that for visitors, the spatial one seemed to be the most interesting. It gave the impression of something coherent. First you are here, then the thing that was right in front of you would respond, and then the neighbouring things would respond. This looks very similar to some of the things that Philip has implemented as preprogrammed behaviours where you see this rippling outwards. However, we didn't preprogram that. That was an emergent behaviour from having this group of individuals, each with their own algorithm and communicating with each other.

Each algorithm is the same. But it is a learning algorithm, so it's possible that different agents learn different things even though they would be running the same learning algorithm. A good example would be when you have an agent located right in the centre of the sculpture where there would be a lot of traffic. They might learn something different from agents somewhere in the corners that might not be accessible to people. So, no matter what this thing does, because people can't actually walk over there, it won't cause people to stand nearby because it is not accessible versus one that can attract people to stand nearby, which will learn different things. It is very much something that you can observe in biology; if you think about children, they learn based on the environment that they are in. If you have a baby who has English parents, that baby will learn English. A baby who has French parents will learn French. Just because that is what they are exposed to in their environment.

My main research question is, how can we develop systems that can be autonomous over the long term?

And in that respect, this idea of complexity is interesting. I don't think it is a straightforward matter of the longer you survive, the more complex you get. Certain environments foster complexity, and certain other environments degrade complexity. So if you have a very severe environment where it is harder to survive, then complexity is lessened. But if you have a very nurturing environment, then greater complexity can emerge. If you want to have a system that can survive for a long time, it needs to be able to modulate its complexity based on how much support there is in the environment.

In this installation, there are regions that are simpler while some are more complex, where there is more foot traffic from visitors. Are you interested in having anything react to the larger environment? Like the movement of the sun moving, the moon?

Yes, I am always pushing for more sensors. But of course, sensors are expensive. But this is exactly my idea, we want the system to learn not just from the human interaction but also from everything in the environment. Lots of the sensors, for example, the ones that can sense both the light generated by the sculpture itself (so in that sense it is a proprioceptive sensor) and the light changes in the environment. If the system is installed in a place that has natural light, you can sense the changes between daytime, nighttime, sunny day, cloudy day.

The same thing for microphones – of course you will hear the sound of people speaking. If you have an outdoor installation, you will hear the sound of the wind through the sculpture. I think that would be something very beautiful and something that could open the door to new emergent behaviour. Maybe if it's very windy, maybe you want to keep the fronds closed in, so they don't get damaged. And if it's not windy, you can open them up. Wind, for example, can be sensed by the accelerometer because the wind moves the system. All of these learning algorithms, they are learning the relationship between the sensors and the actuators. It is really kind of agnostic to the environment – anything that can cause a change in perception can be used as signals for learning.

Dana Kulić received the combined B. A. Sc. and M. Eng. degree in electro-mechanical engineering, and the PhD degree in mechanical engineering from the University of British Columbia, Canada, in 1998 and 2005, respectively. From 2002 to 2006, Dr. Kulić worked with Dr. Elizabeth Croft as a PhD student and a post-doctoral researcher at the CARIS Lab at the University of British Columbia, developing human-robot interaction strategies to quantify and maximize safety during the interaction. From 2006 to 2009, Dr. Kulić was a JSPS Post-doctoral Fellow and a Project Assistant Professor at the Nakamura-Yamane Laboratory at the University of Tokyo, Japan, working on algorithms for incremental learning of human motion patterns for humanoid robots. In 2009, Dr. Kulić established the Adaptive System Laboratory at the University of Waterloo, Canada, conducting research in human robot interaction, human motion analysis for rehabilitation and humanoid robotics. Since 2019, Dr. Kulić is a professor at Monash University, Australia. Her research interests include robot learning, humanoid robots, human-robot interaction and mechatronics.

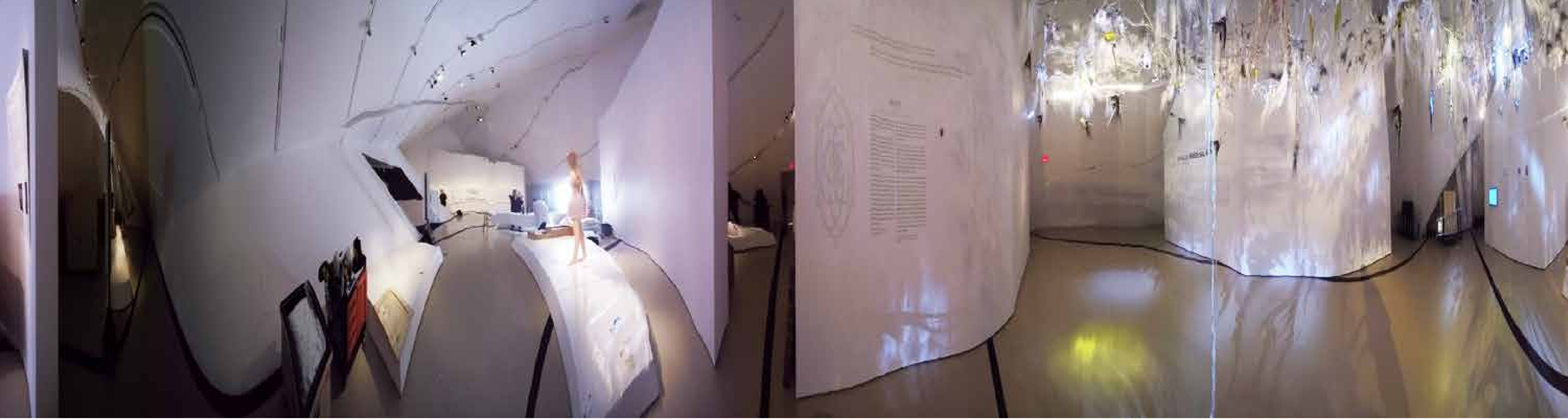
In Theoretical Physics
PB, IvH, and the LASG

Michael Awad
Artist, Architect and Independent Academic, Toronto, Canada

Michael Awad is an artist, architect and independent academic. His experimental photography has shown at three public exhibitions: The PowerPlant (2001), the Art Gallery of Ontario (solo 2005), and the Royal Ontario Museum (solo 2014). His photographic commissions include the City of Toronto (currently displayed in Mayor John Tory's office), the Schulich School of Business at York University, Pearson International Airport, Telus House, St. Josephs Media, the ROM, the AGO, the Canadian Consulate of Chicago and currently The McMichael Gallery. In 2002 Awad's experiment urban photography was selected to represent Canada at the Venice Architecture Biennale. His university studies included theoretical physics, mathematics, computer science, architecture and urban design. He holds three professional degrees from The University of Toronto (two) & Syracuse University (one). He has taught analogue & digital photography, video production, computer programming, robotics, media art and architectural design at the University of Toronto School of Architecture, and recently cultural planning policy in the School of Urban Planning at Ryerson University. Awad's public art received a Toronto Urban Design Award in 2011, He served on selection juries for all three levels of government,& he is currently the Co-Chair of the InterAccess Media Art Centre.

In theoretical physics, proof of concept requires years of applied trial and error.

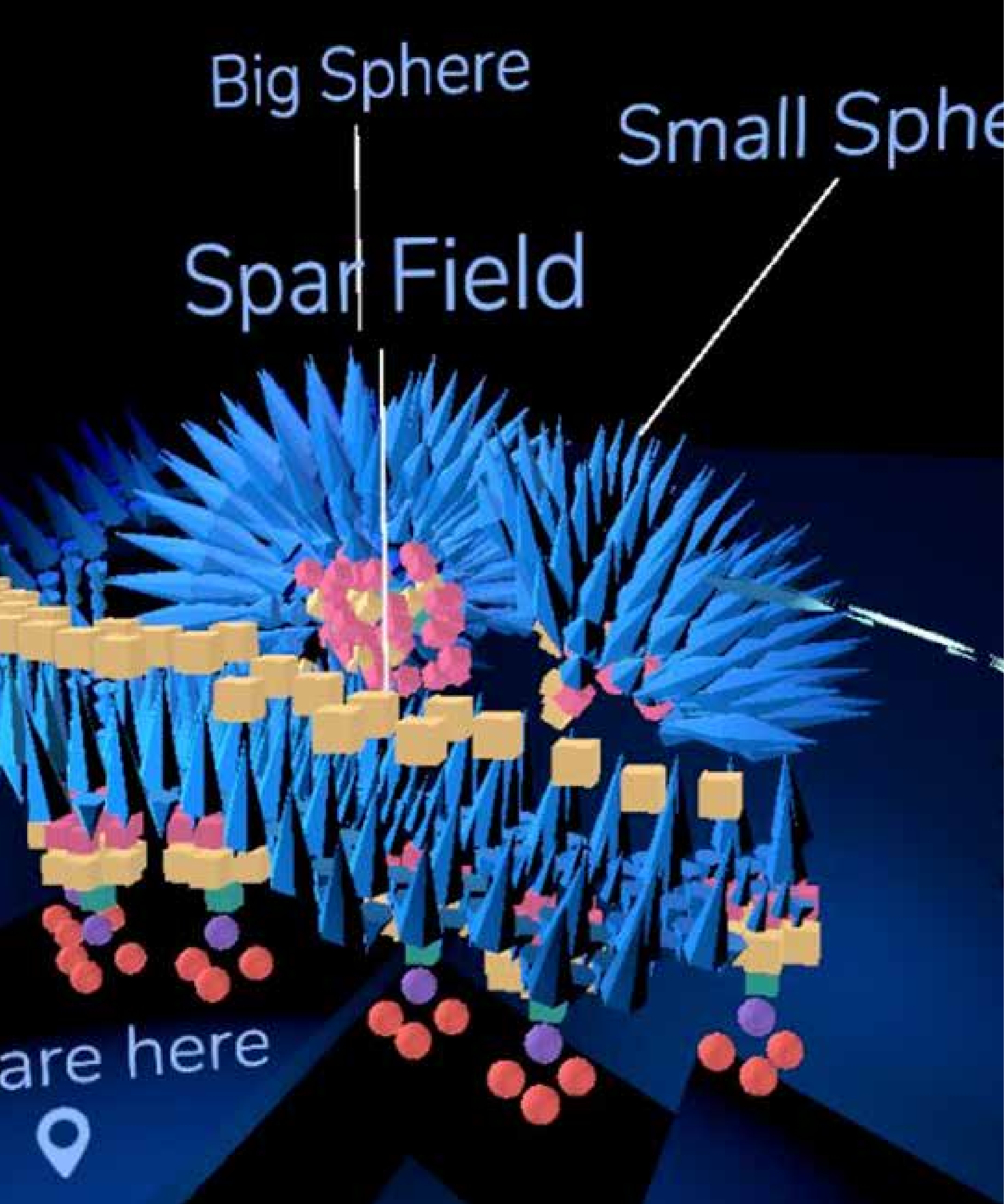
It was 55 years after *General Relativity* when the first black hole was discovered.



It took 48 years to confirm the actual existence of the Higgs Boson particle.

Experimental architecture based on living systems will also require several

generations of technological advancement to fully manifest as Living Architecture.



Envisioning Intelligent Interactive Systems

Data Visualizations for Sentient Architecture

Katy Börner & Andreas Bueckle
Indiana University, Bloomington, USA

Cover Image Tavola, scene 1: *Amatria* overview.

This paper presents data visualizations of an intelligent environment that were designed to serve the needs of two stakeholder groups: visitors wanting to understand how that environment operates, and developers interested in optimizing it. The visualizations presented here were designed for *Amatria*, a sentient sculpture built by the Living Architecture Systems Group (LASG) at Indiana University Bloomington, IN, USA, in the spring of 2018. They are the result of an extended collaboration between LASG and the Cyberinfrastructure for Network Science Center (CNS) at Indiana University. We introduce *Amatria*, review related work on the visualization of smart environments and sentient architectures, and explain how the Data Visualization Literacy Framework (DVL-FW) can be used to develop visualizations of intelligent interactive systems (IIS) for these two stakeholder groups.

1. Introduction

Increasingly, our everyday environments are becoming smarter and more connected. IIS is an umbrella term to describe environments that can process data and generate responsive behaviors using sensors, actuators, and microprocessors in order to bridge the gap between humans and machines (1, 2). Sentient architecture implements IIS through artful, imaginative, and engaging architectural artifacts with which we can experiment and observe human behavior and capabilities when confronted with IIS (3, 4). Due to the transformation of the physical environment achieved through scaffolds, sensors, actuators, and microprocessors, new experiences are possible for humans inhabiting these spaces.

Image 1 ***Amatria*** Philip Beesley (Bloomington, Indiana, 2018).

Amatria is one such sentient architecture piece on display in Luddy Hall at Indiana University.[1] Foreshadowing a future where the Internet of Things (IoT) is omnipresent, *Amatria* stands as an artful interpretation of a data-driven environment adapting to what it senses about its physical surroundings. She demonstrates how IoT technologies can affect humans—be it with amazement, unease, mystery, or curiosity. Luddy Hall is a 124,000-square-foot public school building, visited by hundreds of students, faculty, staff, and external guests every day for work, study, talks, and conferences.[2] Conspicuously placed on the fourth floor of Luddy Hall overlooking the atrium, *Amatria* is not simply a piece of art seen by hundreds of eyes every day; more significantly, *Amatria* is embedded into the lives of students, faculty, and staff who strive to develop self-driving cars, explore the social aspects of machine learning, or engineer next-generation robots. In short, *Amatria* embodies a future rich with data where machines and humans live and work together.

1 "Amatria: Sentient Architecture," Cyberinfrastucture for Network Science Center, https://cns.iu.edu/amatria

2 "Luddy Hall," Indiana University Bloomington School of Informatics, Computing, and Engineering, https://www.sice.indiana.edu/about/luddy-hall.html

The presence of *Amatria* raises the question of how her human cohabitants perceive and understand her. *Amatria* tours have introduced her to elementary children, retirees, invited speakers, advisory council members, wealthy donors, and the president of IU. In order to enrich the experience of each of these stakeholder groups, it is essential to understand their insight needs, meaning what information these groups need to enhance and/or satisfy their interest in the sculpture.

This paper presents research and development efforts on data visualizations that facilitate the communication and exploration of IIS in the form of sentient architecture such as *Amatria*. First, we will introduce related work on the visualization of IIS, and on sentient architecture. Second, we will explain how the Data Visualization Literacy Framework (DVL-FW) can be used to develop visualizations of IIS for two stakeholder groups: visitors and developers. Specifically, we will introduce the Tavola (Italian for "table") 3D visualization for visitors along with two graph-based visualizations for developers, plus informal user study results that informed the current version of Tavola. Finally, we will discuss lessons learned and planned future work.

2. Related Work

2.1 Visualization for IIS

Previous research on data visualization for IIS is diverse and broad, but a common goal across many lines of research is to provide insights into the observed system, necessitating visualization as an integral part of the system architecture. Common challenges identified in the literature are: system infrastructure, data acquisition, and end-user usability.

Roalter et al.[3] implemented a "Cognitive Office" using the Robot Operating System (ROS)[4] as middleware between a physical office space and a virtual model of it, allowing users to view temperature, humidity, and other data in a 3D model in real time. On the other hand, Jeong et al.[5] opted for a web-based IoT framework and WebGL[6] to allow users to control a virtual home.

3 Roalter, Luis, Matthias Kranz and Andreas Möller. "A Middleware for Intelligent Environments and the Internet of Things." International Conference on Ubiquitous Intelligence and Computing, (Berlin/Heidelberg, Germany: Springer, 2010), 267 - 281.

4 ROS http://www.ros.org

5 Jeong, Yuna, Hyuntae Joo, Gyeonghwan Hong, Dongkun Shin and Sungkil Lee. "AVIoT: Web-based interactive authoring and visualization of indoor internet of things." IEEE Transactions on Consumer Electronics 61.3 (2015): 295 - 301.

6 "WebGL: 2D and 3D graphics for the web," MDN web docs, https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API

While the former developed their setup alongside a physical space, the latter simulated input and output of their system, i.e., sensation and actuation, in code only. Furthermore, they presented a two-way communication solution where an end user can both monitor the system and send commands to it. In a user study with 24 participants (14 of whom had some experience in programming), they compared two modes of authoring actions: text-based and visual. They found that user satisfaction, user understanding, user efficiency, and user preference are significantly greater for the visual programming mode. In the area of health management, Hassanalieragh et al.[7] surveyed health monitoring frameworks, particularly noting the need for comprehensive, integrated solutions as a result of the increasing availability of wearable sensors and their data. Similarly to Jeong et al.[8], they emphasize that visualization is needed for end-users (physicians, in this case) to gain actionable insights from heart rate and blood pressure data. Belimpasakis et al.[9] propose a framework for home entertainment using augmented reality, employing cell phone cameras as an interface through which a user can have a two-way communication with an IIS. SensMap[10] features an outdoor view, an indoor view, and a topological view of sensors in a building. This allows the user to view sensor location and data, and link quality to other sensors on a Google Maps basemap in different levels of detail to facilitate data interpretation. As opposed to Raolter et al.[11] and Jeong et al.[12], SensMap uses 2D visualizations only.

Existing visualizations of IIS data help a broad range of stakeholders understand data streams. What's needed now, however, is a method for systematically designing such visualizations. In this paper, we aim to provide guidelines for designing effective data visualizations that empower different stakeholder groups to explore and optimize IIS.

2.2 Sentient Architecture

Sentient architecture is a type of interactive art. Various approaches from different disciplines exist, including architecture, robotics, and data visualization. In their *Hylozoic Ground* series, Beesley et al.[13] investigate if and how architecture can be perceived as alive by visitors. Building on this, and interested in creating such life-like behaviors, Chan et al.[14] detail the Curiosity-Based Learning Algorithm (CBLA) that implements Intelligent Adaptive Curiosity, as described by Oudeyer et al.[15] As the purpose of CBLA is to increase a system's behavioral adaptivity through self-experimentation, the team presented a prototype interactive sculpture featuring an implementation of CBLA using Teensy microcontrollers with ambient light sensors, IR sensors, and accelerometers alongside LED lights and kinetic actuators. Subsequently, Chan et al.[16] tested interactions between human subjects and the testbed. In a user study with 10 participants, they created two test conditions: one with pre-scripted behaviors for the testbed, the other one with CBLA running, switching between modes halfway through the experiment. Performing a quantitative analysis, they found no significant difference in self-reported interest score by the participants between the conditions and noticed only a weak correlation between average activation value and participant interest level. Elsewhere, Börner et al.[17] presented *Lifting the Veil*, a 3D visualization of the *Sentient Veil* sculpture in the Isabella Stewart Gardner Museum in Boston, MA, USA. The purpose of the work was to apply data visualization to sentient architecture in order to satisfy visitor insight needs and help them identify the structure, dynamics, and state of a sentient architecture piece. This work also informed the research and development in this paper.

We consider sentient architecture an instantiation of IIS where two stakeholders exist: visitors who consume (and hopefully enjoy) the art piece, and developers (usually engineers or architects) who build and maintain it. In the following chapter, we will present the various data visualization types implemented for *Amatria*, and we will detail how theory from the DVL-FW was applied during every step of development for each stakeholder group.

3. Sentient Architecture Visualizations

The development of Tavola, a 3D tool for visualizing *Amatria's* structure and data flow (see *Images 4 - 5*), was guided by a visualization framework, which we will detail in the following section. But the story of Tavola's creation is also the story of close interdisciplinary collaboration between architects, engineers, software developers, designers, and visualization experts, highlighting the diverse skill requirements needed for data visualization in IIS and in general.

Visualizations usually support two different paradigms of functionality: communication and exploration. Communication refers to instances where visualizations convey insights from data upon which a user can act in an informed manner (such as polls on the news or graphs in a textbook). Exploration, on the other hand, refers to an iterative process where insights from one

7 Hassanalieragh, Moeen, Alex Page, Tolga Soyata, Gaurav Sharma, Mehmet Aktas, Gonzalo Mateos, Burak Kantarci and Silvana Andreescu. "Health Monitoring and Management Using Internet-of-Things (IoT) Sensing with Cloud-Based Processing: Opportunities and Challenges." 2015 IEEE International Conference on Services Computing, (Washington, DC: IEEE Computing Society, 2015), 285 - 292.

8 Jeong et al, "AVIoT: Web-based interactive authoring and visualization of indoor internet of things."

9 Belimpasakis, Petros and Rod Walsh. "A Combined Mixed Reality and Networked Home Approach to Improving User Interaction with Consumer Electronics." IEEE Transactions on Consumer Electronics 57.1 (2011):139 - 144.

10 Simek, Milan, Lubormir Mraz and Kimio Oguchi. "SensMap: Web Framework for Complex Visualization of Indoor and Outdoor Sensing Systems" International Conference on Indoor Positioning and Indoor Navigation (Washington, DC: IEEE Computing Society, 2013), 1-5.

11 Roalter et al. "A Middleware for Intelligent Environments and the Internet of Things."

12 Jeong et al, "AVIoT: Web-based interactive authoring and visualization of indoor internet of things."

13 Beesley, Philip, Rob Gorbet, Pernilla Ohrstedt and Hayley Isaacs. Hylozoic Ground: Liminal Responsive Architecture (Toronto: Riverside Architectural Press, 2010).

14 Chan, Matthew TK, Rob Gorbet, Philip Beesley and Dana Kulić. "Curiosity-Based Learning Algorithm for Distributed Interactive Sculptural Systems." International Conference on Intelligent Robots and Systems (Washington, DC: IEEE Computing Society, 2015), 3435 - 3441.

15 Oudeyer, Pierre-Yves, Frédéric Kaplan, and Verena V. Hafner. "Intrinsic Motivation Systems for Autonomous Mental Development." IEEE Transactions on Evolutionary Computation 11.2(2007): 265 - 286.

16 Chan, Matthew TK, Rob Gorbet, Philip Beesley and Dana Kulić. (2016) "Interacting with Curious Agents: User experience with Interactive Sculptural Systems." IEEE International Symposium on Robot and Human Interactive Communication (Washington, DC: IEEE Computing Society, 2016), 151-158.

17 Börner, Katy, Andreas Bueckle, Philip Beesley and Matthew Spremulli. "Lifting the Veil: Visualizing Sentient Architecture." Future Technologies Conference (Vancouver, Canada: 2017). acc Jan 22, 2019 https://cns.iu.edu/docs/publications/2017-Lifting-the-Veil.pdf.

visualization lead to questions in need of more insights. Exploratory data analysis, for example, is the process of descending into a dataset by means of multiple visualizations to uncover new questions. Communication is certainly a function of Tavola, particularly in its ability to reveal the hidden structure of *Amatria* to the untrained eye. But even more significant is Tavola's ability to encourage *Amatria*'s visitors to explore the sculpture more deeply. Tavola lifts the seemingly impenetrable veil of technology for untrained visitors, drawing them into the experience of interacting with a sentient sculpture made out of acrylic, sensors, and microprocessors, forming a coherent and highly technical art piece. In summary, the main goal of Tavola is to encourage visitors to leave their comfort zone and peek ever so slightly behind the curtain of high-tech.

3.1 DVL-FW – Typology and Workflow Process

Our development of sentient architecture visualizations followed the Data Visualization Literacy Framework (DVL-FW) introduced in the *Atlas of Knowledge*[18] and detailed in a forthcoming paper. The DVL-FW is based on an extensive review of literature from more than 600 publications documenting 50-plus years of work by statisticians, cartographers, cognitive scientists, visualization experts, and others. The DVL-FW process model is shown in Image 2.

The visualization process starts with investigating the insight needs (sometimes also called "task types") of one or multiple stakeholders. Insight needs dictate which data is to be acquired, what analyses need to be made, and what visualization types are to be chosen. Understanding one's stakeholders is essential to creating a visualization with actionable insights. Operationalization is needed to guide both data acquisition and the requirement for data cleaning and refinement that comes with it. Analysis then allows the developer of a visualization to reveal patterns and trends in the data, and to refine insight needs and associated questions to the data. Only after these steps are completed can the actual visualization process start. The developer chooses one or multiple visualization types, such as table, chart, graph, map, or network.

Deployment refers to the act of exporting a visualization to a particular medium, such as a piece of paper, a touch screen, a 33-million-pixel video wall, or a virtual-reality headset. Deciding which method of deployment to use is often done early on in the process as some media offer affordances

18 Börner, Katy. Atlas of Knowledge: Anyone can Map (Cambridge: MIT Press, 2015).

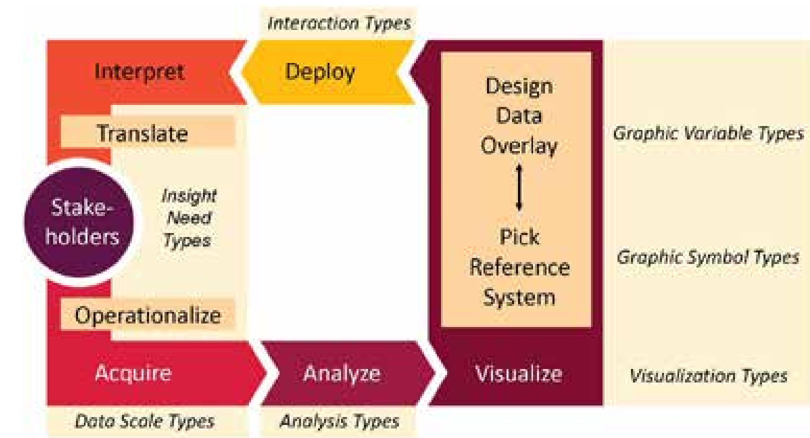


Image 2 Data Visualization Literacy Framework (DVL-FW) process model.

more suitable to satisfy user insight needs. For example, visualizations deployed to paper are usually static, fit within a standard book page, and feature annotation in close proximity. Touch screens or keyboard-mouse interfaces, on the other hand, allow users to manipulate their view of the data, or even the data itself. Interactions with data visualizations are only possible if an input device is available and the visualization can receive input in the first place. Interpretation, finally, requires stakeholders to assess what insights can be gained from the visualization with regards to the originally identified insight needs. Very often, results of this interpretation are communicated with a write-up or in annotations to the visualization. After the interpretation is completed, the workflow begins again.

Due to its iterative nature, the DVL-FW process model captures repetition and refinement of insight needs and data visualization not only for the whole series of workflow process steps but also for cycles between just a subset. For example, developers might acquire data based on a perceived insight need, analyze it, and realize that the dataset is not a good fit to provide answers to the stakeholders' questions—in which case they will likely ask for different data. Similarly, developers might deploy a dynamic visualization and realize that it could be enhanced by adding a second, static visualization. They would then revert to the "Analyze" step to prepare a new chart, graph, map, etc.

3.2 Stakeholders and Insight Needs

While the different stakeholders are quite diverse, we can identify two main groups for which we discuss visualization work here: visitors and developers. Visitors are individuals either unfamiliar with sentient architecture in general, or *Amatria* in particular, who come to the sculpture either on purpose (such as for a tour) or by chance. Developers are engineers or architects who are interested in how to debug or improve a sentient architecture sculpture.

As outlined in the DVL-FW process model, identifying the rather different insight needs for both types is an essential first step in the DVL-FW process model. While our visualization tool Tavola is primarily geared towards visitors (see section 3.4.1), the data collected in the development process can also be used by developers for debugging purposes (see section 3.4.2).

In order to provide value for visitors, Tavola aims to empower them to explore physical and imaginary spaces. This is called *geospatial* exploration, a superset of various insight needs usually satisfied with maps. Tavola presents geospatial information from *Amatria* in a 3D map layout. Maps are among the oldest, most established, and most readable types of visualizations, and Tavola enables visitors to explore *Amatria* as a physical space. Another insight need addressed by Tavola is *comparison*, which we achieve by adding a real-time element that shows the consequences of a visitor's interaction on *Amatria*. In this iteration, Tavola separates these two insight needs and presents them in different scenes. Finally, Tavola can also be used to identify *trends* over time, albeit in small units.

Developers, as the second stakeholder group, need to make sure each sensor and actuator functions properly by *comparing* expected and observed values and behavior. To that end, we developed a real-time bar graph visualization (see section 3.4.2, *Image 9*) for on-site comparison of IR sensor values. However, developers are also interested in monitoring behavior *trends over time* in order to find bugs, optimize code, and create improvements based on observations. To this end, we used the same real-time data to develop a graph showing IR sensor values over a 24-hour period (see *Images 7 – 8*). As the preceding discussion illustrates, it is quite common in the process of data visualization to find that different stakeholder groups are best served by different views of the same data.

3.3 Data: *Amatria* Setup, Software, Networking

In the previous subsection, we investigated insight needs for visitors and developers. This subsection discusses the data acquisition required to implement visualizations for both stakeholder groups.

To satisfy visitor *insight need geospatial*, a highly detailed parametric model of *Amatria* was shared with the Tavola team. While the original *Amatria* 3D model featured hundreds of thousands of individual pieces, the simplified model was reduced to primitive shapes and 3D objects to represent only the scaffold of *Amatria*, significantly decreasing the performance requirements for whatever target device Tavola would run on. Since *Amatria* took several weeks to install, and since the venue was on the same floor as the offices of the Tavola team, hours of close cooperation and informal exchange were possible. The *Amatria* team helped us understand and prepare for visualization both the model and the real-time data stream (see *Image 3*, right); additionally, close onsite collaboration during the installation process allowed the Tavola team to gain valuable insights into how *Amatria* functions before it was even finished. Tavola uses the *Amatria* model in two capacities: as a whole, embedded in an additional 3D model of Luddy Hall (also developed by the *Amatria* team based on blueprints from the architects of the venue), and as more high-resolution subset of the model with only parts of the sculpture visible. Planes with opaque material were inserted to replace the transparent walls in the Luddy Hall model, and a highly eclectic, ambient deep-blue light was added to set the building into the background and focus the user's attention on the sculpture (see *Images 4 – 5*).

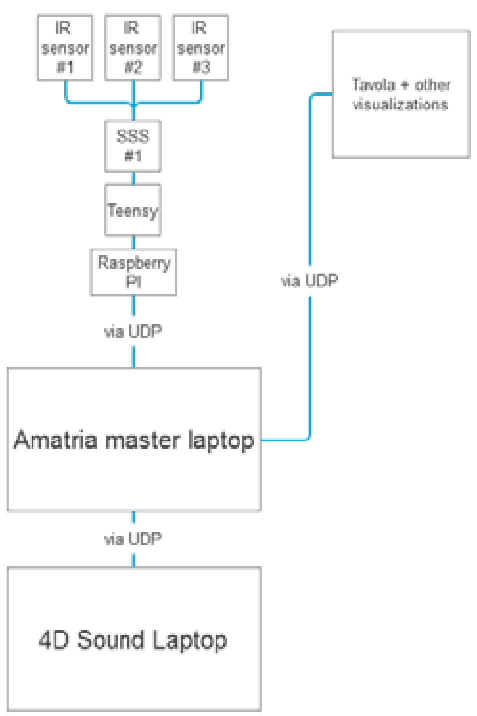
In order to satisfy *insight need comparison* for both visitors and developers, state information about parts of the sculpture needed to be made available for visualization. IR sensor data was chosen to be streamed from *Amatria* to Tavola by means of universal datagram protocol (UDP). The master laptop (see *Image 3*) sends commands, retrieves sensor information, and transmits data values to a set of specially assigned IP addresses on the *Amatria* virtual local area network (VLAN). A device running Tavola will get one of these IP addresses upon signing into the network, then receive and parse the data stream. Note that in the current implementation of Tavola, no data is shared about other hardware such as the Raspberry Pis[19] and Teensy node controllers[20] that are an integral of *Amatria's* data infrastructure (see *Image 3*).

19 Raspberry Pi https://www.raspberrypi.org/

20 "Teensy USB Development Board." PRJC. https://www.pjrc.com/teensy/

Specifically, Tavola runs a C# script, creating a UDP client that listens to incoming messages. The master laptop sends out values for all 18 IR sensors at three values per message, with a frequency of 2 Hz. This results in 12 messages per second. The values are packed into a string message and then received in Tavola, where the values are parsed at runtime.

The values arrive in bundles of three because each message contains data for all IR sensors on an individual sound sensor scout (SSS), a distinct part of the sculpture that carries multiple sensors and actuators. Thresholds are set for each IR sensor, which, when reached, trigger a neighbor behavior where the IR sensor's SSS plays a scripted sequence of actuations. Subsequently, the neighboring SSS perform the same action until the actuation wave has reached the outermost SSS (#1 and #6). SSS #1, specifically, is the focus of scene 2 in Tavola (see *Image 5*). The message format is to be interpreted the following way: "b" is a prefix added by the Python shell




```
b'TV/TRIGGER/SSS2/105/4/1'
b'TV/TRIGGER/SSS5/207/1/1'
b'TV/TRIGGER/SSS4/163/0/0'
b'TV/TRIGGER/SSS3/142/36/2'
b'TV/TRIGGER/SSS6/198/4/2'
b'TV/TRIGGER/SSS1/199/1/3'
b'TV/TRIGGER/SSS2/86/4/6'
b'TV/TRIGGER/SSS5/213/1/1'
b'TV/TRIGGER/SSS4/154/0/0'
b'TV/TRIGGER/SSS3/198/31/2'
b'TV/TRIGGER/SSS6/200/15/17'
b'TV/TRIGGER/SSS1/258/1/4'
b'TV/TRIGGER/SSS2/62/2/4'
b'TV/TRIGGER/SSS5/126/1/1'
b'TV/TRIGGER/SSS4/132/0/0'
b'TV/TRIGGER/SSS3/192/37/6'
b'TV/TRIGGER/SSS6/155/1/3'
b'TV/TRIGGER/SSS1/308/24/10'
b'TV/TRIGGER/SSS2/237/0/2'
b'TV/TRIGGER/SSS5/221/1/1'
b'TV/TRIGGER/SSS4/45/0/0'
b'TV/TRIGGER/SSS3/196/27/5'
b'TV/TRIGGER/SSS6/162/3/1'
b'TV/TRIGGER/SSS1/257/2/4'
b'TV/TRIGGER/SSS2/177/7/0'
b'TV/TRIGGER/SSS5/246/1/1'
b'TV/TRIGGER/SSS4/83/4/0'
b'TV/TRIGGER/SSS3/255/24/5'
b'TV/TRIGGER/SSS6/256/1/1'
b'TV/TRIGGER/SSS1/226/7/12'
b'TV/TRIGGER/SSS2/200/8/4'
b'TV/TRIGGER/SSS5/201/1/1'
b'TV/TRIGGER/SSS4/38/0/0'
b'TV/TRIGGER/SSS3/204/26/1'
b'TV/TRIGGER/SSS6/205/1/3'
b'TV/TRIGGER/SSS1/217/8/11'
b'TV/TRIGGER/SSS2/115/0/5'
b'TV/TRIGGER/SSS5/203/1/1'
b'TV/TRIGGER/SSS4/52/0/0'
```

Image 3 Simplified system architecture (left); raw data stream from Amatria master laptop as logged in Python shell (right). The three numbers at the end of each message are IR sensor values.

when printing the incoming bytes and can be ignored. "TV" is a callsign for Tavola, distinguishing visualization-related UDP messages from others on the network. Then follows the SSS for which values are reported, identified by its number (1 - 6). Finally, values for the three IR sensors attached to the SSS are shown.

In order to address *insight need trends over time*, the same real-time UDP data stream was used. However, while Tavola uses sensor data for live updates, visualizations geared towards developers require data aggregation for an extended period of time. While Tavola parses incoming data at runtime and does not store any data (locally or online), a time series for developers required data storage. Section 3.4.2 details our implementation.

3.4 Analysis, Visualization, and Deployment

In the previous subsections, we investigated insight needs and data acquisition, and illuminated challenges faced along the way. In the following subsections, we detail the visualization process by stakeholder group.

3.4.1 For Visitors

In order to enhance visitors' understanding of *Amatria*, we decided to build two scenes in Tavola (see *Images 4 – 5*). This allowed for an easier-to-maintain application to which we can add more scenes in the future while providing a minimal amount of variety. *Scene 1* serves as a structural overview; *scene 2* prompts users for physical interaction with the sculpture and enables them to see their own behavior visualized on a small scale. This two-step gave users a gentle introduction to the use of visualization for sentient architecture, while allowing the small visualization team to keep the workload manageable.

We used Unity 3D[21], a video game engine increasingly used to develop all sorts of interactive 2D and 3D experiences such as games and architectural visualizations.

21 Unity. https://unity3d.com/

Scene 1 addresses *insight need geospatial* by allowing users to control a virtual camera pointing at the *Amatria* model, using the physical layout of the sculpture as a reference system. A data overlay consisting of graphic symbols encodes the location of sensors and actuators using graphic variables

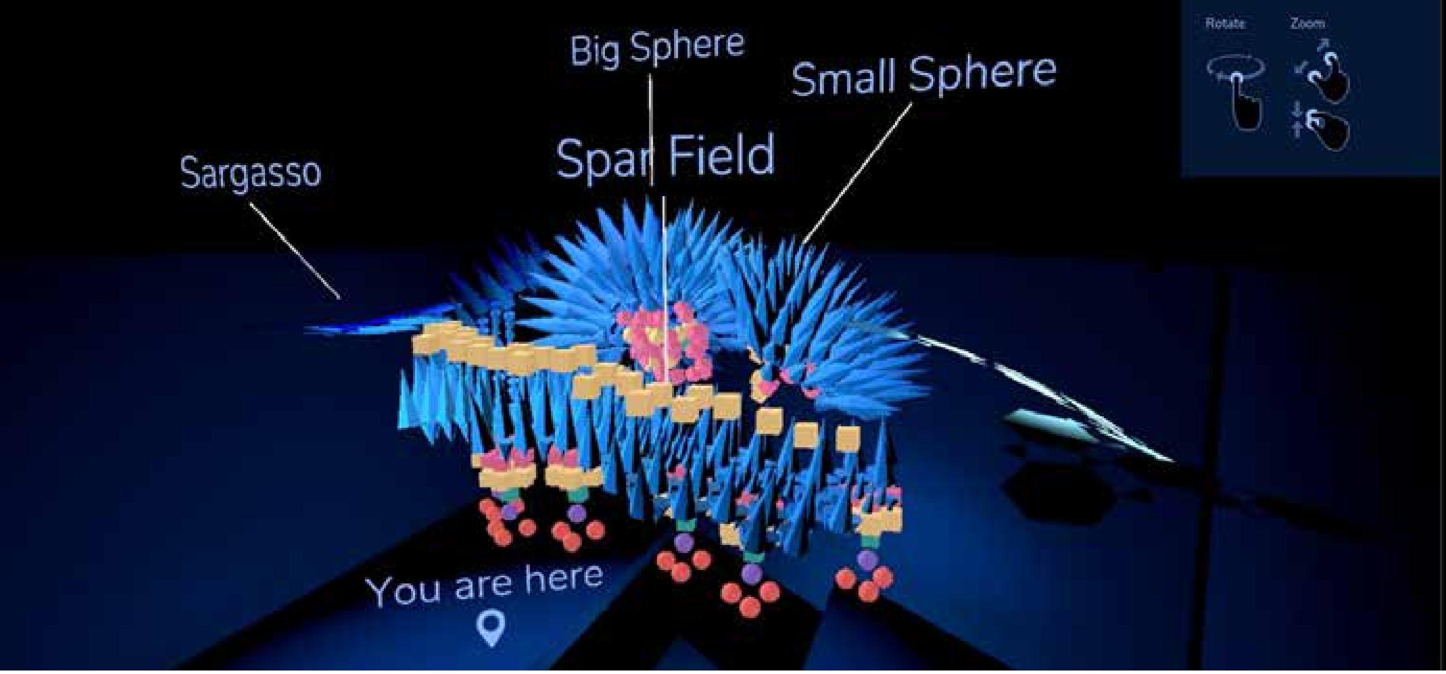


Image 4 Tavola, scene 1: *Amatria* overview.

Image 5 Tavola, scene 2: *Amatria* Sound Sensor Scout.

(see *Table 1*). Scene 2 addresses *insight need comparison* where a live sensor value data overlay is updated twice a second over an SSS, allowing visitors to compare that particular sensor's states based on their own input when waving their hand in close proximity. Similarly, *trends over time* can be identified as the visualization visualizes each data point for exactly 5 seconds, allowing visitors to see whether values increase or decrease.

On the SSS model, apart from the three IR sensors the SSS carries, one microphone sensor, six rebel star lights, six vibration motors, and one speaker are also visible, although no data for them is streamed or visualized at this point. At this point, only sensor readings from IR sensor #2 on SSS #1 are visualized in real-time, encoding human proximity to the sensor via various graphic symbols and graphic variables (see *Table 2*). A sensor value over approximately 400 indicates the presence of a foreign object such as a human hand; a number under 200 shows the lack thereof. We created a data overlay with different encodings: a particle cone and a proximity index (see *Image 5*, center-left and lower-left respectively). Tavola is used under SSS #1 (see the location marker in *Image 4*) to ensure that visitors using the application without a docent understand the real-time character of scene 2, where their physical proximity to the marked IR sensor produces state changes in Tavola. While we only visualize data from one sensor, we are planning to scale up and include more sensor data in the future. Visualizing just one sensor was a good step in developing a visual encoding that can then be applied to other parts of the sculpture. In a significant investment of time and resources, a dark blue user interface (UI) was developed to complete this as a professionally made and user-friendly visualization.

Graphic Symbols & Graphic Variables

Readily available common graphical elements of interactive experiences simplified the implementation of Tavola (e.g., highly adaptable particle systems, various types of lights (point, spot, area, directional) can be created with a few mouse clicks). Similarly, materials can be assigned before and at runtime, prompting us to leverage Unity's great functionality to create highly custom visualizations with templates for simple and advanced 3D graphics.

In scene 1, to encode the structural data of *Amatria's* physical layout, we use one graphic symbol (volume) and six graphic variables (see *Table 1*).

Sensors and actuators are encoded by shape (sphere vs. cube). Each type of sensor and actuator is encoded by one color hue. Each element has a unique position in 3D space. The graphic symbols in the spar field were placed manually. Those in the large and small sphere of *Amatria* (only actuators) were laid out using a custom algorithm that assigned every graphical symbol a 3D location within an invisible spheroid, the center point of which was aligned with the middle of the sphere. Since scene 1 does not contain any real-time data, the visual encoding is static. Additionally, note that we use color intensity to encode qualitative data (whether parts of the data overlay are turned on or off). Usually, color intensity encodes quantitative data.

In scene 2, to encode the real-time sensor data stream, we use one graphic symbol (volume) and six graphic variable types (see *Table 2*).

Angle, color intensity, and speed are used for quantitative data encoding. The minimum and maximum values for each graphic variable might be improved by user testing. White and red were chosen as the start and end point of the color intensity gradient, both to ensure maximum visibility against the dark background of the scene and to reflect the red color of the IR sensors in scene 1. The use of x, y, and z-coordinates to encode the location of IR sensor #2 in SSS #1 is analog to how these graphic variables are used in scene 1.

		Graphic symbol types				
		Volume				
Graphic variable types	Shape*	Sphere: sensor		Cube: actuator		
	Color hue*	#EF5350 (red): IR sensor	#9575CD (purple): microphone sensor	#FFCC80 (yellow): light	#26A69A (green): speaker	#f06292 (pink): vibration motor
	Color intensity*	Opacity: 0%: graphic symbol turned off Opacity: 100%: graphic symbol turned off				
	x-position**	Location of sensor or actuator in 3D space				
	y-position**					
	z-position**					

Table 1 Graphic symbol types vs. graphic variable types in scene 1 of Tavola. *qualitative **quantitative

It is, of course, debatable whether the particle system should be considered a volume (seen as a whole) or as a scatter graph (seen as individual graphic symbols of type point). In the latter case, the graphic variables used would be velocity, color intensity, and speed. We concluded that humans likely perceive changes in the direction of the moving particles as a whole rather than as a collection of points. However, a focused user study could help confirm this.

Also in scene 2, in order to guide visitors to interact with this specific IR sensor on SSS #1, its current value is visualized within a 2D proximity index, using the graphic variable types of line and pictorial symbol (see *Image 5*, bottom-left corner).

We compute the x-position of the pictorial hand symbol based on the current IR sensor value. There is no name for this type of visualization, but the 2D reference system and the use of position as graphic variable type for lines of different size could qualify this proximity index as a bar graph. The color intensity gradient of the bars corresponds to the color scheme of the particles. Notably, the proximity index is a 2D visualization within a 3D visualization and introduces purposeful redundancy so that a visitor's interaction with IR #2 on SSS #1 (in the form of the IR sensor value) is encoded multiple times to maximize visitor understanding when using Tavola unsupervised.

		Graphic symbol types	
		Volume	
Graphic variable types	Angle**	0°: low sensor value	90°: high sensor value
	Color intensity**	#FFFFFF (white): low sensor value	#D50000 (red): high sensor value
	Speed**	0.2 scene units per second	0.4 scene units per second
	x-position**	Location of IR sensor	
	y-position**		
	z-position**		

Table 2 Graphic symbol types vs. graphic variable types for particle system in scene 2 of Tavola. *qualitative **quantitative

In addition to reference systems and data overlays, annotation plays an essential role in allowing the user to extract meaning from a visualization. In the case of Tavola, annotation is provided in the form of explanatory text and symbols (such as information on how to use the camera, acknowledgements, etc.), accessible via the UI.

Interaction Types

To satisfy visitor *insight need geospatial*, Tavola uses the interaction types *overview, zoom, rotation & panning*, and *filter*. Many interaction types support one of two functionalities: either manipulating the data or manipulating the view. Tavola users can do both. They can manipulate the data by *filtering* which parts of the data overlay should be displayed (by means of the toggles in the UI). But they can also manipulate the view of the data. For example, *overview* and *zoom* can be used to switch between viewing the whole sculpture and displaying just a small portion of it. *In scene 1, rotating & panning* the camera enables the user to see *Amatria* from different viewpoints, especially those that may not be reachable (such as overhead or very up-close). We support these interaction types by putting a gaze lock on the camera, causing the camera to always face an invisible vantage point in

		Graphic symbol types			
		Line		Pictorial (hand)	
Graphic variable types	Color intensity**	#FFFFFF (white): low sensor value	#D50000 (red): high sensor value		
	Size**	Width: 31 pixels ***: low sensor value	Width: 6 pixels***: high sensor value		
		Height: 0 pixels***: low sensor value	Height: 14 pixels***: high sensor value		
	x-position**	min (relative): low sensor value	Max (relative): high sensor value	Min (relative): low sensor value	Max (relative): high sensor value

Table 3 Graphic symbol types vs. graphic variable types for proximity index in scene 2 of Tavola. *qualitative **quantitative ***pixels measured in original vector graphic

the middle of the sculpture, between the spheres and the spar field. Also, the camera is at a fixed distance from the vantage point and moves on the surface of an invisible spheroid, facing inward (a similar gaze lock is in place in *scene 2*). We should also note that *rotating & panning* is not part of the DVL-FW but would need to be included to capture the full breadth of 3D visualizations for IIS.

Aside from visualization-related interactions, both scenes require different kinds of real-world interaction between visitor and sculpture due to the fact that this is a visualization of a physical object: observation (*scene 1*), observation and providing sensor input (*scene 2*). Through the use of the proximity index and explanatory graphics in the UI, we hope that visitors feel prompted to interact with *Amatria* and see their influence on the sensors visualized. Whether this works as intended, however, needs to be shown by user studies.

Deployment

As mentioned in section 3.1, interactions often create requirements for preceding steps in the DVL-FW process model (see *Image 2*). Because Tavola allows the user to control camera movement, it was designed to run on touch-enabled devices. Initially, we tested Tavola on a 9.7” tablet. By using a Unity companion app, we could develop the touch interface without needing any time for compilation between versions. As of January 2019, deployment is underway for constructing a kiosk with a 32” touch screen to be placed under *Amatria* for visitor engagement. Users will be prompted to explore the sculpture in a way that organically adds to the experience of walking under it. This large display will run Tavola for visitors without any supervision or guidance from docents.

Informal Usability Study Results

In order to inform our development process, we frequently conducted informal user studies with team members and visitors during *Amatria* tours. While subjects had different levels of familiarity with Amatria, none understood the sensors and actuators in the sculpture. Broadly speaking, there were two categories of feedback: *feedback on design* and *feedback on functionality*.

The most common remarks we received were on *functionality*. Upon seeing Tavola running on a tablet, many visitors assumed it was possible to control the sculpture; they interpreted the presence of a 3D model as an affordance for a two-way communication. While this is not part of Tavola, we are in the process of developing such an interface, named “Encefalo” (Italian for “brain”), which is, however, still in a very early stage as of January 2019. We received lots of variations of this particular feedback, such as “I want to see more consequences of my actions on the sculpture,” and “Is the stand *Tavola* what controls *Amatria*/acting as her brain?” and “I want to interact with the sculpture via the app.” Comments on design were usually a lot more specific. We readily implemented feedback such as “I should be able to turn specific data overlay elements on and off by touching the corresponding entry in the legend,” and “Attach lines to bottom middle of text labels,” and “Remove [the 3D models of the] focus rooms [next to the *Amatria* model].” Testing the usability of Tavola is an ongoing effort and will most certainly figure in future research and development.

Image 6 Early prototype of Tavola where the IR sensor on the right reports consistently high proximity values.

3.4.2 For Developers

When creating Tavola, we did not have developers in mind as potential stakeholders. For the *Amatria* engineering team which implemented the UDP stream, observing behavior in the sculpture was essential, but individual sensor values were of limited importance, and the team used the Python shell while observing behaviors in the sculpture for debugging.

In an early prototype of Tavola, we visualized IR sensors #1 and #2 on SSS #1 (as opposed to just #2 in the current version). Image 6 shows this prototype in a state when no one is present under the sculpture. The particle cone on IR sensor #2 on the left is white, at a small angle, and the particle speed is at its minimum value, which is expected behavior. The cone for IR sensor #1 on the right, however, seems to indicate the close proximity of a foreign object.

Working with the developers to investigate this behavior uncovered an issue with the configuration of that sensor. This led to the realization that data visualization tools can also be helpful for developers, allowing them to "look under the hood" of a complex system.

While Tavola was developed for visitors, in this instance, we could satisfy *insight need comparison* for developers using the same data, which prompted us to consider this stakeholder group in our visualization design. In the following paragraphs, we will detail two visualizations for developers: a trends-over-time visualization (*Images 7 – 8*) and a real-time bar graph (*Image 9*), along with the visual encoding used for both (see *Tables 4 – 5*).

Graphic Symbol & Graphic Variable Types

Interested to understand if this was an isolated bug or the same for all 18 IR sensors distributed over the six SSS, we logged data for all IR sensors to answer other questions about *Amatria's* optimal configuration. Over the course of 24 hours in May 2018, we stored UDP messages from *Amatria* carrying IR values to address the insight need of identifying *trends over time*. Aiming to see if the thresholds for IR sensors need to be set dynamically based on the time of day (which varied by amount of people in the building, levels of ambient light during the day vs. at night, etc.), we created the graphs in Image 7-8. Here, time is plotted on the x-axis where the leftmost point is the beginning of the observation period (May 7th, ~7pm EST) and the rightmost point is the end thereof (May 8th, ~7pm EST). In order to maintain a manageable dataset size, we plotted only 1% of messages from *Amatria*, resulting in a message frequency of ~7.2 messages per minute. The data was then grouped into individual tables for each SSS and imported into Processing.[22] In order to create the final visualizations, graphs for all 18 IR sensors were created, and grouped into packs of six to get three visualization sheets. Each of these visualizations show six IR sensors with the same label, consisting of "IR" plus a number from 1 to 3.

Two *trend*-related insights can readily be gained from these graphs: No threshold change for IR sensors seems to be needed based on differences

22 Processing. https://processing.org/

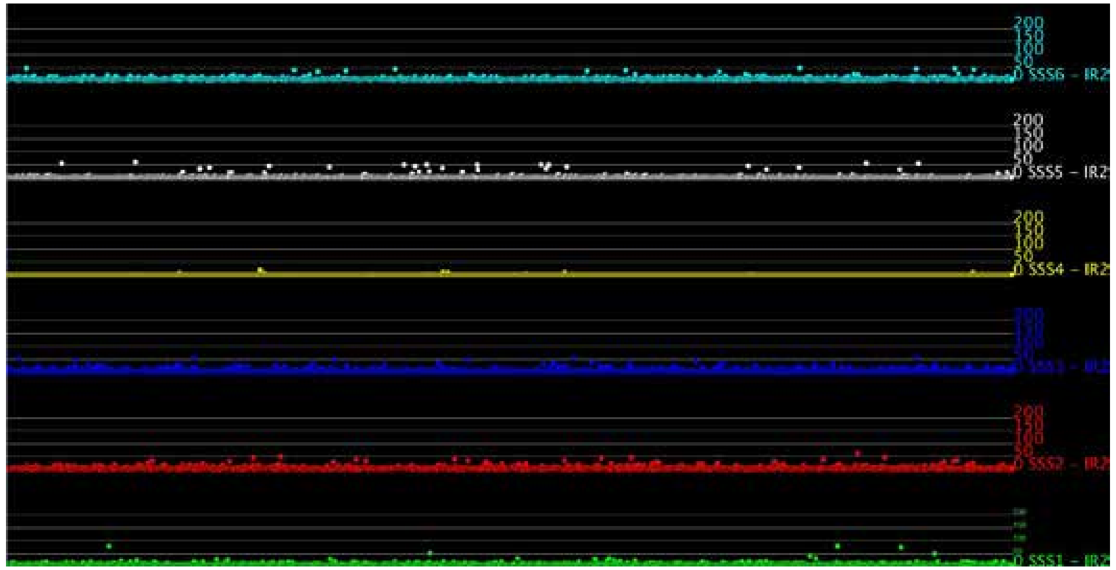


Image 7 Raw sensor data from six *Amatria* IR sensors (labeled "IR2") plotted over 24 hours

between day and night. But more importantly, we found that the consistently high sensor value for IR sensor #1 on SSS #1 is not an isolated incident; in fact, we encountered the same problem for all 6 SSS, specifically in their IRs #1. This actionable insight hinted at a challenging problem for the *Amatria* and Tavola team that is going to be tackled in the future.

To satisfy the developer *insight need comparison*, we wanted to allow an on-site team to see state change at sensor level during a maintenance visit in October 2018. This is why we created a real-time bar graph visualizing each IR sensor, grouped by the SSS to which they are attached. Image 8 shows this bar graph at a moment with no person underneath the sculpture; normally, all bars would be expected to hover at 0 or slightly above. What becomes clear is that all IR sensors labeled "IR1" report constantly high values.

Tables 4 and 5 below present the data mappings to graphic variables and graphic symbols used for the visualizations in Images 7 - 9.

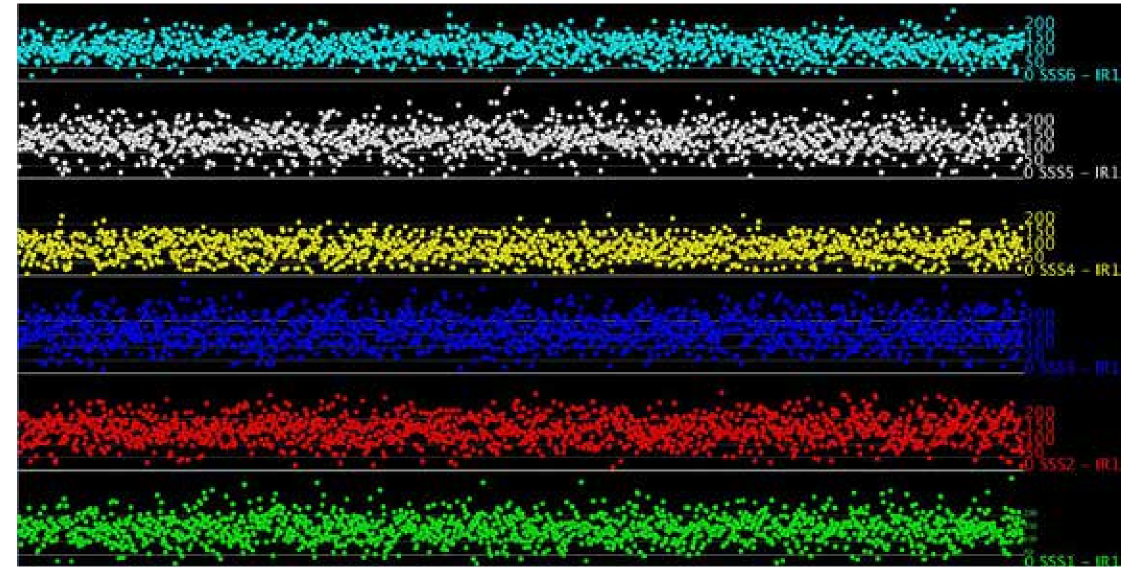


Image 8 Raw sensor data from six *Amatria* IR sensors (labeled "IR1") plotted over 24 hours

Interaction Types

Neither the trends-over-time visualization nor the real-time bar graph require interaction to satisfy developer *insight needs comparison* and *trends over time*.

Deployment

To keep the use of the trends-over-time visualization and the real-time bar graph simple, they were deployed on the same 9.7" tablet used for Tavola's initial development, and a laptop, respectively. The tablet can be carried around under the sculpture when testing IR responses, and the renderings of the trends-over-time visualizations can easily be shared via email or shown at talks and workshops. Thus, deployment meets insight needs.

3.5 Interpretation

The data visualizations presented here differ greatly by stakeholder. User studies will help us evaluate if the visualizations help explore and communicate *Amatria's* state and functionality.

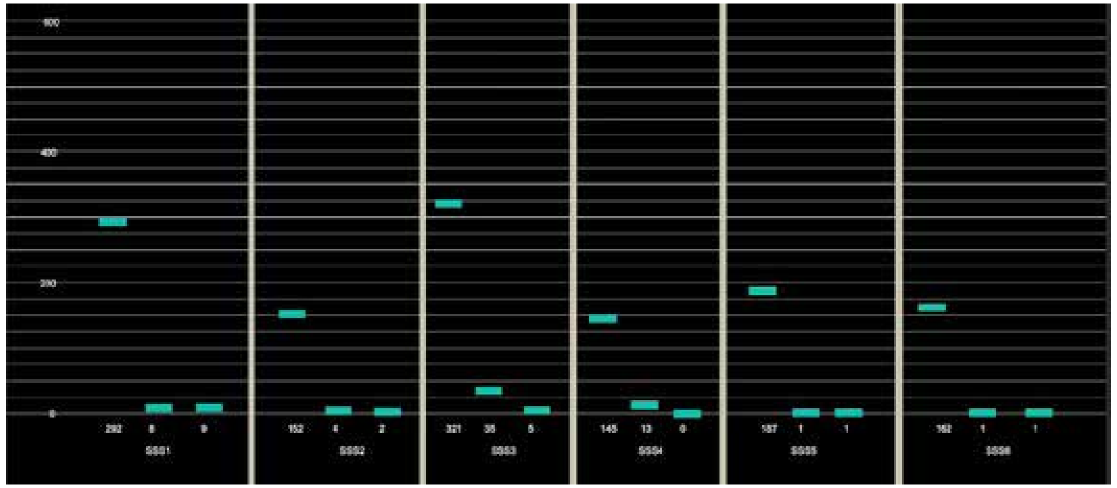


Image 9 Bar graph visualization showing all 18 IR sensor values in real-time.

Visitors are enabled to explore *Amatria* geospatially, compare IR sensor states based on their own input, and see trends over time for a fraction of the data traveling through *Amatria's* network. The expectation is that that visitors who used Tavola will understand *Amatria* measurably better than those who did not. Since no formal user studies have been conducted yet, we are enthused about the possibility of investigating user interpretations of Tavola (see Section 4).

Developers share some of the insight needs of visitors (*comparison* and *trends over time*), but their requirements for data visualization are quite different. Developers need to ensure *Amatria's* systems work properly and must check whether observed behavior is expected behavior. Plus they already have a firm *geospatial* understanding of the sculpture. While seeing values for all 18 IR sensor simultaneously in real-time (see *Image 9*) is a convenient way of ensuring proper functionality of sensors, developers must make decisions based on more information than just sensor values. Hence, to enable developers to make interpretations of the whole sculpture, visualizations with more data need to be implemented in the future.

Table 4 Graphic symbols and graphic variables for trends over time graph
*qualitative **quantitative

		Graphic symbol types	
		Point	
Graphic variable types	Color hue*	To distinguish all IR sensors with the same label by which SSS they are attached to	
	x-position**	min: recording time (start) May 7th, ~7p EST	min: recording time (end) May 8th, ~7p EST
	y-position**	min: 0 no proximity of foreign object	max: ~800 high proximity of foreign object

Table 5 Graphic symbols and graphic variables for real-time bar graph of 18 IR sensors. Note that x-position is qualitative in this case.
*qualitative **quantitative

		Graphic symbol types	
		Point	
Graphic variable types	x-position*	To separate bars areas for different sensors (no quantitative relationship)	
	y-position**	min: 0 no proximity of foreign object	max: ~800 high proximity of foreign object

4. Discussion and Outlook

This paper discussed different visualizations of sentient architecture data: Tavola for visitors and simpler graphs for developers. For all visualizations, we detailed the graphic variable and graphic symbol types, as well as interaction and deployment types. In this last section, we discuss planned research and development.

Going forward, we plan to run formal user studies where a control group of visitors would get a basic oral introduction to *Amatria* and would then be asked questions about its structure, such as "How many IR sensors are there in *Amatria*?" or "Which part of the sculpture is not actuated?" An experiment group would also get this introduction but then explore Tavola before answering the very same questions. Comparison of both user groups—quantitatively in terms of the time needed to complete the questionnaire and accuracy of answers, but also qualitatively based on verbal feedback—will help us understand the utility and usability of Tavola and its impact on how visitors understand and interact with Amatria.

In addition, we are interested to visualize more of *Amatria's* real-time data, more specifically the interactions between various parts of the sculpture that are not sensors or actuators (e.g., Teensies and Raspberry Pis. During a behavior workshop with *Amatria* and Tavola team members in Toronto in December 2018, alternative data transmission protocols were tested. Open sound control (OSC), already used for communication between the master laptop and a 4D Sound Laptop (see *Image 3*), has been found to facilitate the formatting of messages. While investigating OSC for Tavola, we discovered that the workload needed for custom parsing in Tavola can be reduced. Additionally, message queuing telemetry transport (MQTT), already in use in many IoT setups, shows promise in terms of the scalability of data streams out of *Amatria*. Rather than sending data to specific IP addresses, the master laptop would publish data to a broker that can be accessed by another machine, eliminating the need for the master laptop to be provided with the IP addresses of the destination for the data stream. Another reason for testing OSC and MQTT was to check the feasibility of two-way communication between *Amatria* and Encefalo, a proposed software to control the sculpture from a graphical user interface. This would enable various stakeholders not only to see *Amatria* data visualized but also to send input back to the sculpture, resulting in a lot of potential interaction between humans and sentient architecture.

To further advance our line of study, we need to also align our research and development to projects in the realm of the Industrial Internet of Things (IIoT), as well as validate findings with applications and user studies across application domains. While sentient architecture is a fascinating artistic view on smart environments, there are many areas of data-driven innovation that could greatly benefit from data visualization.

As we move forward, we will need to address questions of efficacy: for instance, is there a measurable difference in IIS understanding between groups who use visualizations and those who do not? Questions arise, as well, regarding the DVL-FW. As mentioned, the DVL-FW draws on much previous research on graphic symbols and variables, data scale types, and insight needs: how, for example, can we use 2D visualization within 3D applications (e.g., what is the optimal visualization of the IR sensor proximity in *Image 5*), or what graphic variables and graphic symbols are useful in 3D visualization? Which interactions are uniquely suited for 2D visualization, and which ones for 3D visualizations, and which can be translated between the two? Furthermore, how can we add interactions that only work on very specific deployment modes (e.g., camera rotation & panning) to the DVL-FW without overloading it?

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Katy Börner is the Victor H. Yngve Distinguished Professor of Engineering and Information Science in the School of Informatics, Computing, and Engineering, Adjunct Professor at the Department of Statistics in the College of Arts and Sciences, Core Faculty of Cognitive Science, Founding Director of the Cyberinfrastructure for Network Science Center at Indiana University, Bloomington, IN. She is a curator of the international Places & Spaces: Mapping Science exhibit that features large-format maps and interactive data visualizations. She holds a MS in Electrical Engineering from the University of Technology in Leipzig, 1991 and a Ph.D. in Computer Science from the University of Kaiserslautern, 1997. She is a member of ACM and IEEE and is an American Association for the Advancement of Science (AAAS) Fellow and a Humboldt Research Fellow.

Andreas Bueckle is a PhD candidate in Information Science in the School of Informatics, Computing, and Engineering at Indiana University. Coming from a background in video journalism and media, Andreas performs research and development of data visualizations in augmented and virtual reality, exploring the possibilities to visualize and allow for immersive interactions with data in 3D worlds. He holds a B.A. in Media Studies from Eberhard Karls University in Tuebingen and an M.A. in Communications in Economic and Social Contexts from Berlin University of the Arts (Germany).

Towards Psychosomatic Architecture

Attuning Reactive Architectural Materials Through Biofeedback

Daragh Byrne & Dana Cupkova
Carnegie Mellon University, Pittsburgh, USA

Cover Image Digital model of Sentient Concrete panel: Point cloud mesh of surface topology embedded with thermal pathways. Dana Cupkova, Dan Cascaval

The built environment is known to affect human health and wellbeing. Yet architecture does not respond to our bodies or our minds. It tends to be static, ignoring the human occupant, their mood, behaviors, and emotions. There is evidence that this monotony of average space is harmful to human health. Additionally, differences in gender, race, and cultural conditions vary the perception of and preferences for temperature and color. To improve the psychosomatic relationship with architectural spaces, there arises the necessity for it to have a greater range of spatial reactivity and better support for personalized thermoregulation and aesthetics. This paper proposes an architecture that operates like a mood-ring, one that creates rich feedback between architecture and occupant towards individualized reactivity and expression. *Sentient Concrete* (*Image 1*) is a prototype of a thermochromically treated concrete panel that is thermally actuated by embedded electromechanical systems and can dynamically produce localized thermally reactive responses. It serves as a test case for outlining further research agendas and possible design frameworks for psychosomatic architecture.

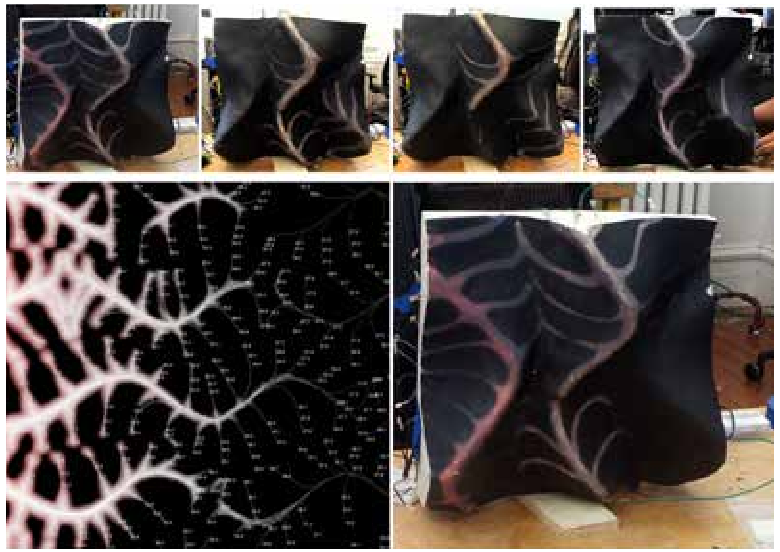

Image 1 Sentient Concrete Panel and thermal network map (Cupkova, Byrne and Cascaval, 2018): The ambition was to prototype an architectural environment that uses energy and matter to tap into sensorial subjectivity as part of the aesthetic and ecological experience. Sentient concrete is a panel prototype that is thermally actuated by its geometry and an embedded electromechanical system that can dynamically produce localized thermally reactive and thermochromic responses on its surface.

Vision

Buildings should operate just like living systems: change their color and self-regulate temperature, tightly coupled with the environment. The psychosomatic architecture is interested in new forms of materiality that draw a connection between energy, human perception, and living systems in architecture, to propose new forms of embedded material responsiveness for architectural surfaces that affect relationships between human health, thermoregulation, aesthetics, and energy usage. Energy is both empirical and perceptual. Inspired by research on human emotional reactivity that can be mapped through temperature gradients of the human body, we explore design through the passive thermoregulation of surfaces. The ambition of this research is to create a new generation of adaptive materials that react to changing conditions of human presence and emotion, to create holistic, responsive, and slow-phased surface changes within the built environment. The intent is to shape and color standard material systems, such as concrete, into surface geometries that are responsive to human tactility and thermal change through the use of convection and thermochromics.[1] Further, the intention is to embed electromechanical systems within these built surfaces to enable directed communication based on biofeedback and sensing.[2]

1 Cupkova, Dana and Patcharapit Promoppatum. 2017. "Modulating Thermal Mass Behavior Through Surface Figuration." In ACADIA 2017: Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture, Cambridge, 2017. 202 – 211. ACADIA Publishing Company

2 Cupkova, Dana, Daragh Byrne and Dan Cascaval. 2018. "Sentient Concrete: Developing Embedded Thermal and Thermochromic Interactions for Architecture and Built Environment." In Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference – Volume 2, Beijing, 2018. 17 – 19.

Psychological effects of color on human perception have been studied. Human brain processing is tightly linked to the perceptual changes in its environment.[3] Color and temperature have a deep effect on our sensory perception. The sensory and emotional states of mind affect physical factors of human health and learning development,[4] and cultural background, difference in age, gender impact perception, and environmental psychology of design.[5] This framework constitutes a potential to build a more robust communication between humans and their environment: a study of psychosomatic feedback[6] rooted in individualized art-based production that would give deeper foundation to treat the everyday design of living environments as an art form attuned with the human mind. Traditionally, the knowledge of color has been used in architecture within the framework of associative symbolic design related to different levels of stimulation. For example: red is arousing, passionate, and provocative; green is balancing, natural, calm, and inspires feelings of simplicity, security, and balance. Over-stimulation or under-stimulation of human sensory experiences can be produced by color range, intensity of patterns, feelings of thermal comfort, and other parameters related to aesthetics of spatial experience. Spatial stimuli have been linked to changes in breathing, increased heart rate, and changes in pulse and blood pressure.[7] Environmental under-stimulation has been linked to restlessness, irritability, and difficulty concentrating. These issues are extremely relevant to the culture of the built environment, educational spaces, and architecture at large. Color and pattern application are design parameters generally used as static design expressions. Psychosomatic architecture intends to explore these parameters within a dynamic framework, related to individualizing human presence in space. The investigation is rooted in design and development of reactive material systems, combining the use of color and surface temperature with ability for greater reactive attunement to the psychological sensory human frameworks and expression of new artistic character.

3 Mahnke, Frank H. 1996. Color, Environment, and Human Response. Hobeken: Wiley

4 Frieling, Heinrich. 1975. The Color Mirror: The Quicktest for Character Diagnosis with the Colors of the "Frieling-Test. Berlin: Musterschmidt.

5 Kopec, Dak A. 2006. Environmental Psychology for Design. New York: Fairchild.

6 Meerwin, Gerhard, Bettina Rodeck and Frank H. Mahnke. 2007. Color - Communication in Architectural Space. Basel: Birkhäuser Basel.

7 Mahnke, 1996.

The Innovation for the Everyday

Investigations to date from art, design, and architecture typically imagine reactive spaces as kinetically actuated physical infrastructure.[8] *Sentient Concrete* prototype helps us re-contextualize 'reactive' as finding new mechanisms for non-deformable everyday materials to find expressive ways to respond to the conditions around them - the environment, the systems

8 Fox, Michael, ed. 2016. Interactive Architecture: Adaptive World. New York: Princeton Architectural Press

that support them, and relationships to humans. The focus is on working specifically with concrete and other cementitious materials (ceramics and plaster) because of the material permanence. Once cast or printed, the form is unchanged. However, treating them with thermochromic inks enables actuation without deformation. This research focuses on the integration of material (characteristics of thermal diffusion, surface effects) and technical features embedding intelligent systems to activate and control responses. Formal characteristics of these surfaces are rooted in passive management of heat patterns and in passive cooling based on convection. Building upon our previous research on thermal actuation through surface geometry and figuration, the form-making is meant to be tightly coupled with expression of color and perception of temperature (*Image 2*).

A common problem within shared workspaces is the thermal comfort and thermal preferences of building occupants. Many previous studies prove that the perception of thermal gradients is hard to average for engineering solutions, as these are conditioned by differences in gender, race, and culture.[9] Two different people from two different contexts may perceive the same thermal condition in extremely diverse ways. Uniformity of current mechanical systems in buildings does not allow for individualized feedback. We focus on fostering the positive relationships between individual thermal comfort, energy usage, color, and human perception. With new thermally actuated materials there is potential to provide individualized thermoregulation, effect large scale energy savings through adaptive thermal comfort, impact human health, and reduce mechanical system loads in buildings. Our solution not only allows for thermochromic effects to be produced but adapts microclimates on the surface of the concrete panels. This in turn radiates heat into the surrounding area. Unlike current HVAC systems, which uniformly direct conditioned air to large areas of buildings, our proposed research can be adapted to panelized systems with the ability to actuate the thermal conditions in highly localized areas through use of radiant heat. The larger application of sense-based radiant heat actuation would be a transformative technology for architecture and engineering and have a positive effect on human perception and individualized thermal comfort. As such, we can imagine that with thermally-reactive, modular, and programmable architecture, a co-working space could be configured to the individual preferences of each person in the space.

9 Karjalainen, Sami. 2012. "Thermal comfort and gender: a literature review." Indoor Air 22. no. 2: 96 – 109.

Background and Related Work

Ubiquitous Computing: In 1991, Weiser suggested that our homes and buildings would soon be made intelligent by embedding hundreds of interconnected computers in a single room.[10] Today, and owing to extensive efforts in networking and computation - spanning distributed networks, context-aware computing, sensing and monitoring, analytics, prediction, and more - this vision of ubiquitous computing is largely realized.[11] This has created emerging markets and consumer adoption for smart objects like lightbulbs, sockets or thermostats[12] that now augment building infrastructure in our homes and workplaces. These connected devices have been demonstrated to improve the thermal comfort[13] and occupant health.[14] As such, ubicomp plays an increasingly important role in today's built environment. Yet, it rarely intersects with the architecture of the spaces it influences: it is rarely embedded in its infrastructure, rarely interacts with building systems (HVAC, etc.), nor do they employ deep integration with architectural forms. Scholars like Picon[15] recognize that this is insufficient and highlight how truly embedded systems could significantly enhance the experience and interactions with physical infrastructure.

Smart and Responsive Environments: Another critique relates to how ubiquitous computing currently responds to human occupants. Lee et al[16] note that "current approaches to personalization either presuppose people's needs and automatically tailor services or provide formulaic options for people to customize." Instead of forming mutually enriching, reciprocal relationships, ubicomp typically provides shallow forms of personalization. To this end, we consider Krueger's definition of 'responsive environments' where "experience is controlled by a composition which anticipates the participant's actions and flirts with his expectations."[17] Krueger proposed a new aesthetic framework where sensing and computation leverage rich context, like body, pose, proximity, and other forms of context to drive intelligent, real-time responses to human behavior with applications within and beyond aesthetic expression, such as psychology and psychotherapy. These are of particular relevance to our work. Despite Kreuger's assertion that responsive, context-aware technology will learn to 'perceive our behavior' and 'enter every home and office,' it has largely failed to do so. Explorations of this framework have been limited to media arts frameworks for performance or to demonstrator platforms. In media arts this is often a vehicle to explore

10 Weiser, Mark. 1991. "The Computer for the 21st Century." Scientific American 269 no. 3: 94 –104.

11 Atzori, Luigi, Antonio Iera and Giacomo Morabito. 2010. "The Internet of Things: A Survey" Computer Networks 54 no.15: doi:10.1016/j.comnet.2010.05.010

12 Perera, Charith, Chi Harold Liu and Srimal Jayawardena. 2015. "The Emerging Internet of Things Marketplace From an Industrial Perspective: A Survey." IEEE Transactions on Emerging Topics in Computing 3 no.4: 585 – 598.

13 Yang, Rayoung and Mark W. Newman. 2012. "Learning from a Learning Thermostat: Lessons for Intelligent Systems for the Home." In UbiComp 2013 Proceedings, Zurich, September 2013. 93 – 102.

14 Schellen, Lisje and Joost van Hoof. (2016). "Thermal Comfort in Smart Homes for an Aging Population." In Handbook of Smart Homes. Eds. Joost van Hoof, George Demiris and Eveline Wouters. 475 – 484. New York: Springer International Publishing

15 Picon, Antoine. 2015. Smart cities: A Spatialised Intelligence. Hobeken: Wiley. 1), 32 – 37.

16 Lee, Ming Kyung, Jodi Forlizzi, Junsung Kim and Sara Kiesler, S. 2015. "Personalization Revisited: A Reflective Approach Helps People Better Personalize Health Services and Motivates Them to Increase Physical Activity." In Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Japan, 2015. 743 – 754. ACM

17 Krueger, Myron W. 1977. "Responsive Environments." In AFIPS '77 Proceedings of the June 13-16, 1977, National Computer Conference, Wisconsin 1977. 423 – 433 ACM.

new performer-machine relationships. For example *Pathfinder*[18], a choreographic research project, combines generative visual prompts projected in performance spaces to guide man-machine improvisation, while *Breath: between two bodies*[19] leverages physiological measures from performers to generate movement vocabularies generating introspective response to sensed information.

These performative efforts are highly attuned to the ways in which sensing and context awareness can provide insight on and respond to human behavior. The relationships, however, operate in highly specialized contexts where movement grammars and behaviors are well defined. Smart space demonstrators aim to respond to more generalized scenarios. Efforts like MIT's House-n and Georgia Tech's Aware Home try to simulate smart home concepts and demonstrate the potential of responsive systems in everyday life. Favoring functional improvement of the home (reducing energy consumption, increasing efficiency, etc.), here sensing is typically situated on more measurable scenarios i.e. appliance use, temperature, etc.[20] Some efforts do incorporate occupant biometrics and context; normally temperature does adapt to interior conditions.[21] However, owing to the technical challenges in generalized environments[22], biometrics are rarely gathered and typically with limited scope. This results in the human occupant being treated as a secondary source. Consequently, smart home explorations rarely approach the aesthetic or experiential personalization that new media installations or performance does. Furthermore, Takayama et al.[23] note the limitations of most simulated smart home deployments; they are excellent tools for exploring issues of usability, but they are not suited to investigating interaction in the long term and fail to simulate the true conditions, practices, behaviors, and attachments which may be observed in real spaces, for example, "the stresses of hectic work and social lives." Our work responds to this, and we aim to re-engage Kreuger's[24] framework in applied settings. Acknowledging this critique of smart space explorations, we aim to prioritize understanding of human behavior to adapt interior spaces towards human benefit.

Responsive Environments and Smart Materials: As part of Kreuger's framework the space must intelligently respond to occupants, as well as *flirting with their expectations*. Yet, responsive architecture has for over 30 years leveraged the same material interactions: overlaid projections, programmable lighting, and mechanical actuation.[25] Recent developments in new programmable materials open up new avenues for unexpected responses. For

18 Pathfinder. generative computing and conceptual choreography by Onformative in collaboration with Christian Loclair. 2015. Retrieved from: https://onformative.com/work/pathfinder

19 Schiphorst, Thecla and Kristina Andersen. 2004. "Between Bodies: using Experience Modeling to Create Gestural Protocols for Physiological Data Transfer." In altCHI, CHI 2004, CHI Vienna, 2014. 1 – 8.

20 Helal, Sumi, William Mann, Hicham El-Zabadani, Jeffery King, Youssef Kaddoura, and Erwin Jansen. 2005. "The Gator Tech Smart House: A Programmable Pervasive Space." Compute 38 no. 3: 50 – 60. IEEE Computer Society Press

21 Helal, Sumi, William Mann, Hicham El-Zabadani, Jeffery King, Youssef Kaddoura, and Erwin Jansen. 2005. "The Gator Tech Smart House: A Programmable Pervasive Space." Compute 38 no. 3: 50 – 60. IEEE Computer Society Press

22 Tistarelli, Massimo, Stan Z. Li, and Rama Chellappa, eds. 2009. Handbook of Remote Biometrics. New York: Springer International Publishing.

23 Takayama, Leila, Caroline Pantofaru, David Robson, Bianca Soto and Michael Barry. 2012. "Making technology homey: finding sources of satisfaction and meaning in home automation." In UbiComp '12 Proceedings of the 2012 ACM Conference on Ubiquitous Computing, Pittsburg, 2012. 511 – 520. ACM.

24 Krueger,1977

25 Fox, 2016

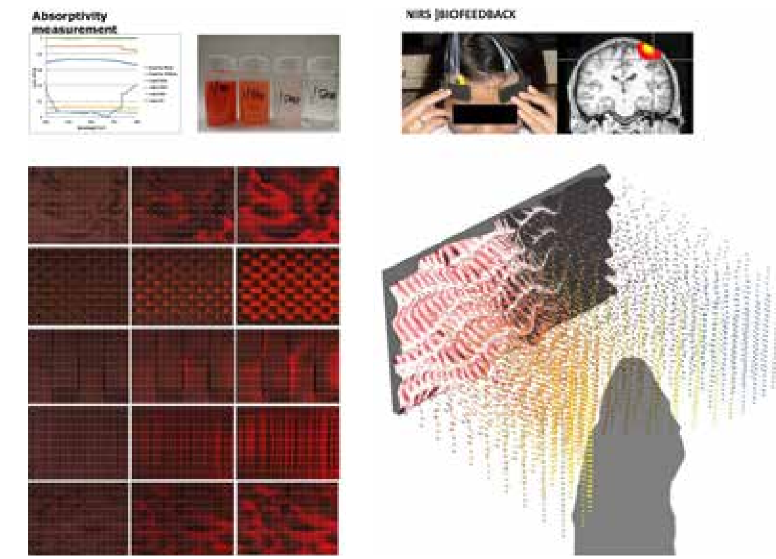

Image 2 Thermally Activated Surface Color change with proposed bio-metric actuation using Nirs Biofeedback: Tests of thermochromic progression of varied surface geometry associating the color change and temperature values to surface geometry variation (Cupkova, 2016). We can activate the surface temperature by sensing human presence and link the visual effects on the surface to an emotive human response, thus creating new form of communication between the environment and the human perception of thermal and physiological comfort. Example of optical probes placed on subject's forehead (top right). The area of the brain probed is shown on the right overlapped on a MRI brain image (Kainerstorfer, 2014).

example, Devendorf et al.[26] explore computationally responsive clothing that create chromic responses as a novel textile display technology. Berzowska[27] similarly explores conductive yarns and thermochromic inks blended with electronic components to create dynamic fabrics, while Yao et al.[28] have explored pneumatic shape-changing systems and biological methods to deform soft materials through environmental changes. Due to their materiality, they also have the potential to be more deeply coupled with architectural forms and truly embed computation into the space it is designed to actuate[29] but - like work in ubicomp - almost all of this work focuses on small, object level interventions, and the potential of these materials to operate at an architectural scale remains unexplored. Robles and Wiberg[30] note the need to interface with computation at scale and through new materials as well as integrative design-led inquiry into these emerging areas:

"With the development of rapid prototyping processes, inexpensive chips, processors, and sensors, and increasingly computational ways of interacting with manufacturing and craft processes, our relationships to materials are rapidly transforming... Open for examination is how the discipline of interaction design might move forward alongside architecture, product design, textile design, and materials science as part of a joint area for inquiry."

26 Devendorf, Laura, et al. 2016. "I don't want to wear a screen: Probing Perceptions of and Possibilities for Dynamic Displays on Clothing." In CHI '16 - Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, New York, 2016. 6028 – 6039. ACM.

27 Berzowska, Joanna. 2004. "Very slowly animating textiles: shimmering flower." In SIGGRAPH 2004 Sketches, Los Angeles, 2004. 34. ACM.

28 Yao, L., Niiyama, R., Ou, J., Follmer, S., Della Silva, C., & Ishii, H. (2013). "PneUI: pneumatically actuated soft composite materials for shape changing interfaces." In UIST '13 Proceedings of the 26th annual ACM symposium on User interface software and technology, United Kingdom, 2013. 13 – 22. ACM.

29 Addington, D. Michelle, and Daniel Schodek. 2012. Smart Materials & Technologies in Architecture. Burlington: Routledge.

30 Robles, Erica and Mikael Wiberg. 2011. "From Materials to Materiality: Thinking of Computation from within an Icehotel." Interactions 18 no. 1: 32 – 37.

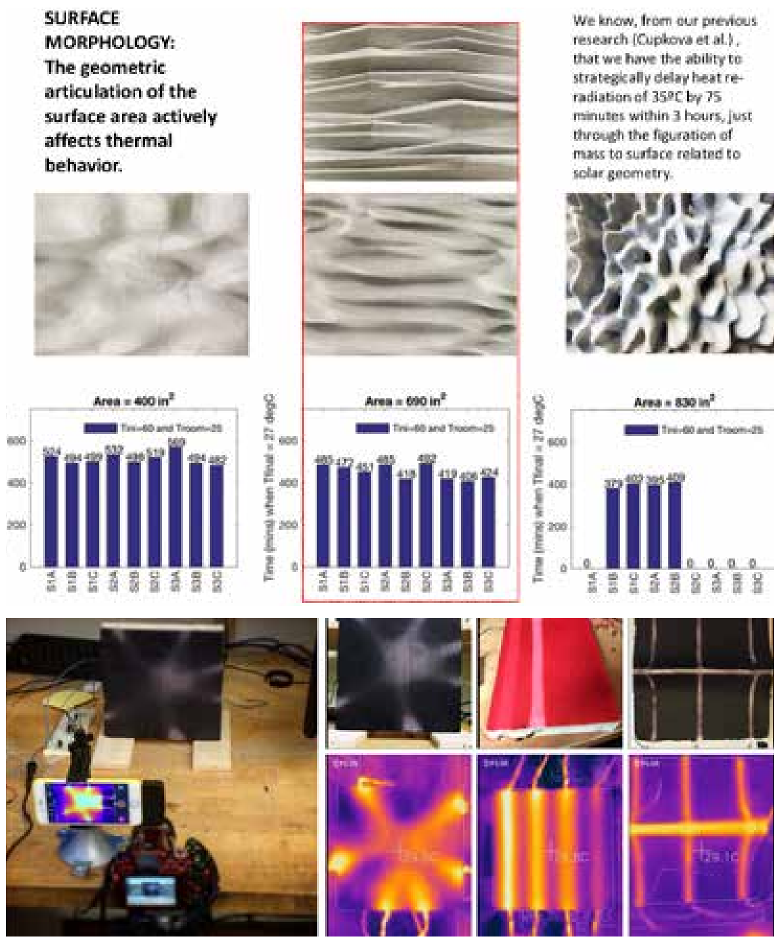

Image 3 The geometric articulation of the surface area actively affects thermal behavior: We know, from our previous research (Cupkova et al.), that we have the ability to strategically delay heat re-radiation of 35ºC by 75 minutes within 3 hours, just through the figuration of mass to surface related to solar geometry. This paper explores combing active and passive systems and features test panels with embedded thermal network testing range of activation: location and depth showing the interaction of surface geometry with chromic pigments and thermal control through electromechanical actuation.

Contextualizing Work to Date

In response to Robles' and Wiberg's call to action, our preliminary work (*Image 3*) recognizes the need for arts-based exploration of new material interactivity. Our prior work explores an alternative approach to the architectural design of passive building systems, actuating passive thermoregulation through the use of surface geometry, material, and color. This ongoing research outlines principles for the design of passive systems with a creative approach towards performance and form. It is built upon the premise that complex geometries can be used to improve both the aesthetic and

thermodynamic performance of passive building systems by actuating thermal performance through geometric surface figuration that is responsive to localized color change, primarily due to convection.[31] We measured up to 45% possible reduction in energy usage if these strategies are used. This phenomenon is primarily caused by the fact that specific types of surface geometry tend to reduce direct surface contact between airflow and wall surface area by creating air pockets, thus generating differences in thermal performance and perception.

Sentient Concrete prototype extends these prior explorations and developed a reactive concrete panel prototype with embedded electromechanical controls. This panel can be programmed to actuate internal thermal changes and produce color effects on the surface.[32] This enables surface thermal, tactile, and thermochromic responses to be reliably actuated in under 1 second. This produces highly reactive character changes in the surface conditions that can be coupled to a variety of human responses and behaviors; in this case, proximity and brain activity were explored. This small-scale panel provides a proof-of-concept of the ability to create responsive, reciprocal interactions between human physiology and smart materials central to this research proposal. To achieve intended goals, these panels need to move beyond small scale tests and laboratory settings.

Accordingly, this will require the development of immersive interactive architectural experiences that respond to human behavior. Insights in producing this real-time emergent responsive system will directly inform the development of this work. The intention is to integrate multiple sensed sources from human participants in ecologically valid conditions and combine design technology approach with neuroscientific feedback within CMU collaborative context, by using non-invasive optical or NIRS techniques: near-infrared light at two different wavelengths is transmitted through the intact scalp and skull to illuminate the brain.[33] An optical fiber is placed in a specific scalp location to deliver an optical signal, while a separate optical fiber, typically placed a couple of centimeters away from the illumination point, collects the light that has probed the cerebral tissue. This optical method can be used to assess changes in tissue perfusion and oxygenation. Positive changes in tissue perfusion and oxygenation are associated with demand, which is seen in functional brain activation. For example, NIRS optical probes can be applied to the motor cortex to reliably detect activities such as finger tapping. In addition to functional activations, Kainerstorfer's work has demonstrated

31 Cupkova and Promoppatum, 2017.

32 Cupkova, Byrne and Cascaval, 2018.

33 Kainerstorfer, Jana M., Angelo Sassaroli and Sergio Fantini. 2014. "Coherent Hemodynamics Spectroscopy in a Single Step." Biomedical Optics Express 5 no.10: 3403 – 3416.

NIRS is sensitive to systemic physiological changes, for instance triggered by changes in mean arterial blood pressure. Those changes include heart beat fluctuations in hemoglobin and respiration.[34] We hypothesize this will allow us to monitor hemodynamic changes in subjects and correlate them to changes and responses in the environment.

34 Kainerstorfer, Sassaroli, and Fantini, 2014.

Projection

This framework is motivated by the belief that today's architectural spaces and systems are insufficient. We hypothesize that our built environment can support healthier relationships with its human occupants if it can understand and respond to them intuitively. To address the limitations of today's environments, our research shall explore reciprocal relationships between mind, body, and space that can be developed with thermally and visually responsive architectural materials:

Mind: Leveraging NIRS signals, we assert that we can measure attention, functional activations in the brain, as well as changes in heart rate and respiration that may indicate stress, affect, and mood. Furthermore, we assert that we can leverage these as inputs to meaningfully augment the environment for a building occupant.

Body: We assert that human somatic behaviors and thermal signatures can be used to improve the personalization and adaptation of the space to each occupant. We assert that knowledge of each individual's location in space, orientation, environmental context, and thermal profile can be used to personalize the aesthetic and thermal conditions of a space.

Space: We assert that psychosomatic knowledge of building occupants will allow reactive architecture to affect thermal and visual change to positively affect health and wellbeing.

To methodologically ground our design-based research process, we will draw on and extend Kreuger's[35] framework for responsive environments. Our research framework will therefore a) develop new psychosomatic concrete panel prototypes and fabrication techniques to support their production; b) examine the sensing, control, and coordination that allows human biometrics, behavior. and response to be reliably gathered as inputs to our architectural system; c) interrogate and design strategies to affect human response through thermal and aesthetic changes in their surrounding; and d) evaluate and assess the degree to which this can affect and impact human wellbeing in the short and long term.

35 Krueger,1977

This proposition extends directly to the design of environments by inciting thermal fields as active spaces that are attuned to the human psyche. Just like a "mood ring," this thermally reactive architecture would renegotiate a sense of individual and collective reflections in lieu of a singular spatial (and thermal) norm that represents an average measurement. Instead we propose a functionality that attempts to produce spaces that respond to human diversity. Attunement in this regard requires a shift away from the data-driven rationales of performative models and the desire for design to tap into architectural sensorial subjectivity as part of the aesthetic and ecological experience.

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Dana Cupkova is a Director of EPIPHYTE Lab, an interdisciplinary architectural design and research collaborative. She currently holds an Assistant Professorship at Carnegie Mellon University School of Architecture and serves as a graduate program Track Chair for the Master of Science in Sustainable Design. She serves on the Editorial Board of The International Journal of Architectural Computing. In 2018 Epiphyte Lab has been recognized as the Next Progressives design practice by ARCHITECT Magazine, The Journal of The American Institute of Architects. Dana's design work studies the built environment at the intersection of ecology, computational processes, and systems analysis. In her research, she interrogates the relationship between design-space and ecology as it engages computational methods, thermodynamic processes, and experimentation with geometrically-driven performance logic.

Daragh Byrne is an Assistant Teaching Professor in the School of Architecture and the Integrated Innovation Institute at Carnegie Mellon University, where he explores the design of experiential media systems through process-oriented methods and human-centered exploration of emerging technologies. His teaching and research reflect this interest with a current focus on the Internet of Things and tangible interaction design. Daragh defended his Ph.D. at Dublin City University in 2011, holds a M.Res. degree in Design and Evaluation of Advanced Interactive Systems from Lancaster University and a B.Sc. in Computer Applications from DCU.

Building on the Intersection of Art, Technology, and Cognitive Neuroscience

A Personal Journey as an LASG Student Researcher

Adam Francey
University of Waterloo, Canada

Image 1 Interactive systems workshop at LASG studio, Toronto.

About two and a half years ago, shortly after a diverse group of artists, architects, researchers, engineers, and scientists started officially calling themselves Living Architecture Systems Group (LASG), I was introduced to the work of Philip Beesley. With my future supervisor Dr. Colin Ellard, I had arrived at the Philip Beesley Architect Inc. (PBAI) studio, an active multidisciplinary STEAM workshop in Toronto, as a prospective graduate student and to see if I would be interested in pursuing cognitive neuroscience research involving the living architecture that I saw hanging from scaffolding and structural elements throughout the studio. At this time, the talented team of designers, engineers, and architects of the studio were busy working on *Ocean* – an installation about to be showcased at Scotiabank's Nuit Blanche: Toronto. I was able to take a peek at various in-house processes used to make the structure: the physical manufacturing and material-forming, the careful architectural considerations and design planning, and the electronics testing rig that spanned half of the studio. Since I had been a software developer until this point, I sat down with the engineering leads to take a look at the innards of the custom software they were building. A week or two later, I began travelling to Toronto on a regular basis to join the studio's engineering team to help with the software and electronics for the upcoming exhibition. While I had some experience with public display of my own projects and had worked on various projects within Dr. Ellard's laboratory, I was now partly responsible for running a huge exhibition located inside Toronto City Hall, where thousands of people would be flowing through.

A couple of weeks into my residency at the studio, shortly after I had been consumed by the studio's relentless drive to complete *Ocean* before the big opening at the end of the month, I started Graduate studies in the Department of Psychology at the University of Waterloo. Over the next two years, I started to incorporate my work at Living Architecture Systems Group into the research thesis for my Master's degree.

To give an impression of the public impact of *Ocean* (local media had named it #1 on their must-see lists), the lineup to see it stretched around the building. This was the first time that I was seeing living architecture in action. It occurred to me that what I was going to be doing as a Graduate student was going to be significantly different from what the other Graduate students were doing. Typically, you'd invite participants into your on-campus laboratory space, but I was using the exhibitions as my laboratory. I started to think about what kind of systems would make viable research projects. *Ocean*, though visually stunning, had no sensors and effectively no input. There was also no way to extract data from the system. The individual microcontrollers could not talk to each other and they could not talk to the outside world.

After the opening of *Ocean*, we resumed work on a project to be installed at the Isabella Stewart Gardner Museum in Boston, which we named *Sentient Veil*. This system would be alive for a couple of months, rather than only one night like *Ocean*, and offered real research potential. While *Ocean* was an incredibly visceral living architecture experience, *Sentient Veil* was the first true interactive system that I would participate in designing with PBAI. By now, I had assumed the role of PBAI's primary software developer. Under control of a network consisting of a Raspberry Pi single-board microcomputer and a handful of Teensy microprocessors distributed within the sculpture, *Sentient Veil* had infrared proximity sensors that allowed it to

Image 5 Banners for *Transforming Space* at the Royal Ontario Museum, Toronto, 2018.

Image 2 Installation of *Astrocyte* shown at Design Exchange EDIT: Expo for Design, Innovation & Technology, Toronto, 2017.

see, microphones that allowed it to hear, speakers that allowed it to talk, and lights that allowed it to emote. It was almost as if you could walk up and converse with the piece, completely forgetting it was simply an array of electronics and scaffolding suspended from the roof. It was responsive to people within the space by having a reflex of propagating sound and light whenever a person walked near one of the sensors.

It was at the installation site visit of Indiana University that Information Science Ph.D. researcher Andreas Bueckle prompted the first crucial step toward data-driven LASG research on interactive systems. For his project to be useful, the system would need to reach beyond its function as an art piece and provide meaningful data to external devices. So, the first ever bytes of data began streaming out of the interactive system. The messages that were being passed around the network of electronics embedded within the sculpture could now be echoed to any other machine that was on the LAN. These messages mainly consisted of sensor triggers and communication among the community of embedded electronics. Andreas and I would begin experimenting with ways that his applications could visualize the data streaming from the system. As the interactive system evolved, active research projects would become a form of natural selection that determines which traits the system will have.

Just after the installation of *Sentient Veil* I took a break from the studio to focus on my Graduate research. Many discussions with Colin Ellard resulted

Image 3 Installation of *Sentient Veil* shown at the Isabella Stewart Gardner Museum, Boston, 2017.

in us landing on my main research question - what makes you think something is *alive*? After all, we are calling these systems *living architecture.* Among the many properties that you may consider a living being to have, the property of agency gives a wide range of abilities. Agents have the capacity to affect their environment of their own volition. They make decisions, have mental states and intentions, and respond to their environment appropriately. If they are physically able, they move under their own power. In my research, I examine the *perceived agency* of an object in the environment. What properties make you think that some objects in your environment have minds, while others do not? While sentient biological organisms are agents in their environment, the condition of being alive does not seem necessary to be perceived as an agent.

The 'grandfather' of psychology research in this area is a 1944 paper titled *An Experimental Study of Apparent Behaviour* by Fritz Heider and Marianne Simmel.[1] In these experiments, participants viewed a simple animation consisting of two triangles and a circle moving in and around a hollow rectangle with a hinged opening. Participants would then describe or answer questions about the scene. The participants proceeded to fabricate elaborate stories about what was happening. The simple geometric shapes on screen had become villains and heroes that were hiding, chasing, and fighting. They had become young adults resolving a love triangle or a family getting into an argument. It seemed that the movement of these shapes implied life, a form

1 Heider, Fritz and Marianne Simmel. 1944. "An Experimental Study of Apparent Behavior," The American Journal of Psychology 57, no. 2: 243 – 259.

of abiogenesis on-screen. However, not all movement should be seen as indicating agency. For example, a rock dropping according to gravity should be seen as an inanimate object moving according to natural forces within its environment. Indeed, it has been shown that objects which seem to consistently move according to Newton's laws of motion are perceived to be inanimate objects,[2] while objects that appear to spontaneously change their speed or direction are perceived to be alive.[3]

2 Stewart, Judith Ann. 1982. "Perception of Animacy," Unpublished Dissertation, University of Pennsylvania

3 Tremoulet Patrice D. and Jacob Feldman. 2000. "Perception of Animacy From the Motion of a Single Object", Perception 29: 943-951

Rather than simple movement, it appeared there was something about the particular way an object moved that influenced whether it was perceived to be an agent or an inanimate object. This would become the basis of my first research experiment titled *Effect of Object Trajectory on Agency Classification and Object Tracking*. The experiment itself was simple. I would have participants watch a plain black ball which represented the centre of mass of some anonymous object. Thrown one at a time, each ball would follow a different trajectory, and the participant would tell me which balls represented 'thinking beings' and which represented inanimate objects. At the same time, they were tasked with predicting where the ball was going to land by moving to that spot. The choice of trajectories was determined by looking at the way inanimate objects moved under the force of gravity.

Given an initial position and initial velocity, and ignoring other forces such as air resistance, there is exactly one unique trajectory that all objects will follow. Namely, it is the trajectory that corresponds to the constant downward acceleration caused by the force of gravity. If you start with an initial velocity that points upward at an angle, this trajectory is a perfect parabola. Inanimate objects, having no agency of their own, are forced to travel this path, whereas agents may make the decision not to. In physical terms, the trajectory of an inanimate object - in this idealized experiment - has no jerk. Just like acceleration is the rate of change of velocity, an object's jerk is the rate of change of that object's acceleration. Since the acceleration induced by the force of gravity is constant, then any object whose motion was influenced solely by the force of gravity must have zero jerk. This is specifically what I would test for my experiment. Would certain types and magnitudes of jerk cause people to think that a trajectory was travelled by an agent instead of an inanimate object? In my experiment, two types of jerk were tested. The first was a simple constant jerk in some direction, which would cause an object's acceleration to constantly increase in that direction. This trajectory looks very similar to zero jerk but follows a warped or skewed parabolic arc. The second type of jerk studied was motivated by watching the movements of familiar agents. As you walk, your head may bob up and down in a pattern resembling a sinusoidal curve, a bird flying through the air will dive and rise as it travels forward, and a monkey moving from branch to branch might swing in a pattern that influences its acceleration in a similar way. From these examples, it seemed reasonable to test a sinusoidal jerk, which oscillates the acceleration back and forth in one dimension. Most people have seen inanimate objects follow a jerk-less trajectory many times, and it is familiar and predictable. The trajectory of an agent might then be unpredictable. One could easily estimate where a thrown ball will land, yet doing the same for a bird might be impossible. Additionally, a person's predictions and perceptions are not perfect, so multiple magnitudes of each jerk were tested to determine its effect. The hypothesis was that those objects which had enough non-zero jerk, therefore sufficiently deviating from the predictable path defined by the physical laws of their environment, would be classified as agents by the observer. This experiment would be conducted with virtual reality as a research tool. Evidently it would be near impossible to create custom trajectories for physical objects, but such a thing is commonplace in the virtual world. Using our laboratory's virtual reality equipment, I began building the simulation that would become my first experiment.

With my research now having a clear direction, I resumed my regular visits to the LASG studio, where we began building the next generation of interactive systems. First in line was *Amatria*, which now lives permanently within Luddy Hall at Indiana University. *Amatria* represented a great leap forward in LASG interactive systems. It was no longer suitable to use a microcomputer to run the system. Instead, systems from this point on would use the processing power of a laptop to govern the network of electronics within the sculpture. Raspberry Pis still existed in the system, and now over a dozen Raspberry Pis were nestled inside of the sculpture to provide communication access points for almost fifty Teensy microcontrollers spread throughout. This distribution of processing power controls hundreds of actuators and sensors. Our collaboration with the Dutch group 4DSOUND was beginning to mature, and a secondary laptop running their custom software would communicate over the LAN to the laptop governing the system and had access to commands that allowed central control of the actuators and readings of the sensors.

Image 4 Opening night of *Ocean* at Scotiabank Nuit Blanche: Toronto, 2016.

Immediately following the launch of *Amatria*, LASG shifted focus to the next upcoming project. This project was to be the most sophisticated to date, from the standpoint of the interactive system. It was also the most high-profile project that I have worked on in my career with LASG. This was *Philip Beesley: Transforming Space* at the Royal Ontario Museum (ROM) in Toronto, where we would install the companion systems *Aegis* and *Noosphere*. I remember thinking to myself, "This is it, the real deal. If I'm going to launch a research project on a live installation, it has to happen here." This was our biggest local project, and the buzz spread across the city. It was great to see advertisements on the street as I drove into the city, but they weren't nearly as impressive as the gigantic banners hanging from the ROM itself. After the system was installed and stabilized, I began to focus on the next stage of my thesis: running a research project in the field on a live interactive system for *Aegis*.

I was not alone in attempting to utilize *Aegis* for my own research. I was simultaneously collaborating with two other LASG graduate student researchers, Daiwei Lin and Lingheng Meng, and we wanted to evolve the system to something unarguably closer to agency than any other interactive system I had worked on yet. Our goal was to make *Aegis* artificially intelligent. Together with Dr. Dana Kulić and Dr. Rob Gorbet, we theorized a number of possible ways for a machine learning algorithm to operate on *Aegis*. At the same time, I was working on implementing the newest version of the LASG software on another installation in South Korea. Given that parts of it were nearly identical to *Aegis*, my plan was to eventually backport this latest version of the software onto *Aegis* and bring it up to date. To make things easier for someone other than me to compose the interactivity of these systems, I exposed many of the control variables to the master laptop. While the microcontrollers were responsible for controlling their actuators, the laptop could now modify parts of the system's function on the fly. Variables controlling the timing and magnitude of *Aegis's* responses could be changed while the system was running. It would be these variables that we would use to make the system artificially intelligent. To do reinforcement machine learning, we'd need three key ingredients: actions, observations, and a reward. Simply put, the reward is calculated by taking observations of the system state. The learning algorithm searches the space of possible actions in an attempt to find the action that corresponds to the optimal reward. In our case, the action space spans all possible values of each parameter, and a particular action is a unique set of parameter values. The observation space spans all possible sensor values, and an observation is a single sample of all the sensors in the system. The reward function was chosen to correspond to user engagement, which was roughly a measure of the density of visitors under *Aegis* determined by the values of the infrared proximity sensor readings. In a moment of cosmic harmony, I realized that I had inadvertently found and started building my second research experiment. Would participants respond to an artificially intelligent system differently than they would to my handcrafted interactive composition, and would those descriptions carry hints of agency?

Lin, Meng, and I began visiting the ROM regularly to prepare for the experiments. As luck would have it, personnel at the ROM would deny my research proposal. I still regularly visited under the guise of 'maintenance' and resumed preparation of my experiment. As I had said to myself earlier, "It has to happen here," and the last two years of my life had been leading up to this very experiment. Weeks later, we were ready to upload the machine learning code to the system. In what felt like a historic moment, at least for us three graduate students, we waited with suspense as the algorithm spent a few minutes initializing itself. Soon enough, *Aegis* came to life. It felt like making first contact with an undiscovered species. A light turned on here, and a light turned on there, and I couldn't tell what was going to happen next, since for the first time since I began with LASG, it wasn't me who was controlling it. The learning algorithm was calling the shots. We started interacting with the system while it was running the algorithm and ... nothing. Nothing happened. Disappointed by our apparent failure, we went to go see what was happening on the laptop running the algorithm. Happily, the algorithm was running as expected and the interactive system was online. The algorithm had simply decided it didn't want to turn the lights on at that time. It was thinking for itself and stubbornly decided not to cooperate. It was an agent!

Lin and Meng proceeded to run their research project over the next weeks, while I continued to convince the ROM to let me run mine. Eventually, with many mutual compromises, I was given the green light for my own research. By the time everything was cleared with the University of Waterloo ethics board, the show was nearly over. I would finally conduct my research experiment on the last two days that *Transforming Space* was open to the public. In this experiment, titled *Perceived Agency of Living Architecture*, participants would interact with the system while it was running the learning algorithm or while it was running scripted behaviour. While doing so, they would be wearing devices that recorded their brain activity, skin conductance, and heart rate. I intend to use these physiological measures as an objective measure of the participant's experiences. Following this, I had them fill out a questionnaire to determine their subjective perceptions. This questionnaire contained questions such as "Does *Aegis* have goals?" and "Will *Aegis* miss you when you leave?" There was also a free answer area which allowed participants to describe the system in their own words. If you'd like to know the full results of my experiments, you'll have to wait until my thesis is complete.

For the curious, the word most commonly used was "beautiful."

Adam Francey is a cognitive neuroscience MA candidate and living architecture researcher from the University of Waterloo. His research investigates manipulations of inanimate objects that seem to make those objects spring to life. As a technologist and software developer, he works closely with the Living Architecture Systems Group on demonstrative exhibitions and testbed installations that showcase the work of Philip Beesley Architect Inc. and provide a platform for LASG researchers to explore and experiment. Under the supervision of Dr. Colin Ellard, Francey's main research and professional interests involve virtual reality, cyberpsychology, and mathematical analysis.

Living Wall System (LIWAS)

Petra Gruber
University of Akron, USA

Image Mushrooms growing mycelium material panel during the growth process.

Nature of the Research and Significance

This proposal is about the design and prototyping of a Living Wall System (LIWAS) as a test bed for integrating concepts from biology into architectural design. *The Living Wall* is a new way of interpreting a wall system that we use in architecture and building. We try to integrate characteristics of living organisms into the wall design to harness some of the intriguing qualities of life into our built surroundings. Living Walls may include flows of water; they may move, adapt geometry, and change appearance; they may be inhabited by algae, plants and other organisms and in general be "alive." The framework of the proposal is the overlap between architectural design and biological research, using biomimicry as a methodology for information transfer between the fields (*Image 1*).

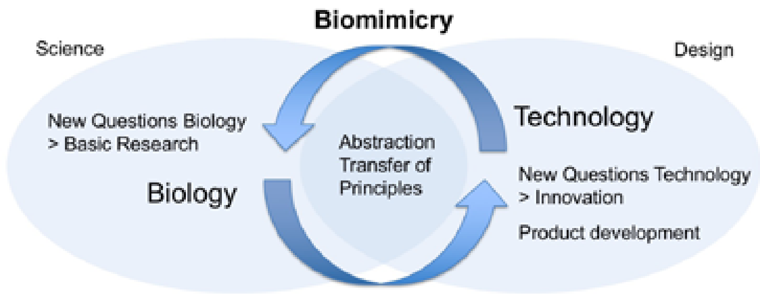


Image 2 Information flow between science and design © Petra Gruber

The comparison between the so-called "signs of life" as defined in biology literature and on different architectural scales (urban design, building, element, materials) reveal a biological paradigm underlying current architectural research.[1 2] This paradigm generates a vision of architecture as a dynamic, adaptable, sensing, reacting, and self-organizing entity with embodied smartness or even intelligence. Within this framework and together with international interdisciplinary groups of scientists and designers, I have in recent years investigated patterns from nature, and specifically biological growth as concept generator for a new, living architecture.[3 4 5] Those projects, and the related publications, have gained broad acknowledgement. The concept of living architecture has since been taken up by different research groups worldwide, for example the Living Architecture Systems Group (LASG) with Philip Beesley in Toronto, Canada,[6] and the Living Architecture (LIAR) project initiated by Rachel Armstrong at the University of Newcastle, United Kingdom.[7]

Walls are especially interesting. They are borders between an interior environment designed for human habitation and a dynamic and changing environment of the exterior. Active and multifunctional wall systems, as proposed in the 1980s,[8] can negotiate between the inside and the outside, integrating functions like energy management, light management, mechanical protection etc. The integration of a set of those functions into technical translations that can finally achieve the users' comfort requirements is the ultimate goal of the proposed research in contemporary building facades using a biomimicry approach.

Contemporary wall systems are also increasingly providing additional functions to the classical provision of shelter from other people, animals, elements, managing of light entry to the inside, and provision of privacy.

1 Gruber, P. 2011. Biomimetics in Architecture - Architecture of Life and Buildings. New York: Springer.

2 Knippers, Jan, Klaus Nickel and Thomas Speck. eds. 2016. Biomimetic Research for Architecture and Building Construction. New York: Springer

3 Gruber, Petra and Barbara Imhof. eds. 2013. "What is the architect doing in the jungle? Biornametics - Architecture Defined by Natural Patterns." Edition Angewandte, Vienna: Springer

4 Imhof, Barbara and Petra Gruber. eds. 2015. "Built to grow - Blending Architecture and Biology." Edition Angewandte Vienna: Birkhäuser Verlag

5 Gruber, Petra and Barbara Imhof. 2017. "Patterns of growth - biomimetics and architectural design." In Special Issue Biomimetics in Sustainable Architectural and Urban Design.

6 Living Architecture Systems Group http://livingarchitecturesystems.com

7 Living Architecture LIAR http://livingarchitecture-h2020.eu

8 Davies, Mike. 1981. "A Wall for All Seasons." RIBA Journal Inst. 88 no. 2. 55 –57.

Today's building facade should deliver energy (solar and photovoltaic systems), customizable transparency (according to the wishes of the user), and signal to the outside (media facades) etc. Many of those systems are available on the market as single-function products that actively control inputs and outputs on the base of computation, relying on mostly centralized digital models that are not integrated, made of unsustainable materials and have a high energy demand.

In order to harness the embodied intelligence of biology, not only the functionality from biology has to be translated, but so do some deep omnipresent principles of design. such as hierarchical structuring of materials, anisotropic characteristics, multifunctional and integrated systems, use of passive mechanisms, local resource harvesting, and fine-tuned adaptation to the environment.

In a previous research project, the potential of biomimetics for future building facades was investigated, and a database of role models was generated.[9] This research suggested that energy management and subsequent metabolic activity would be specifically interesting aspects to be translated into design. In the current proposal, the technical approach taken in BioSkin shall consider an experimental and artistic approach for integrative design and prototyping, as carried out in follow up projects, for example "Growing as Building" (GRAB) (*Image 2, 3*).

Current research on thermodynamics of plants[10] will be a starting point for translating morphological principles into spatial structures and for establishing a system to integrate flows of water and humidity layering into wall systems. Further concepts will concern hierarchical material systems on different levels of scale, integrated efforts to use locally available materials and upcycle waste materials, as well as the integration of biological organisms like plants, algae, fungi, and microbes into the system.

At the University of Akron, the field of design research is now being developed by the Biomimicry Research and Innovation Center located at the Myers School of Art, in biomimicry design classes, and within the IB program and PhD Research Fellowships in Biomimicry. The research will take place in my current lab at the Department of Biology, in collaboration with two PhD students in Integrated Biosciences.

9 Gruber, Petra and Susanne Gosztonyi. 2010. "Skin in Architecture: Towards Bioinspired Facades" In Design and Nature V, Comparing Design in Nature with Science and Engineering, Conference Pisa ed. BREBBIA Southampton: WIT Press.

10 Gruber, Petra and Ariana Rupp. 2017. "Investigation of leaf shape and edge design for faster evaporation in biomimetic heat dissipation systems." International Workshop on Bionic Engineering IWBE2017 Energy and Bionics, Deutsche Institute für Textil- und Faserforschung. Germany.

Image 2 Algae Bioreactor ©GRAB

Image 3 Mycelium material shells ©Bruno Stubenrauch

During the research and design phase, colleagues from the Biomimicry Research and Innovation Center, the Department of Biology as well as Myers School of Art will engage in exchanges and discussions. For design and production phase, there will be a collaboration with Drew Ippoliti, Assistant Professor in Ceramics at Myers School of Art. A funding component for the LIWAS is also to establish and maintain exchange with other external researchers for reviews and discussions. The prototype of the research will be implemented at the University of Akron's Biology Fieldstation at the Bath Nature Preserve (BNP) for long term exposure of at least six months to environmental conditions. Lara Roketenetz, the field station manager of the Department of Biology, will support the implementation and presentation activities on site.

The results of this project will generate an important example for a research-based design prototype that can be used to visualize the potential of biomimicry in architecture, and also in subsequent grant proposals with external funding organizations. As an experimental design concept, the final project represents a potential solution for the defined outset of design interests and parameters. In addition to the public presentation, the results will become part of the publishing activity of the lab, including papers produced by PhD students with their own approaches to the topic.

Goals and Objectives

The goal of this research proposal is to generate a collection of case studies in the field of living architecture in order to create a variety of design proposals presenting new approaches to translating sets of life criteria into design, and to create and build a prototype of a living wall system at the University of Akron BNP as a test bed for furthering design research in this field.

Objectives of the proposal are:

1. Furthering research and development of "living architecture" as an application field for biomimicry research and development.
2. Generating design proposals for living wall systems integrating new signs of life such as metabolic activity etc.
3. The main objective of the proposal is to build a prototype for a "living wall system" at the University of Akron's Department of Biology field station at BNP as a long-term installation to serve as proof of concept example.
4. Long-term monitoring of the installation and hands-on presentation of the research field.

In addition to the biomimetic approach, important design goals are sustainability and integration of biology into the systems.

Broader impacts of this proposal are:

1. Visible and tangible results from the design research implemented at BNP will promote the University of Akron, STEAM approaches, and biomimicry to an audience based in the surrounding community and regional schools hosted at the BNP field station.
2. LIWAS will serve as a proof of concept example to further the intersection between art, architecture, and science.

Procedures

The project's research methodology includes literature reviews, expert discussions, biology literature research, abstraction of basic design principles from biology, biomimicry information transfer, ideation and creation of concepts, architectural design, and experimental prototyping in the following phases:

1. Literature and case study research
2. Selection of biological role models for specific signs of life, and abstraction of their principles
3. Creation of designs that translate the principles into a technical system of a living wall
4. Evaluation of designs, and selection of a transferable concept
5. Building an experimental prototype installation
6. On-site implementation and presentation of the prototype
7. Long-term observation and monitoring of the system within PhD research beyond the funding phase of the University of Akron grant

Phase 1 will research the literature and interview relevant researchers in the field. Phase 2 will take on existing datasets from previous projects as well as current research on the thermodynamics of plants conducted in my lab. Phase 3 will be a series of creative design sessions and workshops with PhD students and collaborators from the University of Akron. Phases 4 to 6 will be in-lab design and prototyping sessions bringing together undergraduate design and biology students.

Facilities in the lab (3D printer, laser cutter etc.) will be used for production, as well as the ceramics lab at the Myers School of Art for larger scale productions.

Table 1 shows the schedule for the research. Research, design, and prototyping will be carried out over the summer and fall of 2019 from May to October. The final installation will be created in October and introduced in a public presentation at BNP.

Expected Results and Data Analysis

The expected research outcome will be a review of current living architecture systems, a set of design proposals taking on a biomimicry approach, and a tangible prototype installed at the University of Akron Biology Fieldstation at Bath Nature Preserve (BNP). The installation will serve as a proof of design concept, creating a tangible example of the potentials of biomimicry as an applied field. In the long term, the installation allows for monitoring of functionality and physical parameters (for example humidity and temperature), as well as observation of long-term behavior, colonization by organisms, and durability of the system.

Publication or Presentation

The results from the research will become a review paper about living architecture systems, and the design process and the prototype will be exhibited at the BNP for a public research presentation. The audience will consist of students, academics, and the public who are interested in biomimicry and experimental architectural design. The BNP hosts hundreds of pupils during organized visits each year. Having the installation there will be a great outreach to potential future STEAM students. The progress of the project will also be published in a blog and on social media. The research will also be part of the publications from participating PhD students.

Image 4 Overview of the Living Wall Systems prototype
Work by Thibaut Houette
© Petra Gruber

Image 5 South Face of the mycelium section © Petra Gruber

Image 6 South Face of the ceramic section
Work by Ariana Rupp
© Petra Gruber

Image 7 Fruiting bodies thriving on the mycelium panels
© Petra Gruber

Image 8 Detail of the ceramic panels © Petra Gruber

Feasibility of the Project

As discussed in the introduction, this proposal is based on a body of previous research in experimental architectural design (see bibliography). The materials from those projects are a starting point for the proposed research, as well as contacts to relevant researchers in the field in order to generate reviews. Two previous projects included large-scale spatial installations that were part of the design-based research. They opened to the public at the University of Applied Arts in Vienna, Austria, and later traveled to Hong Kong, Brazil, and Australia (Image 2, 3). In 2017, we organized the exhibition *BIOSCOPE* at the Emily Davis Gallery at Myers School of Art with design proposals created in the Biomimetic Design class.

The proposed project is highly experimental and still far from production stage. As a proof of concept, the project would be instrumental in getting external grants to continue researching in the field of biomimicry in architecture and design, and to accelerate establishing the research field at the University of Akron with follow up projects.

Team

Petra Gruber, Assoc. Prof. at at Biomimicry Research and Innovation Center BRIC at the University of Akron (UA)

Ariana Rupp, PhD student in the IB progam at UA, Biomimicry fellow (Engineer and designer), research, design and production

Thibaut Houette, PhD student in the IB progam at UA (Architect), research, design and production

Brian Foresi, Biomed student at The University of Akron, research and production

Drew Ippoliti, Assistant Prof. Ceramics, UA Myers School of Art, design and production support

Lara Roketenetz, Field Station Manager BNP, UA Department of Biology, on-site support

Jeff Spencer, Lecturer and Lab coordinator at UA, prototype building support

Funding Status

The project was funded by The University of Akron with a Faculty Research Grant.

Dr. Petra Gruber is an architect with a strong interest in inter- and transdisciplinary design. In addition to her professional work as an architect, she holds a PhD in Biomimetics in Architecture from the Vienna University of Technology in Austria. She also collaborated as a research fellow at the Centre for Biomimetics at The University of Reading, UK. She taught Biomimetics in Energy Systems at the University of Applied Sciences in Villach, Austria, and held lectures and workshops at universities worldwide.

As a visiting professor for Architectural Design and Building Science, she set up a Master's program in Advanced Architectural Design at the Addis Ababa University in Ethiopia. Her research spans from projects for the European Space Agency on lunar base design informed by folding principles from nature to arts-based research on the translation of growth principles from nature into proto-architectural spatial solutions.

Dr. Gruber is based at the Myers School of Art and the Department of Biology for the Biomimicry Research and Innovation Center or BRIC at the University of Akron.

Worldmaking as Techné

Participatory Art, Music, and Architecture

Mark-David Hosale
York University, Toronto, Canada

This article is an adaptation of a talk given by Mark-David Hosale at the Worldmaking as Techné: Participatory Art, Music, and Architecture *book launch that took place at the Toronto Media Arts Centre on September 26th 2018.*

It began in a pub in Milan…

Sana Murrani, Alberto de Campo and I had the first ideas for this collaboration in 2010 over a beer on a snowy December day at the end of a conference on Generative Art at the Politecnico University in Milan.[1] The conference's theme of generative art attracted participants from various disciplines, and as a result, the presentations included almost as many approaches to the subject as there were participants. Without exception our backgrounds and perspectives added to the tapestry of this milieu as well.

1 GA2010, the 13th Generative Art Conference at Politecnico di Milano University, December 14th – 17th, 2010.

Image Empty Space
photo by Laura Beloff, 2009.

Sana Murrani is an urban theorist and an experimental architect. She currently holds the position of Associate Head of School for Graduate Affairs for the School of Art, Design and Architecture at the University of Plymouth, UK. This is in addition to her role as the Stream Leader for History and Theory of Architecture and Critical Context. Sana's main research interest lies in the ztions of marginality and displacement.

Alberto de Campo is a composer and performer, and teaches Generative Art/Computational Art. He is Associate Professor at the University of Art (Universitäet der Küenste) in Berlin. In his work he explores a wide range of topics in collaborations with other artists and students: code-based network music performance, biologically informed/inspired art, hybrid audiovisual performance instruments and interactive systems, and improvisation strategies in different contexts.

I am a computational artist and a composer. Within the collaboration I could be seen as a bridge between the domains of architecture and music. At the time of the conference I was an Assistant Professor in Architecture at the Technical University of Delft in the Hyperbody Research Group. While I am not a trained architect, architecture and music have a large role to play in my works, which explore the boundaries between the virtual and the physical world through immersive interactive environments.

While at the time of our conversation in Milan we used different terminology and perspectives to describe our work, we still recognized in each others' work some common themes. One was the integration of theory and practice, an integration to the extent that theory and practice are indistinguishable from one another. This included the use of the same system to embody theory and practice from process to dissemination. In exploring this integration, we had each arrived at the use of frameworks to govern our methodology, as well as the role of the observer in our works. While our works may affect the observer, the observer is also part of the system, reciprocally affecting the work.

The challenge in describing these ideas to each other was in finding a common language around these approaches. After some deliberation we arrived at two terms: *techné* and *worldmaking*.

Techné

We used the term techné in our work to describe the process from creation to presentation as part of a continuum. Techné (which literally means *art* or *skill* [2]) is an ancient philosophical concept that, in simplified terms, is concerned with the art and craft of making. For Aristotle, techné is also key in the completion of the *hexis* of a virtuous person.[3] As Aristotle stated, "art is the same thing as a rational quality, concerned with making, that reasons truly." From this definition one can understand techné as a mode of rationalization capable of concept forming, a form of discourse in its own right.[4]

Like Aristotle, Heidegger saw techné as a form of discourse and concept making. He states: "techné is the name not only for the activities and skills of the craftsman, it is also the name for the arts of the mind and the fine arts." As an *art of the mind*, techné is a fundamental tool in the exploration of knowing, and key in the process of revealing truth.[5]

In Heidegger's essay, *The Question Concerning Technology*, the need for techné is presented with urgency. Heidegger does not think we can escape the rise of new technology; therefore, in order to make the world a better place we must embrace technology responsibly. For Heidegger, technology at its worse has the potential to be out of control, at its best to benefit humankind. As he states:

> Because the essence of technology is nothing technological, essential reflection upon technology and decisive confrontation with it must happen in a realm that is, on the one hand, akin to the essence of technology and, on the other, fundamentally different from it.
>
> Such a realm is art. But certainly only if reflection on art, for its part, does not shut its eyes to the constellation of truth after which we are *questioning*.[6]

For Heidegger art is something fundamentally different from the frenzied nature of technology. Especially when the artwork is not complacent in the trajectory of technology, but confronts that trajectory by questioning it through a critical discourse grounded in techné.[7]

2 Merriam-Webster. 2017. "Dictionary and Thesaurus - Merriam-Webster Online." Encyclopedia Britannica. http://www.merriam-webster.com/dictionary/techne acc October 11, 2018

3 Including "Art or technical skill, Scientific Knowledge, Prudence, Wisdom, and Intelligence." Aristotle. 1934. Nicomachean Ethics. Rev. ed. Edited by H. Rackham. Loeb Classical Library. Cambridge, MA: Harvard University Press. 1139b.

4 Techné, episteme, phro-nesis, sophia, and nous are part of a spectrum of reason which can be understood in terms of three qualities: techné, having to do with making/action with intent; episteme and nous, having to do with knowing and intel-ligence based on rationality; and, phronesis and sophia, having to do with virtue and conduct (ethics). Ibid. Bekker page 1140a. This ecology of techné, knowing, and ethics is what we attempted to articulate in the curation of this book.

5 Heidegger, Martin. 1977. The Question Concerning Technology, and Other Essays.12 – 13.

6 Ibid.

7 Ibid. 35.

Worldmaking

For Heidegger technology is also the means whereby we enframe the world. As we enframe the world through an apparatus, an instrument or a device, we also shape it. But the world is made perceptually as much as it is made physically; and therefore while we are shaping the world, we help reveal it at the same time.[8]

8 Ibid. 25 – 26.

If the essence of technology lies in *enframing*, the questioning of technology lies in *how* the world is *enframed*. Through our apparatuses and media we can manipulate the senses, shifting perception in order to critique and question the world. We change the frame, change the perspective, and thereby change our understanding of it. To make a (different) world is to know (differently).

In this spirit Nelson Goodman stated:

> Worlds are made by making such versions with words, numerals, pictures, sounds, or other symbols of any kind in any medium; and the comparative study of these versions and visions and of their making is what is called *a critique of worldmaking*.[9]

9 Goodman, Nelson. 1978. Ways of Worldmaking. Vol. 51. Indianapolis: Hackett Publishing. 94.

The domain of worldmaking is one of possibility. When we make worlds, we conject the Other. In doing so we also help shape the world and its trajectory. One of the leading thinkers in the domain of speculative worldmaking is researcher, artist, theorist, and *transarchitect* Marcos Novak.

According to Novak, the extreme changes brought forth by technology create unprecedented new opportunities to conceive of new kinds of spaces[10] (or worlds). The characteristics of these spaces transformed conventional modalities of expression from a familiar medium to a new and unfamiliar form, what Novak calls an *extreme intermedium.*[11] In *Liquid Architectures in Cyberspace*, Novak's describes the extreme intermedium:

> Architecture becomes liquid, music becomes navigable, cinema becomes habitable, dance becomes disembodied. As distant as these new options seem from their origins and from each other, they are related to one another by what can only be called 'worldmaking.'" He goes on to say, "Worldmaking is … the key metaphor of the new arts.[12]

10 Novak, Marcos. 1997. "Trans-TerraForm: Liquid Architec-tures and the Loss of Inscrip-tion." KR Knowbotic Research http:// www.krcf.org/ krcfhome/PRINT/ nonlocated/ nlonline/nonMarcos. html acc. July 13, 2017

11 Ibid.

12 Ibid.

The emergence of new domains is happening at a frenzied, exponential pace. In recent history this has been evident in the rise of digital technologies, the internet, and related technologies; and it is present in newer domains such as nanotechnology, biotechnology, quantum technology, robotics, and artificial intelligence. In this rising tide we are faced with two options: we can wait and see how these domains take shape, then respond; or we can try to anticipate, even *derail* the course of these domains and help create them, thereby shaping the world.

Structure of the book

The book is organized into three sections: *po(i)etic, machinic, and cybernetic*. The intent in creating sections in this book was not an attempt to create rigid categories within the discourse; rather we wanted to create connections between them. We did this by selecting unconventional texts by familiar authors and by including texts in sections that fall outside of their normal categorization in order to break the frame.

Po(i)etic

The title for the first section of this book is a portmanteau between the terms *poiesis* and *poetry*. Poiesis is an ancient Greek term meaning to bring something new into existence, which either involves autopoiesis (self-creation) or allopoiesis (the creation of the other).[13] The concept of poiesis provides a meta-description of the processes of nature, readily encapsulating systems of evolution, homeostasis, emergence, and similar processes that are the foundation of the living world.

13 "Poiesis" Wikipedia https:// en.wikipedia.org/ wiki/Poiesis acc January 29, 2019.

Poetry, which means making, is derived from poiesis.[14] Often understood as a literary form, etymologically the origins of "poetry" can refer to any kind of making, especially any human-made work that brings forth aesthetic results.

14 Ibid.

The bringing together of these two related terms is meant to describe the drive to make living artworks. Living artworks are poietic (unexpected/emergent), but are shaped by the artist (poetic) in order to express a particular idea or experience that is either a reflection of the known world or a view into a world that is alien and unfamiliar. The balancing of poiesis and poetry is fundamental in the aesthetics of worldmaking and computational art.

Machinic

The machinic section includes contributions by authors who use abstract assemblages and frameworks to describe and implement their work. We derived the term *machinic* from the first chapter in this section, *Machinic Heterogenesis*, by renowned philosopher Félix Guattari. In the simplest terms the machinic describes the relationship between human and machine. *Machinic Heterogenesis* also includes the world of living beings, which have similar qualities to machines (or are even considered machines in their own right) but without an anthropocentric purpose (or any "purpose" at all).[15]

15 Guattari, Felix. 1992. "Machinic Heterogenes" Chaosmosis: An Ethico-aesthetic Paradigm trans. Paul Bains and Julian Pefanis. Bloomington: Indiana University Press. 33.

Machinic Heterogenesis provides a description of the high-level processes that govern a machine and its modality of production. There are two aspects to the machinic: the diagrammatic and the materialized machine. The diagrammatic machine exists virtually, as a *protomachine*. The materialized machine exists as an instance of the diagrammatic. The diagrammatic is capable of producing many materialized machines and, unlike the materialized machine, is unfixed and always in flux.

The domain of the computational is an exemplar of the machinic. Computational processes are not limited to digital computation and can include mathematical, biological, and other systems as their basis. What is unique in the digital domain is that the diagrammatic computational system (model) and the materialized result of that system (instance), are created using the same tools. As a result, the machinic processes of abstraction and implementation are often blurred. For instance, the materialized form of the computational machine has the ability to evolve, *dematerialize*, and produce other machines *auto-* and *allopoietically*. The diagrammatic can even produce materialized machines that recursively rewrite the diagram and re-instantiate themselves as they run.

Cybernetic

Cybernetics is a meta-discipline that aims to describe and understand systems and processes from very different domains with the same set of fundamental concepts. It was constituted as a field in the Macy conferences organized by Warren McCulloch from 1946 to 1953, who invited the leading scientists of the times from fields like anthropology, mathematics, neurology, psychiatry, biophysics, and others.[16]

16 Hayles, N. Katherine. 2008. How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics. Chicago: University of Chicago Press.

The Cybernetic section of this book explores the world as a system (as manifested in First Order Cybernetics) and leaps into the new cybernetics of participatory environments where systems are in fact actor, agent, and observer dependent (as seen in Second Order Cybernetics). This connection is based on a feedback loop, where the participant and the environment are just as much a part of the system as the algorithm (and interface to the algorithm) itself. As with the machinic, cybernetic systems can be seen as having diagrammatic and materialized forms. Because of this, cybernetics could be seen as a branch of the machinic.[17] One of the key differences between cybernetics and other machinic systems is the approach. While other systems tend to approach the *question of technology* by seeking to shape the frame, re-enframing the world, cybernetics attempts to change the manner in which we associate with technology altogether by engaging the processes of nature as part of a system.

17 Guattari considered the cybernetic as fit for his description of the machinic. see Guattari, p. 144.

As the pioneering cybernetic artist Roy Ascott, states:

> In this sense, art itself becomes, not a discrete set of entities, but rather a web of relationships between ideas and images in constant flux, to which no single authorship is attributable, and whose meanings depend on the active participation of whoever enters the network. In a sense, there is one wholeness, the flow of the network in which every idea is a part of every other idea, in which every participant reflects every other participant in the whole... The observer of the 'artwork' is a participator who, in accessing the system, transforms it.[18]

18 Ascott, Roy, 2003. Telematic Embrace: Visionary Theories of Art, Technology and Consciousness, Berkeley: University of California Press. 199.

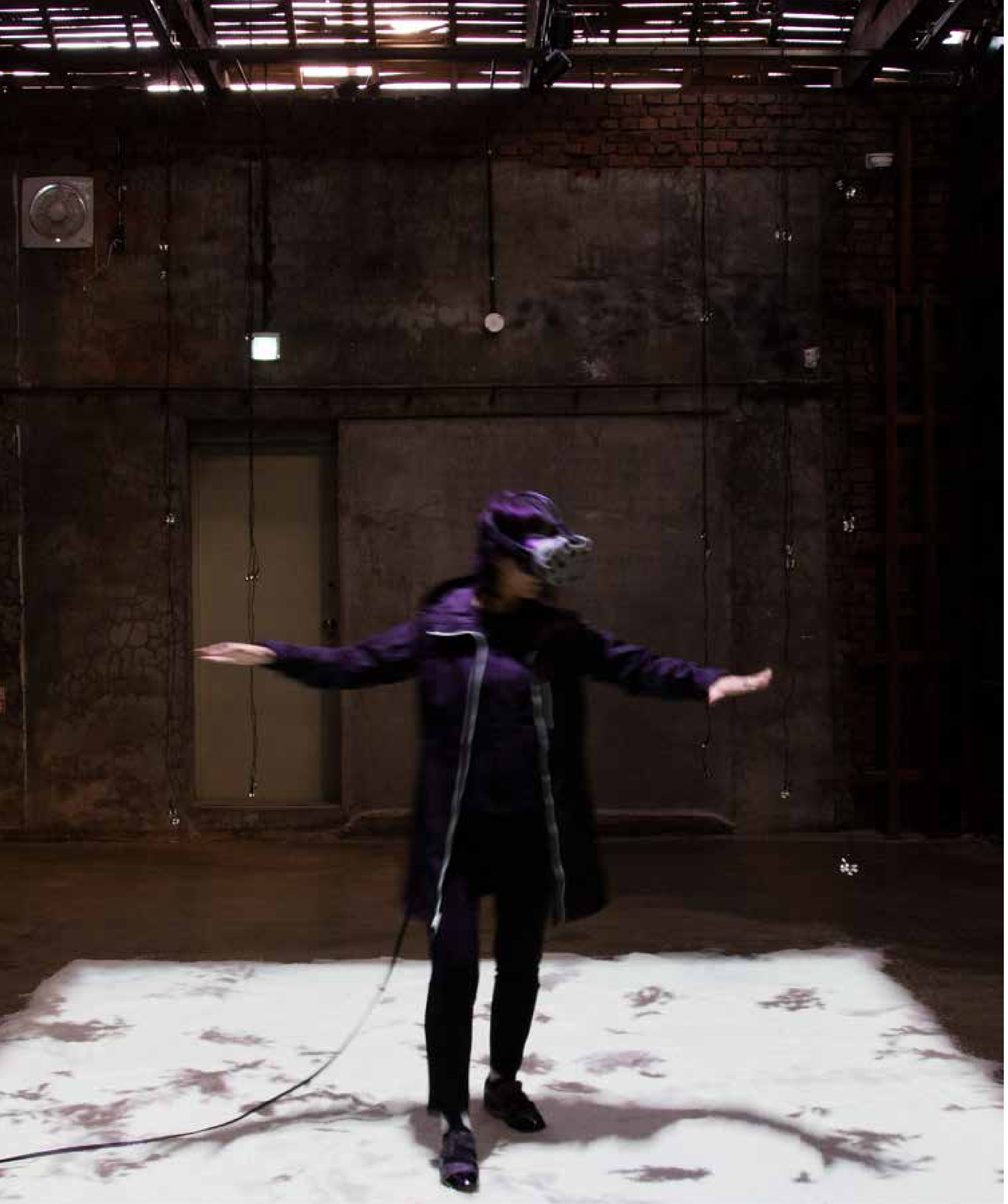
Future Directions

Our ambitious goal in this volume is to attempt to outline practices that challenge the world and its possibilities through a kind of future-making, and/or other-world making. But most importantly, what we strive to create in our work are alternate realities that are simultaneously ontological propositions that can be understood through experience as much as through language. By exploring art as techné we create experiential concepts that enframe the world we live in. In doing so we offer a critical discourse about our world and how the world is constructed.

While the foundation of worldmaking is deeply philosophical and rigorous, there is a need to connect this work to the world of our everyday experience. As we contemplate issues of why we might want to make a world, we are confronted with the responsibilities of making the world as well. There is an ethical urgency in the world today to change from a path of mutually assured destruction to one that leads to viability. In this context, we see the future of a worldmaking based practice as an opportunity to explore the world as it is, and the myriads of ways how it could also be, to make the world a better place for now, and for future generations.

Mark-David Hosale is a computational artist and composer. He is an Associate Professor in Computational Arts at York University, Toronto, Ontario, Canada. He has lectured and taught internationally at institutions in Denmark, The Netherlands, Norway, Canada, and the United States. His solo and collaborative work has been exhibited internationally at the SIGGRAPH Art Gallery (2005), International Symposium on Electronic Art (ISEA 2006), BlikOpener Festival, Delft, The Netherlands (2010), the Dutch Electronic Art Festival (DEAF 2012), Biennale of Sidney (2012), Toronto's Nuit Blanche (2012), Art Souterrain, Montréal (2013), and a Collateral event at the Venice Biennale (2015), among others. He is co-editor of the anthology, Worldmaking as Techné: Participatory Art, Music, and Architecture (Riverside Architectural Press, 2018).

Mark-David's work explores the boundaries between the virtual and the physical world. His practice varies from performance (music and theatre) to public and gallery-based art. The connecting tissue in his work is an interest in knowing. How do we come to know something? How do we know we know? And, how do we express what we know to each other? Through immersive art we are able to create new experiences that express concepts that are beyond language and only genuinely knowable through the senses.



Selected Artificial Natures, 2017–2018

Haru Hyunkyung Ji & Graham Wakefield
OCAD University and York University, Toronto, Canada

1 Ji, Haru Hyunkyung, and Graham Wakefield. 2017. "Biotopes Computationnels (Computational Biotopes)." In Stream 04: Les Paradoxes du vivant (The Paradoxes of the Living). Philippe Chiambaretta Architecte, Paris: 304-316.

Image 1 Conservation of Shadows. Haru Ji & Graham Wakefield, 2017. 330kg salt, 12 nD::Node Arduino boards, 140 motor-actuated bells, 150m wire, Kinect sensors, projector, HTC Vive HMD. Requiem for Hybrid Life, Seoul Museum of Art Chang-go, Seoul, Korea. 2017-10-17 - 2017-10-23. Image by artists

Artificial Nature is a research-creation collaboration co-founded by Haru Hyunkyung Ji and Graham Wakefield in 2007. It has led to a decade of immersive installations in which the invitation is to become part of an alien ecosystem rich in feedback networks.[1] Here we present four recent works in this series between 2017 and 2018.

Inhabitat

Inhabitat is a mixed-reality artwork of creative exploration within an alternate ecosystem of life-forms and a playful engagement with the complex interconnectivity of nature. It was exhibited at MOXI, The Wolf Museum of Exploration + Innovation, Santa Barbara, USA, from August 2017 through January 2018, receiving around 65,000 visitors.[2] *Inhabitat* was born out of a desire to bring biologically inspired complex systems into human-scale physical spaces while displacing the human from the center of the world. *Inhabitat* is a single world that awaits active observation and playful engagement through three distinct perspectives of scale and agency—three ways to see with other eyes. At the macro-scale, the entire world is experienced as projection-mapped landscape of sand upon a hand-sculpted substrate that forms the centerpiece of the exhibit. Visitors may wander freely around the landscape observing the behaviors of the alien life-forms that inhabit it as they busily forage, metabolize, reproduce, and emit sounds. A mediated meso-scale view of the world is projected onto the museum wall behind. By donning a virtual reality (VR) head-mounted display, visitors enter the world at the micro-scale.

Image 2 A participant wearing a VR headset exploring the *Inhabitat* world in the first-person micro-perspective.

2 Ji, Haru Hyunkyung, and Graham Wakefield. 2018. "Inhabitat: An Imaginary Ecosystem in a Children's Science Museum." Leonardo 51.4: 343 – 348.

Image 3 *Inhabitat.* Haru Ji & Graham Wakefield. Sand-sculpture augmented reality, head-mounted virtual reality, large-scale projection. Interactive Media Theater, MOXI (The Wolf Museum of Exploration + Innovation, Santa Barbara, USA. 2017-08-11 - 2018-01-08 (Commissioned). A participant interacting with the *Inhabitat* world at the macro-perspective. Behind the participant is a third-person perspective as the camera follows one creature in the world at a time.

Conservation of Shadows

Conservation of Shadows is a site-specific mixed reality installation artwork for the Seoul Museum of Art Chang-go in the Seoul Innovation Center, Korea. This gallery was previously occupied by the Korea Center for Disease Control and Prevention for medicinal storage and animal experimentation. This work responds to very specific history of the host venue as a former centre for disease control and reagent storage, through a central conception of shadows as shared physical images between visible and invisible worlds. For this historically charged space we imagined unknown new beings growing fond of the wet texture of old wood, the fragrance of sunshine smeared between cracks, and the quietness of murmuring and whispering. To let them live, we extended senses to mix realities surrounded by softly ringing bells and the crunch of salt underfoot as their shadows pass by; and an alternate perspective through head-mounted display in which we become the shadows around which new beings play.

Image 4 *Conservation of Shadows* Haru Ji & Graham Wakefield. 330kg salt, 12 nD::Node Arduino boards, 140 motor-actuated bells, 150m wire, Kinect sensors, projector, HTC Vive HMD.

Image 5 *Requiem for Hybrid Life,* Seoul Museum of Art Chang-go, Seoul, Korea. 2017-10-17 - 2017-10-23.

Insuperposition

Insuperposition is an installation constituting an immersive, multi-perspective virtual ecosystem of vegetal and motile creatures subsisting on island-like topologies. Visitors experience the work as mixed reality: an ecosystem in which, through various interfaces, they become one component among many. The topologies are physical sculptures of CNC-cut cardboard covered with a non-drying sand to allow continual reshaping, sensed by depth cameras and projected upon from above. Visitor's shadows destroy and refertilize the land, and movements distribute thousands of seeds through the spaces between islands. With the VR headset, visitors are shrunk to around one inch in height upon the islands, surrounded by foraging quasi-species lifeforms, chirping their songs around the worlds. The change of spatial scale is echoed in a change of temporal scale on the large gallery wall, where a time lapse at a slower vegetal phenomenology scanning around the islands gradually unfolds. The interfaces and boundaries of this ecosystem, its conditions and its regularities, are probabilistic and responsive to human interaction, however the importance of the human is limited. While you can become part of the ecosystem, your role is not dominant; the world will also thrive without you. It is an infinite game evolving from inside and outside, and an alternate world in superposition to us.

Infranet: Gwangju

Our city is an organism of infrastructure and transport. Born curious, we observe it, explore it, and metabolize, taking on views contagiously, excitedly, or by sway. Sometimes our associations are too scattered, sometimes too close-knit. The living Gwangju we draw observes itself, spawning immune responses against overwhelming communicability, evolving variety over variety. We may become more or less factory, farm, or forest. Let us see what unfolds.

Infranet: Gwangju is a generative artwork interweaving machine learning and evolutionary algorithms in a population of artificial life agents, thriving upon geospatial data of the infrastructure of Gwangju city as its sustenance and canvas. Each agent has a neural network open-endedly developed through the technique of neuro-evolution of augmenting topologies. However the genetic information that defines the neural networks is not simply inherited, but spreads rapidly through horizontal (lateral) gene transfer, as a form of social network communication between agents. Each agent has a goal to draw out geospatial features such as commercial or residential buildings, water or electricity tracks, as well as various roads and pathways of Gwangju city. Then through sync (entrainment) pulses, what has been learned is absorbed by the most differentiated neighbors. Observing eyes continuously surveil agents, however they appear to produce ever-changing patterns without need for extra regulation. It an aesthetic-cybernetic experiment in homeostasis as precursor of heterostasis.

Image 6 ***Insuperposition***. Haru Ji & Graham Wakefield. Sand, CNC-cut cardboard, projected augmented reality, motion sensing, head-mounted virtual reality, large-scale projection, loudspeakers.

Image 7 Daejeon Biennale 2018 "Bio", Daejeon Museum of Art, Daejeon, Korea. 2018-07-16 - 2018-10-24.

Haru Ji is a media artist exploring the subject of life in art through artificial life worldmaking, and co-creator of the research project, Artificial Nature. She holds a Ph.D. in Media Arts and Technology from UCSB and is an assistant professor in DPXA & the Digital Futures programs at OCAD University in Toronto, Canada. Artificial Nature is a collaborative research-creation project since 2008 concerned with the creation of immersive virtual ecosystems. Artificial Nature artworks have been presented in art festivals, conferences, and venues including SIGGRAPH, ISEA, EvoWorkshops, La Gaite Lyrique, ZKM, CAFA, MOXI, the AlloSphere, and Seoul City Hall, and recognized in the 2015 VIDA Art & Artificial Life competition and the 2017 Kaleidoscope Virtual Reality showcase.

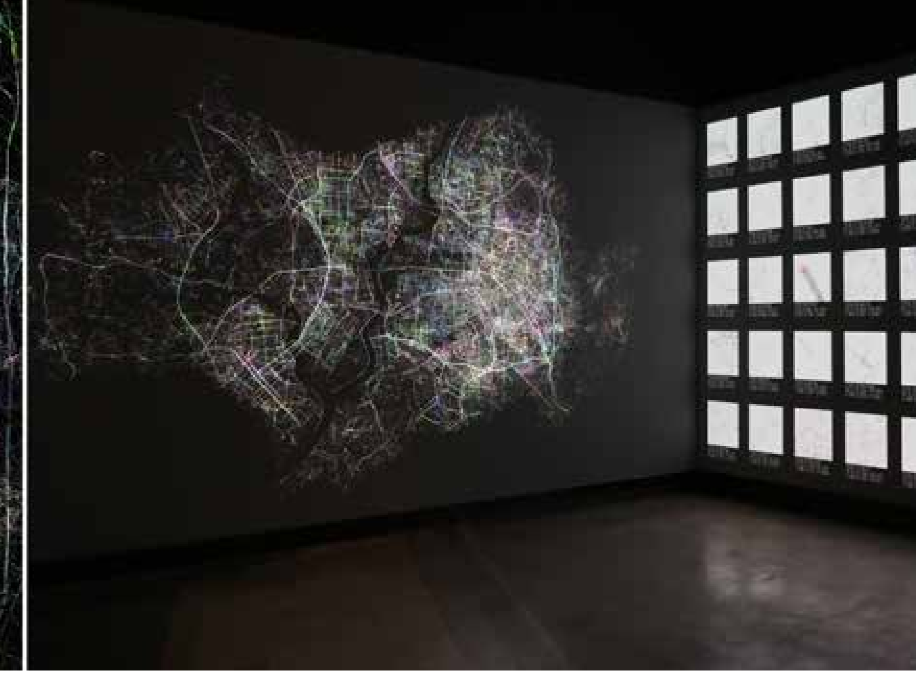


Image 8 ***Infranet: Gwangju***.
Haru Ji & Graham Wakefield.
Projections, Sound, Evolutionary Neural Networks, Geospatial Visualization.

Image 9 Gwangju Media Art Festival 2018 "Algorithm Society: Birth of The Machine-God", Asia Culture

Center (ACC), Gwangju, Korea.
2018-11-28 - 2018-12-7.

Infranet: Gwangju website:
https://artificialnature.net

Graham Wakefield is an artist-researcher and software developer exploring the liveness of computation across immersive media. As Assistant Professor in Computational Arts and Canada Research Chair in Interactive Visualization he directs the Alice Lab at York University. The lab develops transferable knowledge and creative coding technology as well as intensifying computationally literate art practice in the construction of responsive artificial worlds experienced through rapidly emerging mixed/hybrid reality technologies including both Virtual Reality (VR) and Augmented Reality (AR), including the Artificial Nature series. Inspired by the creativity of nature, its research-creation program leverages strong simulation and the self-modifying capacity of computational media to create artificial worlds whose rules can be rewritten while participants interact within them for heightened levels of human-machine interaction and intensified aesthetic engagement using the whole body.

The Work of Terreform ONE

Mitchell Joachim
Terreform ONE and New York University, USA

Alternative Practice

Image 1 Cricket Shelter and Farm Credit: Mitchell Joachim, Terreform ONE

At this stage, we've deliberately sought to avoid maintaining a traditional architecture office. We did not desire to ceaselessly toil for a private client or affluent developer. To operate as a nonprofit group inside a cluster of other innovative tech companies marks us as distinctive. Our studio space is similar to a "science garage." The garage has long been the pinnacle of American invention. It's an informal anarchic space where everything can be physically manipulated. There is nothing sacred in a garage. One can also identify them as "hackerspaces." Located in an urban fringe zone, such a variegated space departs drastically from the cherished atelier models of previous centuries. We find this flowing topology the best-suited spatial arrangement for producing projects that react dynamically to undeviating, transient, or long-lasting issues.

As architectural designers confronted with a cumulative assortment of technical, manufactured, formalistic, and speculative alternatives, it becomes a formidable task to find a focus. It becomes simpler to mix one's designs from numerous sources and check its justification to the measurable and physical aspects, be it scientific or economic. This narrow-minded inclination, arguably resulting from a reaction to the utter expansive nature of the field, from our outlook, has led to a palpable level of indifference resulting in abundant forms of conflict within the discourse. This anesthetized state within which others function becomes an involuntary proliferation of the banal, the exceedingly consumptive, the inconsequential, and the haphazard. If the concern is toward extending the influence of good design without surrendering its profound qualities, then it becomes essential that the discipline is infused by architects who are analytically considerate of the ramifications of their work from biological, native, regional, and global standpoints.

Architectural designers need to work within nature. The mixture of hi-tech tuning and formalistic liberties that are available to designers today can be significantly developed only through critical foundational principles in each scheme; a grounding which stresses design to pursue consequence by probing the greater and obscured natural environments of every discrete project. Such expeditions of critical discourse and attentiveness necessitate exactitude but, foregoing that, an inclination, which can be encouraged during the developmental stages of a given aspirant's architecture education. Ultimately for architects, and their education, it ought to be almost indistinguishable from lessons in biology. Admittedly, the agency of architecture has yet to achieve this union. Our aim is to push the theoretical nature/design boundary until it becomes permanently fused.

Primary Principals

Our research topics span over twenty years of illuminating environmental issues as an amalgam of anthropocentric and ecologically balanced artifacts, procedures, and spaces. Over this period, it has established works that serve as an interdisciplinary authority in nature-intensive design operations at the intersection of art, architecture, and cities. Searching for how design intentions are derived and why they are cultivated into tangible site-specific interventions, the work is fortified in embodied knowledge or an understanding attained through practice and field deployment. These arts intensive schemes find continuous dissemination for public consumption.

Currently, there is no prevailing distinct set of enduring methodologies or theoretical approaches that define a designer. We are inclined to work within a shifting cohort of creative arts practitioners that channel DIY communities, anti-discipline factions, hacker enclaves, well-intentioned entrepreneurs, makers, crowdsourcing advocates, and ample other creative outlets. These are fluid tactical linkages used to decipher boundless design problems. In most cases, our generation is unified at solving a host of fluctuating wicked environmental problems. Concerns in climate dynamics, uncontrolled urbanization, lack of social justice, and deficient housing are the explicit challenges we seek to answer though formidable acts of architectural design.

Architectural design, in and of itself, has astonishing power. It's also simultaneously both perpetual and ethereal, like painting a watercolor in a stream. Design is not art. Contrariwise, the differences between art and design are heavily muddled. Design can juxtapose imperceptible properties and just as equally foreground the obvious general physics of almost any challenge. We see design as an action that blends benevolence with radical intelligence. Virtuous architectural designers work together to invent original contributions towards refining human knowledge. Architectural design today, as we see it, is an open, free, limitless, and an exceptionally self-governing process.

Teaching Elements

The following directives characterize our views that generate the teaching methods in a workshop, seminar, or architecture studio setting. It is the confluence of a spirited equanimity amongst methodological priorities, student inputs, and critical interests that trace the roots of our instruction.

We instinctively care about teaching and working with engaging thought-provoking scholars. For this explicit reason, we are continuing to pursue academia on numerous levels. We passionately believe that teaching and research must balance each other. We've had the privilege to be exposed to diverse pedagogical methods and extraordinary mentors within our own completed degree programs. These influential academicians from dozens of wide-ranging fields have undeniably tested and shaped our philosophy as university professors and design practitioners.

Predominantly, we think that successful teaching consists of two key components: first, inspiring the students by being impassioned about the topic and second, elevating them to vigorously learn the subject through active participatory group exercises and to invoke solutions by themselves independently beyond class. In our educational experience, we have attempted to not merely deliver the material, but to aid students in comprehending the perceptions behind architectural design choices and have them interrelate with other colleagues. For instance, when deliberating the trade-offs of dissimilar design tactics, we involve students by posing step-by-step queries and by soliciting reactions from them. This permits students to transmit the material, emboldens them to come up with the benefits and constraints of numerous frameworks on their own and enables us to evaluate their understanding. We trust that this approach and other methods help scholars develop valuable experiences that open pathways to designing superior techniques themselves. We also believe that hands-on proficiency is essential for students to cognize the tangible experiments of architecture. Additionally, we've continually crafted and improved upon syllabi for the interdisciplinary courses we have taught for years. We've advised students to participate in advanced studio sequences that focus across deep-learning multivalent research endeavors. We believe that wicked problems created by certain adverse activities of society can only be solved by equally rigorous efforts of humankind buttressed by in-depth edifying measures.

Teaching at the university level is a clear privilege and an undertaking that can attain immense gratification. We've been teaching in the role as professors in various fields of art, architecture, environment, biology, media, and transportation. Our instruction primarily revolves around issues of ecological design thinking. For the most part, students we've encountered have been extraordinarily affable, intelligent, and prolifically creative. They are almost all interested in being challenged. Many of them are focused and dedicated to intellectual purists that will evolve their current worldview. Students, we've found, are seeking to keenly reshape and amplify their individualized filters of reason. They wish to grasp the ideas and methods of architecture education and nurture concepts themselves.

Customarily, we have design students in a conservatory-based learning model bent on a single pre-defined concentration. Instead, we encourage them to seek new adaptations to their education as a young newfangled artist, architect, designer or something else entirely. They often wish to include overlapping interests culled from separate fields of knowledge. In short, they are fascinated being taught something that is atypical.

Our courses are deliberately attenuated and tailored to gather a myriad of individualized modes of expression. We've found each and every student has a particular skill set they like to communicate in class as answers for assignments. We are delighted to accommodate their method of choice to manifest a unique resolution in their projects.

Design Research

An appetite for innovation and change drives the research work we do. This requires many vantage points to address a given investigation. Therefore, it's important to emphasize our research is intrinsically collaborative in nature. We almost always work in teams of assorted disciplines and heterodox knowledge sets.

Our hypothetical explorations, in the most fundamental of interpretations, are in the study of socio-ecological design and architecture. A nascent term that recognizes science-based design alone is not enough to confront the enormous issues facing humanity with regards to climate dynamics. It is our understanding that no matter how comprehensive the technical solutions are to climate change, the socio-cultural constraints are a considerable factor. The knowledge of ecology combined with various methods of design is necessary to achieve planetary stability, but only in tandem with corresponding societal elements. That is why we describe it specifically as socio-ecological designing, not merely eco-design, sustainability, green or biomimicry. Even if the key factors in both science and design are tenable, the capricious public still may have an opposite perspective. We've been making headway in this self-defined interdisciplinary approach for almost two decades.

Research is the area of work we sense has been our most successful contribution. At Terreform ONE, we've been able to complete numerous projects that bring the elements of socio-ecological design to a greater level of depth, consistency, and refinement. We've explored these issues at three primary scopes of inquiry: mobility, architecture, and urbanization. We've been designing environmentally-driven transportation systems, buildings, and urban neighborhoods since 2006. They are all cross-linked and integrated with one another at different scales of operation to mitigate issues of waste, energy, water, materials, sustenance, and air quality. All of them are grounded and manifested in substantially visual items. A few key examples are: Urban Tangle spliced map fragments, Mini-stacking electric cars for China, Mycoform structures grown from strains of fungi, Gen2Seat biopolymer compostable chair, Governor's Hook resilient waterfront infrastructure made of decommissioned military ships, and the Bio City Map of 11 Billion People using genetically modified E. coli colonies as printed geographies.

Public Outreach

Outside of the local spectrum, we're also responsible for enlivening the public in an international dialogue on ecological design, art, and urban culture. In this manner we serve as noted public intellectuals and directors of the research institute, Terreform ONE, presenting arguments that help justify the meaning and power of design in relationship to local communities and planetary metabolism. We are intensely involved in publicly speaking, visualizing, and writing about our discipline and how it relates to the cultural and social world around it. This kind of discourse is extremely crucial, and it involves good, clear, simplified explanations of design that bridge many mindsets. Our projects aim to remove obstacles that distort meaning or fail to connect with the general public. Our objective is to annihilate the effects of climate change through spatial and visual vocabularies that promote ecological design thinking.

Project: Cricket Shelter

The UN has mandated that insect-sourced protein will become a major component in solving global food distribution problems. This impacts people globally, since continuing to raise livestock is not possible at our current rate of consumption and resource extraction.

It is a well-established fact that industrialized animal agriculture accounts for a fifth of all human greenhouse gas emissions. With global demand for meat projected to double by 2050, the industry's land requirements constitute one of the most significant drivers for deforestation in the world. This project proposes an alternative: with 1% of the greenhouse gas emissions and requiring 0.001% the land to produce the same amount of protein annually as cattle farming, we feel that environmental destruction need no longer be the consequence of ensuring our food supply. Cricket Shelter is a prototype for an urban farming strategy that minimizes the ecological footprint of protein-rich food production.

The continuous impact of climate dynamics, armed conflicts, non-stop urbanization and economic upheavals present a distinct need for a hybrid architectural typology to deliver parallel solutions for food and shelter in distressed regions. Our proposal is a dual-purpose shelter and modular insect farm in one structure.

Raising cattle, pigs, and chickens for meat all require immense amounts of fresh water, land and energy. Breeding insects for food typically takes three hundred times less water for the same yield of protein. Our project aims to maximize access to nutrient resources and to support local communities in anticipation of post-disaster scenarios. This also targets societal upgrading strategies in both developed and developing countries as the temporary shelter easily converts to a permanent farming system/eatery after the crisis has dissipated.

Cricket Shelter is a self-sufficient, interconnected array of structural pods that fosters an optimal environment for supporting the life cycle of crickets. The embedded ecosystem was developed to permeate the structural system, each independent module linked by tubes connecting the elements to render the crickets "free-range." Whereas in many parts of the world entomophagy is more common but contamination is more likely, Cricket Shelter's innovative process offers a sanitary and hygienic solution.

Cricket Shelter was conceived as a hybrid architectural typology delivering parallel solutions for food and shelter in distressed regions throughout the world. As a modular structural system it lends itself to simple construction and deconstruction in various site-specific orientations, making it easy to educate consumers on use and maintenance. As an architectural object, the shelter can contribute to the public realm inhabiting into vacant lots, pocket parks, and rooftops, bringing agriculture and entomophagy into focus for the local populations. In this way we can fulfil our aim of educating the public about their role in sustainable consumption

Credits

Terreform ONE
Mitchell Joachim (PI), Maria Aiolova, Melanie Fessel, Felipe Molina, Matthew Tarpley, Jiachen Xu, Lissette Olivares, Cheto Castellano, Shandor Hassan, Christian Hamrick, Ivan Fuentealba, Sung Moon, Kamila Varela, Yucel Guven, Chloe Byrne, Miguel Lantigua-Inoa, Alex Colard.

Sponsor: Art Works for Change.

Project: Monarch Sanctuary

Our mission is to design against extinction. The monarch butterfly of North America is a species at risk. The U.S. Fish & Wildlife Services is currently assessing whether the monarch needs to be granted "endangered species" status, while the monarch population erodes due to the combined forces of agricultural pesticides and habitat loss. Monarchs are a delicate presence in New York City.

Monarch Sanctuary will be eight stories of new commercial construction in Nolita, NYC. Central to its purpose is serving as a breeding ground and sanctuary for the threatened monarch butterfly. It aims to be socio-ecologically robust, weaving butterfly conservation strategies into its design through the integration of monarch habitat in its façade, roof, and atrium. Not just a building envelope, the edifice is a new biome of coexistence for people, flora, and butterflies.

The double-skin street façade, with a diagrid structure infilled glass at the outer layer and with "pillows" of ETFE foil at the inner layer, encloses a careful climate - controlled space, 3' deep. This "vertical meadow," the terrarium proper, serves as an incubator and safe haven for Monarchs in all seasons. It contains suspended milkweed vines and flowering plants to nourish the butterflies at each stage of their life cycle. Hydrogel bubbles maintain

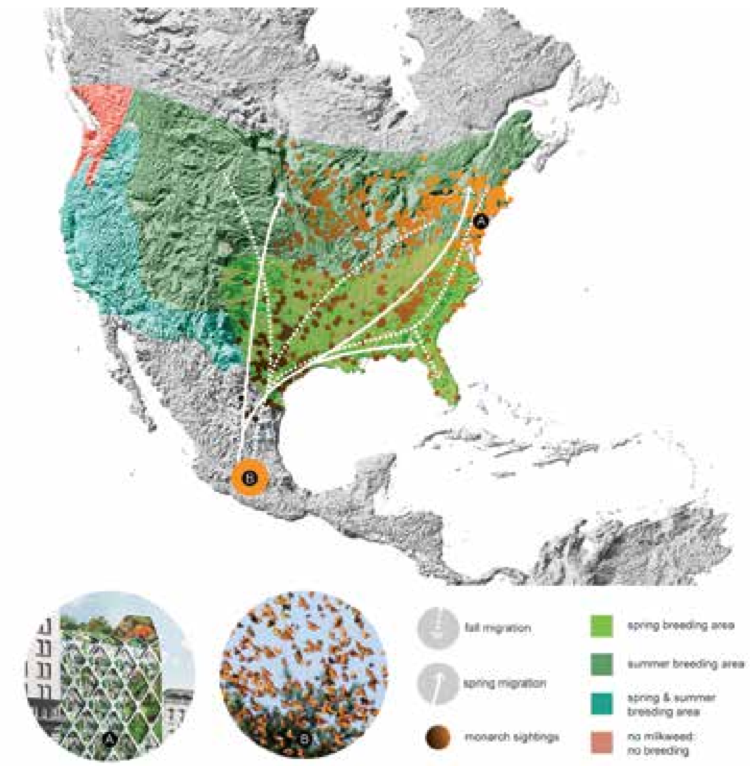
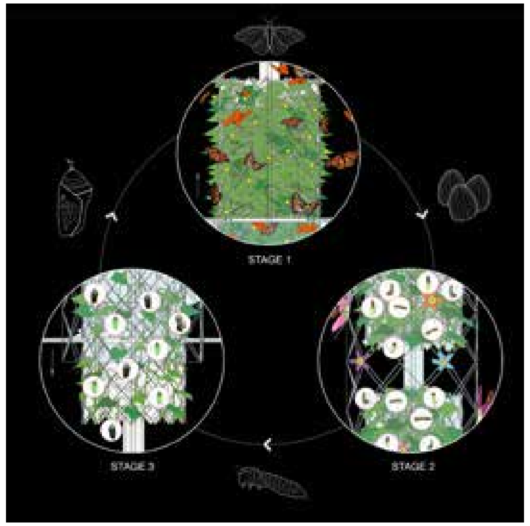


Image 2 Annual migration pattern of monarch butterflies from the United States to Mexico

Image 3 Building section perspective mapping the trajectory of butterflies from across the street Petrosino Park through the double-skin facade vertical meadow finally up to the pollinator rooftop garden.



optimal humidity levels, and sacs of algae purify the air and wastewater. LED screens at the street level provide magnified live views of the caterpillars and butterflies in the vertical meadow, which also connects to a multi-story atrium.

Image 4 Linked stages of milkweed columns and butterfly life cycle:

Stage 1: Milkweed column rises from glass casing. Fresh milkweed exposed to butterflies allowing them to lay eggs

Stage 2: Milkweed column fully contained within glass casing. Caterpillar development isolated from butterflies. Leaf count slowly diminishes.

Stage 3: Milkweed column lowers from glass casing. Chrysali and hatching butterflies exposed to inner facade. Little leaf structure remains on column.

Image 5 An architecture that aims to be ecologically generous, weaving butterfly conservation strategies into its design through the integration of monarch habitat in its façades, roof, and atrium. Not just a building envelope, the edifice is a new biome of coexistence for people, plants, and butterflies.

An Ecological Building Façade System Designed to Stop the Extinction of the Monarch Butterfly

How the Design Anticipates the User Experience and Benefits Society

The building will present a striking public face and a powerful argument in favor of a diversity of life forms in the city. The façade of the Monarch Sanctuary building will add a lush vertical meadow for butterflies.

The building is intended to serve as an object lesson in enhancing the urban environment with green technologies, including plant life and other creatures, in designing for other species, and in conveying images of new possibilities for the urban environment. This project alone will not save the Monarch but it will crucially raise awareness about our much-loved insect residents.

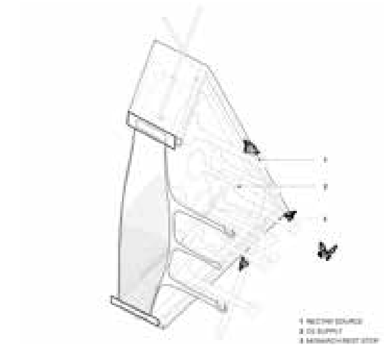


Image 6 3D Printed prototype featuring elongated spoons as vessels of nectar dispersion.

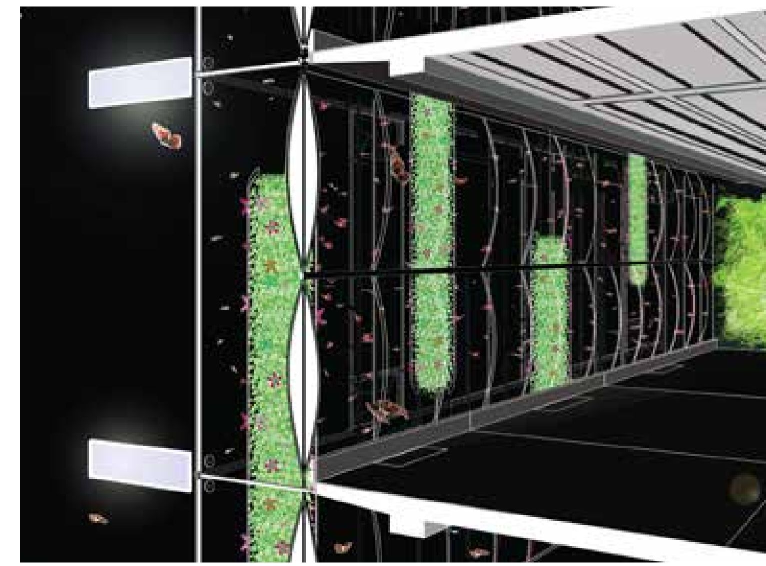


Image 7 Wall section perspective emphasizing rising milkweed growing cylinders located between outer glass and inner ETFE foil panels.

How the Design is Original and Innovative

The innovation of this project is to serve as a large-scale Lepidoptera terrarium. This type of façade has never been constructed before in any known context. It will bolster the monarch's presence in the city through two strategies: open plantings of milkweed and nectar flowers on the roof, rear façade, and terrace will provide breeding ground and habitat for wild monarchs, while enclosed colonies in the atrium and street side double-skin façade will grow monarch population. The insects will be periodically released to join the wild population, enhancing overall species population numbers.

How the Design Captivates

Key features of the project are equally in service of the insects are meant to captivate people. Giant LED screens on the surface of the building provide a spectacle of caterpillars, chrysalis, and butterflies. Interior partitions are constructed from mycelium, and additional planting at the ceiling enhances the interior atmosphere and building biome. The entire project is meant to make ecological systems visible to the public in as many scales as possible.

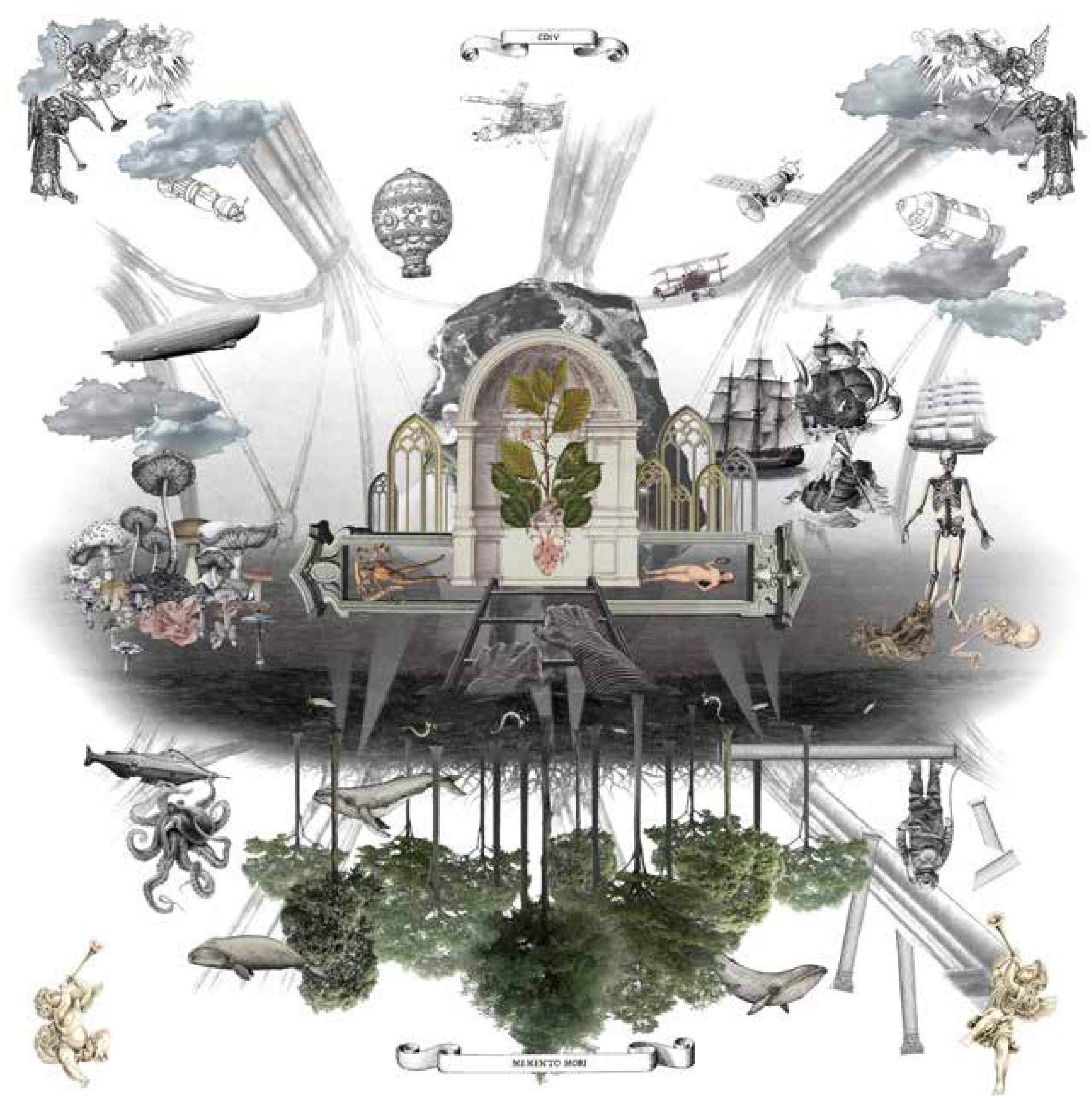
Credits

Terreform ONE
Principal: Mitchell Joachim.
Project Management: Vivian Kuan.
Designers: Christian Hubert, Nicholas Gervasi, Maria Aiolova, Anna Bokov, Kristina Goncharov, Yucel Guven, Zhan Xu, Larissa Belcic, Shahira Hammad, Deniz Onder, James Leonard, Zack Saunders, Xinye Lin, Sabrina Naumovski, Daniel S. Castaño, Aidan Nelson, Aleksandr Plotkin, Kristian Knorr, Sophie Falkeis, Rita Wang, Michael Brittenham.
Tech Consultant: Anouk Wipprecht.
Sponsors: BASF, Intel, RNR Foundation.

Image 8 Lobby interior with lush butterfly atrium ascending through the building and mycelium and moss planted wall

Image 9 Enlarged detail of ETFE algal sacks, milkweed caterpillar chambers, and recycled aluminum exterior structure.

Mitchell Joachim, Ph.D., Assoc. AIA is the Co-Founder of Terreform ONE and an Associate Professor of Practice at NYU. Formerly, he was an architect at the offices of Frank Gehry and I.M. Pei. He has been awarded a Fulbright Scholarship and fellowships with TED, Moshe Safdie, and Martin Society for Sustainability, MIT. He was chosen by Wired magazine for "The Smart List" and selected by Rolling Stone for "The 100 People Who Are Changing America". Mitchell won many honors including ARCHITECT R+D Award, AIA New York Urban Design Merit Award, 1st Place International Architecture Award, Victor Papanek Social Design Award, Zumtobel Group Award for Sustainability, History Channel Infiniti Award for City of the Future, and Time magazine's Best Invention with MIT Smart Cities Car. He's featured as "The NOW 99" in Dwell magazine and "50 Under 50 Innovators of the 21st Century" by Images Publishers. He co-authored three books, XXL-XS: New Directions in Ecological Design, Super Cells: Building with Biology, and Global Design: Elsewhere Envisioned. His design work has been exhibited at MoMA and the Venice Biennale. He earned: PhD at Massachusetts Institute of Technology, MAUD Harvard University, MArch Columbia University.



Tomorrowland

Manuel Kretzer
Anhalt University of Applied Sciences, Dessau, Germany

Part 1: Change

In 1978 the science fiction writer Isaac Asimov published an essay titled 'My Own View', in which he stated:

> It is change, continuing change, inevitable change that is the dominant factor in society today. No sensible decision can be made any longer without taking into account not only the world as it is, but the world as it will be. […] This in turn means that our statesmen, our businessmen, our everyman, must take on a science-fictional way of thinking.[1]

This kind of change, which Asimov already described some forty years ago, becomes ever more obvious today. We live in a time where technology is multiplying around us at an ever-increasing pace. If we are to believe

1 Isaac Asimov, "My Own View," In Asimov on Science Fiction (Garden City: Doubleday, 1981), 5.

Image 1 Tomorrowlands
Fabrizio Silvano, Institute of Media and Design, Technical University Braunschweig, 2017
Image of student work, created during a 24 hour short project, depicting visions of the year 2050. The images were to be based on current developments and tendencies, which could be technological, geographical, geological, social, cultural, psychological, physiological, or a combination.

the Director of Engineering at Google Ray Kurzweil, who has analyzed the growth rate of various technological systems, then by 2045 this development will lead to a certain state of Singularity, a point where progress will be so fast that it exceeds our ability to comprehend it, implying an infinite rate of change happening momentarily.[2] Once this moment has been surpassed mankind will reach a state of transhumanism, where human will merge with intelligent machines and through this surmount the biological restraints of its physical and psychological constitution.

A similar kind of growth can also be observed demographically. Since 1960 the world population has more than doubled, growing from 3 billion to about 7.5 billion today. According to a 2014 UN study, it is expected to rise to roughly 10 billion people by 2050,[3] and 70% of them are going to be living in large megacities.[4]

At the same time the average global life expectancy has in the last 100 years increased from 46 years of age in 1910 to 70 in 2014 and is supposed to exceed 76 by mid-century.[5]

By 2050 we will also need 80% more energy than today,[6] consume up to 90% more food,[7] have more trash in the ocean than fish,[8] almost every vehicle on the planet will be autonomous and self-driving, and apparently human-robot or human-computer relationships could have become common. Obviously all these tendencies not only have an impact on ourselves and our behavior as a species but also on our planet's ecological system, its biodiversity, climate and atmosphere. An impact that is actually so severe and irreversible that scientists are proposing to constitute a new geological epoch: the Anthropocene - the age of humans.

The Anthropocene is a period, beginning in the 1950s with atomic bomb testing, throughout which the face of earth has been largely defined by human activity. However, the Anthropocene is not only a time of man-made disruption, it is also - at least more recently - a moment of awakening, of blinking self-awareness in which we are becoming conscious of ourselves as a planetary force. We are not only driving global warming and ecological destruction, we *know* that we are.

Ironically, it is only by despoiling the planet that we have understood just how much a part of it we are. But what to do when everything one does

2 Ray Kurzweil, The Singularity is Near: When Humans Transcend Biology (New York: Viking, 2005), 9, 56-57, 136.

3 Central Intelligence Agency, "The World Factbook, Country Comparison: Life Expectancy at Birth," accessed July 22, 2013, https://www.cia.gov/library/publications/the-world-factbook/rankorder/2102rank.html.

4 Mark Wilson. (2012). By 2050, 70% Of The World's Population Will Be Urban. Is That A Good Thing?. Available: https://www.fastcodesign.com/1669244/by-2050-70-of-the-worlds-population-will-be-urban-is-that-a-good-thing. Last accessed Feb. 27, 2017.

5 Central Intelligence Agency, "The World Factbook, Country Comparison: Life Expectancy at Birth," accessed Feb. 27, 2017, https://www.cia.gov/library/publications/the-world-factbook/fields/2102.html.

6 Kumi Kitamori. (2012). OECD Environmental Outlook to 2050: The Consequences of Inaction - Key Facts and Figures. Available: http://www.oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaloutlookto2050theconsequencesofinaction-keyfactsandfigures.htm. Last accessed Feb. 27, 2017.

7 Maarten Elferink and Florian Schierhorn. (2016). Global Demand for Food Is Rising. Can We Meet It?. Available: https://hbr.org/2016/04/global-demand-for-food-is-rising-can-we-meet-it. Last accessed Feb. 27, 2017.

8 Graeme Wearden. (2016). More plastic than fish in the sea by 2050, says Ellen MacArthur. Available: https://www.theguardian.com/business/2016/jan/19/more-plastic-than-fish-in-the-sea-by-2050-warns-ellen-macarthur. Last accessed Feb. 27, 2017.

becomes an environmental question? When every time we start the engine of our car, every time we pick up a plastic bag in the supermarket, every time we eat a burger at McDonald's, we change the world? And it is not because of our individual actions but it is due to our collective acta as a species.

Part 2: Adaptation

So the question I think we should be asking is not whether climate change or any other of these "things" are real, nor when they will happen, since it doesn't really make a difference if it's in five or ten or fifty years. The question would be "What is the most human and sustainable way to adapt?" or as Norbert Wiener put it in 1954:

> We are the slaves of our technical improvement and we can no more return a New Hampshire farm to the self-contained state in which it was maintained in 1800. [...] We have modified our environment so radically that we must now modify ourselves in order to exist in this new environment. We can no longer live in the old one.[9]

Unfortunately, when facing unprecedented challenges, oftentimes we tend to do the exact opposite to Wiener's suggestion. Instead of adapting, changing, evolving and trying to understand the cause and reason of these events, we block their symptoms through a viscious fight for preservation. We build walls against rising sea levels, walls to keep those in need away from those who have, walls as the encapsulating response to a growingly globalized world.

Maybe it is time to reconsider our attitude; maybe it is time to stop fighting change, stop mourning after the good old days and instead embrace it as something from which the new can emerge. And in that context, transformation and mutation, paired with a good portion of optimism and curiosity at what the future might behold, may create environments and experiences that can adapt, grow, evolve and include rather than excluding.

Returning to the acceleration in technological progress I personally see amazing potential in developing solutions based on adaptive materials, solutions which have not only one single state or purpose but which behave multidimensionally. Such materials can change their shape, change their

9 Norbert Wiener, The Human Use of Human Beings: Cybernetics and Society (Garden City: Doubleday, 1954), 46.

color, produce light or electricity, store heat or water, or even adjust their surface texture. However, despite a growing interest in the performative aspects of this kind of materiality, most design scenarios are still rather traditional and far from exhibiting any of the radical opportunities that these materials offer.

There are several reasons:

Firstly, many new materials are still technologically immature and often not developed with respect to design or architectural applications. Even when they are available as finished products, they have rather narrow properties since they are always designed for a very specific purpose, limiting their scalability and durability.

Secondly, there is a big gap between the artistic disciplines and scientific research. The amount of information on new material developments that is comprehensible without having expert knowledge or insights is very limited and often scientifically mystifying.

And lastly - and this is something that we as designers have to address - there is a lack in ideologically distinguishing smart materials from traditional ones. The defining dynamic properties are either constrained by forcing them onto existing structures and systems, or even neglected by standardizing and categorizing them to make them comparable to non-active materials and include them in existing databases and catalogues.

In an attempt to overcome these issues, since 2012 I have initiated 'materiability' - an online platform, an educational framework and open materials database that provides in-depth access to emerging material developments. The core content is divided into three categories:

1. A constantly growing compilation of physical projects and experiments, which focus on using new materials in a creative and innovative way.
2. A collection of theoretical scientific essays on a growing number of smart materials, which explain the materials in terms of their technological context.
3. A selection of illustrated step-by-step tutorials on how to self-produce emerging materials in an informal environment.

Image 2 Screenshot of Materiability Website, 2017

Part 3: Make

The core idea behind this website, with a strong focus on experimentation and intuition, is similar to what I try to address in my teaching: a philosophy of design by making, which understands design as a dynamic process and not as the result of a predetermined idea; or as Kurt Schwitters described it in 1924:

> Every form is the frozen instantaneous picture of a process. Thus a work is a stopping-place on the road of becoming and not the fixed goal. We acknowledge works which contain a system within themselves, a system which has not been evolved before the work started but has evolved in the course of it.[10]

10 El Lissitzky and Sophie Lissitzky-Küppers, El Lissitzky: Life, Letters, Texts (Greenwich: New York Graphic Society, 1968), 351.

To mediate this concept to my students I run explorative and playful workshops and courses, where the students are encouraged to physically experience the functionality of materials, comprehend their working principles and composition and understand the relationship between fabrication procedures and materials' performance. The results are usually rather speculative installations of the relation to reality and presence which is left open to the students, and where the use, functionality and even the idea have evolved from what was learned and discovered.

Image 3 Phototropia
Chair for Computer Aided, Architectural Design, ETH Zürich, 2011.

One of my favorite projects to date that emerged from this idea is *Phototropia*. The project was realized at the Chair for CAAD, ETH Zürich in 2012. The key topic of this course was "autonomy"- not only in the sense that the designer would become independent from commercially available and industrially (pre)fabricated materials, but also as a method to combine all the applied materials into a self-sufficient system, which would create the energy it required by itself. The materials that we used shared common characteristics. They were thin, flexible and lightweight, and they could be produced following a set of rather simple instructions. Throughout the course, we had produced electro-active polymers, which are thin-film membranes that can change their size or shape in response to a strong electrical field. We created electroluminescent displays, which emit a cold, perfectly homogeneous light in any colour across their surface. We collaborated with scientists from the EPFL Lausanne to produce dye-sensitized solar cells, a type of solar cell that uses an organic dye to convert sunlight into electricity. All these components were merged and held together by a structural system made of bioplastic struts.[11]

11 More info on Photoropia, including video: http://materiability.com/portfolio/phototropia/

Resinance was another project that we did the year after. The core question we asked ourselves was: 'What if we had materials that were - at least to some extent - truly alive?' The final installation, which was a collaboration with TU Delft and Tsinghua University, consisted of 40 hollow plastic elements, which could change their color in response to a change in temperature, both independently but also in unison within a larger system.[12]

12 More info on Resinance, including video: http://materiability.com/portfolio/resinance/

A more recent work resulted from a collaboration with AUDI, *Concept Breathe*. The point of departure here was to rethink the notion of car seat and imagine that - in respect to the future of autonomous driving and an increasing demand for customization and individualization - our cars would become more than mere means of transportation. Instead, they could exhibit aspects of living creatures, to become our friends and companions. The project started with an intense ideation phase. Since we wanted to diverge from classical forms and shapes, we strongly looked into patterns and structures that are available in nature. We then explored how these inspirations could lead to a certain formal language and how they can be described using computer scripts and algorithms. However, we quickly understood that even though it was possible to visualize our geometry, it would be difficult to realize it using conventional technologies. Eventually we teamed up with Berlin based company BigRep, a global producer of large-scale 3D printers, to print the seat in 1:1; a process that took almost ten days to complete. In addition to the 3D printed structure, the seat contains 38 bespoke, active components that were incorporated into its surface to dynamically adjust its visual and haptic properties. And finally, a number of customized cushions from a high-performance fabric were added in five separate areas to guarantee the necessary comfort and stability.[13]

13 More info on the project, including videos: http://materiability.com/portfolio/concept-breathe/

Anima was the second iteration of the aforementioned collaboration with the German car manufacturer. Building upon the experience from the previous project, we again investigated into the future of mobility, this time rethinking the classical middle console in respect to upcoming (autonomous) driving scenarios. 17 students worked in four groups to develop their own specific scenario and design approach. Each group had to address requirements such as functional aspects (e.g. tray or cup holder options), formal expressions (using parametric/ generative processes), technological production (applying digital fabrication techniques), sustainability (e.g. materiality, recycling, etc.), interaction with and adaptation of the system and embedding the object into a larger narrative context.

Alcyon, derived from the Latin word *alcyoneum* (coral), proposes a bio inspired central console produced by 3D printing, using a biodegradable filament made from algae. The structure is further planted with reindeer

Image 4 ***Concept Breathe***, Braunschweig University of Art, 2017.

lichen - an organism consisting of algae and fungi, living in symbiosis without the need for human intervention. Lichen are used as bio-indicators to demonstrate a habitable air quality while the algae provides oxygen through photosynthesis, impacting and improving the indoor climate and therefore generating a better working and living environment. Through merging advanced digital design and fabrication techniques with material research and natural organisms, *Alcyon* creates a piece of nature and calmness inside the smallest urban space.

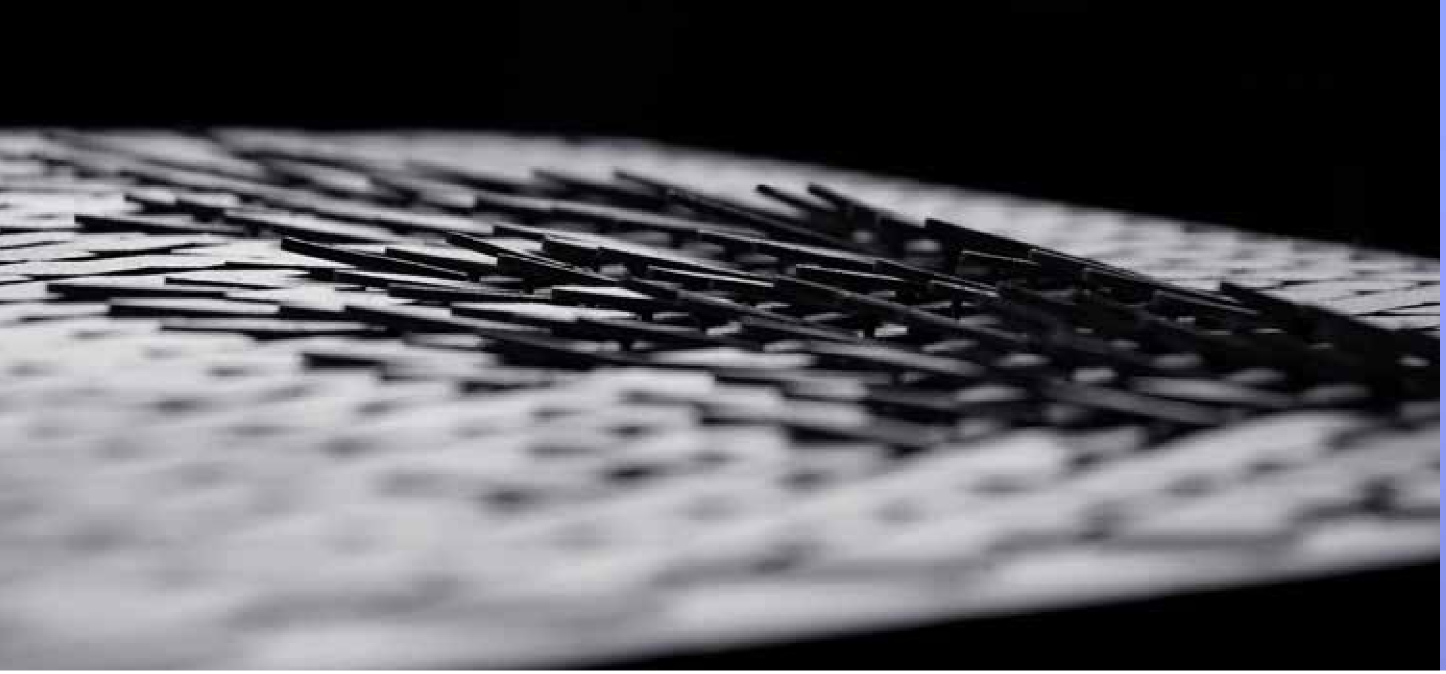
Image 5 ***Alcyon***, Dessau Department of Design, 2018.

Okura focuses on the identification of the driver with the vehicle. While a driver today is an active part of a large system, the future shift will be more and more towards passive scenarios where the user will become a mere passenger. To compensate for loss of control, alienation and a lack of security, the connection between man and machine must be improved. *Okura* presents an innovative solution with an interactive surface that informs, adapts and reacts. The dynamic scales of the surface move according to behavioral patterns, which are derived from nature, such as the slow and constant movement of the ocean. *Okura* transplants these (e)motions into the interior of the vehicle, and thus establishes trust in autonomous driving and artificial intelligence. Moreover, the surface can change its color from black to white in response to a change in temperature, which can improve the interior climate.[14]

Something a bit more abstract is *Skin2* - a course I taught together with Anastasia Pistofidou at the Institute for Advanced Architecture of Catalonia in 2016. Here the students were first encouraged to think about speculative future scenarios resulted from some of the global tendencies described earlier. They then were to develop a physical intervention that dealt with the human body and skin as an extension of our senses and a mediator between us, others and the environment. To communicate their ideas, they were asked to make short teaser-like videos.[15] The results were disturbingly dark and dystopian. Even though they were to some extent plausible and certainly

14 More info on the project, including videos: http://materiability.com/portfolio/anima/

15 More info on the project, including videos: http://materiability.com/portfolio/skin-2/



highly entertaining, I was a little confused why they all had such pessimistic visions of the future. And it is not only the Spanish students; similar visions are coming from many other architecture and design schools around the globe. In wondering whether it was just much easier to focus on the dark side than on the light, I decided to approach this idea from a slightly different angle.

Image 6 Okura Dessau Department of Design, 2018.

Part 4: Optimism

After converting his home to wind-generated electricity so he could produce far more energy than he ever needed, the American philosopher Timothy Morton posted a tweet in which he stated: "You think ecologically tuned life means being all efficient and pure. Wrong. It means you can have a disco in every room of your house."[16]

16 Timothy Morton on Twitter, accessed Apr 26, 2018, https://twittevr.com/the_eco_thought/status/714803735470297088

The essence of this statement, understanding current trends like dwindling energy resources not as threats but instead as motivations to find alternatives, became the basis for an experimental design studio: *Synthetic Ecologies*. The course I ran at the Dessau International Graduate School of Architecture together with Adil Bokhari in fall of 2016 was an attempt at approaching the unknown from a radically optimistic perspective. It was organized into three phases. In the first part, the students, working in groups of two, performed extensive research into various contemporary tendencies, their cause, current state, and possible further progression, including air pollution, littering, deforestation, space exploration, depression and the rise of sea level. To conclude their findings, they generated highly detailed imagery of speculative future scenarios, optimistically blurred visions of drastic global developments. Whilst this was an incredibly difficult yet astonishingly liberating task, a second track for the detailed study of material behaviors was opened. Through hands-on experimentation the groups explored the logic of particle aggregation, non-Newtonian fluids, smoke or the growth of crystals. This switch between the macro and the micro level, between theoretical speculation and practical exploration, allowed the students to project their abstract visions into physically "graspable" scenarios. Finally, each group was asked to synthesize and translate their findings into architectural proposals responding to the global opportunity identified in the first phase and based on their material discovery. One of the criteria was the spatial and sensual experience of the user and the atmosphere of their newly developed architecture within the context of a radicalized global phenomenon.

Image 7 Skin2 Institute for Advanced Architecture of Catalonia 2016

A small collective - twelve students and two teachers - through a semester-long research, started to develop patterns that addressed not only a contemporary outlook of the world, but also the limitations of our knowledge as architects. Psychological circumstances began to be placed within the medium of contemporary architectural processes. Grasshopper definitions with tabs naively titled: happiness, sadness, freedom, etc. also emerged. Trash turned into an element that architecture could use as building material; deforestation became not a scenario that was plausible but needed or even wanted through the beauty of the visions that were developed. “Strange” ideas of occupation of space, “strange” ideas of the construction processes involved in buildings, “strange” ideas of synthetic ecologies started to emerge. All ideas, proven through architectural documentation, became more real than the future scenarios that they set out to explore.

Part 5: Atmosphere

Whilst the development of *Synthetic Ecologies* was an extremely satisfying experience, it was, however, somehow lacking the dynamic power of the moving images produced during the *Skin2* seminar. During the last course I wanted to take that final part even a little further and focused on how such scenarios, which exist at the intersection of the real and the virtual, the imaginable and the imaginary, could become even more convincing and persuading. *Ribofunk* was the seminar I taught at Institute of Media and Design, TU Braunschweig. Instead of focusing too much on analyzing and understanding the “now” in order to make predictions on how the future might become, we could simply take the ideas and visions of someone else as a basis on which to develop our own speculative scenarios. *Ribofunk* is a collection of short stories written by the Science Fiction author Paul Di Filippo in 1996, with a focus on synthetic biology and gene manipulation. The task for the students was to read and analyze these stories, select certain scenes that they found architecturally inspiring, and then try to visualize its spatial atmosphere in the form of a short video clip. (The links to the videos are given in the footnotes or can be found here http://www.responsivedesign.de/ribofunk. It is recommended to watch the clips to better understand the following paragraphs.)

Big Eater is set in 22nd century Chicago where all humans have some sort of cybernetic implants or are genetically modified. The story revolves around Corby, who works for the so-called Eater Corp., a government company that produces disposable animal hybrids to clean up wastelands, and his sister Charmaine, who is part of an underground terrorist group called the Roaches, whose aim is to free all artificially created creatures from their

Image 8 Synthetic Ecologies Studio DIA / Dessau International Architecture Graduate School, 2016

slavery. The group chose the scene where Corby and his sister fly in their cruiser through nighttime Chicago. It was strongly inspired by set making of the original *Bladerunner* movie.[17]

“One Night in Television City” is about Dez, a 15-year-old who would do anything to be part of the coolest gang in town - the Body Artists - a group who use body and mind amplifying drugs to increase their physical abilities to roam the city. At a party in one of the town’s hippest clubs, Dez finally succeeds in convincing the gang’s leader Turbo to give him a chance to prove himself. The video that the group made traces Dez’s adventures after taking one of the drugs, and his new skills to explore the cityscape.[18]

“Distributed Mind” is essentially about some smart meta-material called the urb, which has swallowed all organic life on the planet and turned the world into a giant super organism that now tries to understand its very own existence. The scene that the team produced shows the urb devouring a city and replacing its buildings with new ones.[19]

From these very many experiments, I can so far draw that: no matter how our future might eventually turn out, we cannot simply surrender to the worst-case scenarios. Whether or not there’s hope for change is not the question. The question is to do what is right, to take action for our spirit and our conscience as well as for society. Rather than waiting to see what

17 Video on Youtube: https://youtu.be/ji4rii3HWos

18 Video on Youtube: https://youtu.be/jSXZByeNXsE

19 Video on Youtube: https://youtu.be/reWWHnF0lJY

Image 9 Stills from the videos Ribofunk, Institute of Media and Design, Technical University Braunschweig, 2018

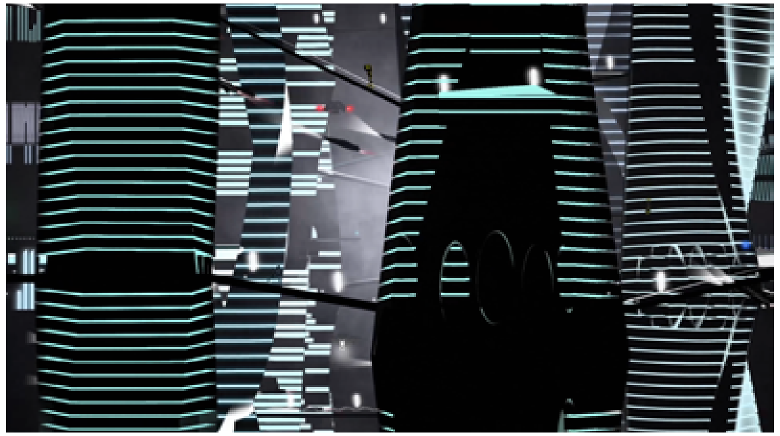


Image 10 Stills from the videos Ribofunk, Institute of Media and Design, Technical University Braunschweig, 2018

happens, *we* should be what happens. And this is essential especially for us as architects, designers and educators. We are the ones who define the environments and experiences for our future generations, and we have to shape the Anthropocene as we want it to be.

This essay is a transcript of a series of lectures I presented entitled 'Tomorrowland' and is partially based on material which has been previously published in 'Information Materials – Smart Materials for Adaptive Architecture, Manuel Kretzer. Bern: Springer International Publishing, 2017' as well as an unpublished paper co-written with Adil Bokhari on our common design studio 'Synthetic Ecologies.'

Image 11 Stills from the videos Ribofunk, Institute of Media and Design, Technical University Braunschweig, 2018

Prof. Dr. Sc. Manuel Kretzer is professor for Material and Technology at the Dessau Department of Design, Anhalt University of Applied Sciences. His research aims at the design of dynamic and adaptive objects with a specific focus on new (smart) material performance as well as applying cutting edge digital design and fabrication tools. In 2012 he initiated *materiability*, a free educational platform that attempts to connect architects, designers and artists and provides access to cutting edge new material developments and technologies. Manuel is also founding partner of responsive design studio based in Cologne. The core ambition of the studio is rooted in advanced design and manufacturing processes and a commitment to exploring responsive, adaptive spatial interventions.

An overview of his work can be found at www.responsivedesign.de, www.digitalcrafting.de and www.materiability.com.

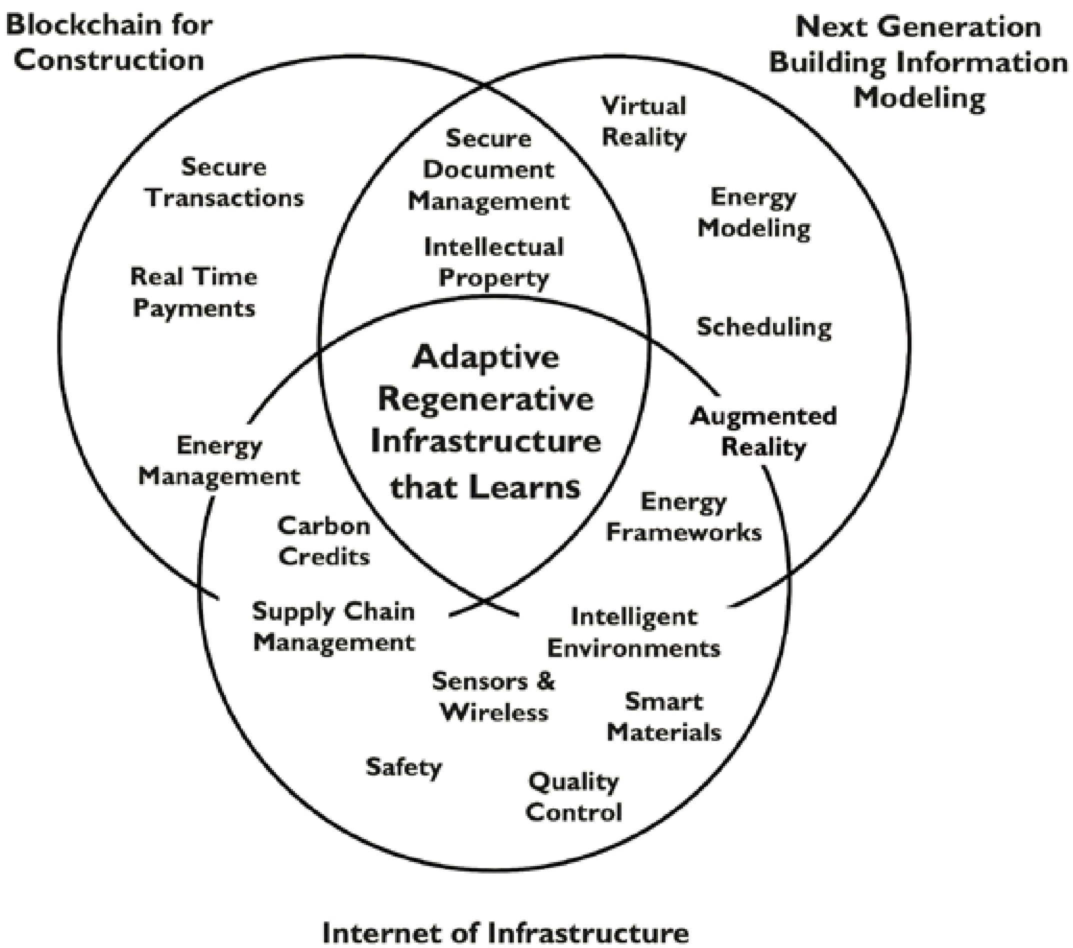


Image 1 New synergies are enabled by integrating technologies and methods (MacLeod, 2018)

Canada's Infrastructure of the Future

Douglas MacLeod
Athabasca University, Canada

In 2013, McKinsey & Company declared that, "Simply to support projected economic growth between now and 2030, we estimate that global infrastructure investment would need to increase by nearly 60 percent from the $36 trillion spent on infrastructure over the past 18 years to $57 trillion over the next 18 years." In 2016, Dominic Barton, Chair of the Finance Minister's Advisory Council on Economic Growth, suggested that Canada alone has a $500-billion infrastructure gap.

There is no doubt that infrastructure plays an essential role in the Canadian and global economies. And because our infrastructure encompasses most of the built environment—from schools and parks to highways and bridges—its health is of critical interest to the profession of architecture.

The trouble is that we may be designing infrastructure for the last century rather than the next. Last year, I was one of the co-authors of a shortlisted submission to the Innovation Superclusters Initiative organized by the federal government that allocated $950 million in targeted investments to industry-led consortia. Our application focused on creating smart, sustainable and resilient infrastructure. It included some of the largest AEC firms in the country, major research universities and a wide range of forward-thinking architects, engineers and entrepreneurs. While ultimately unsuccessful, our investigation suggested totally new ways of looking at infrastructure—and by extension, at architecture.

Because we are one of the few truly multidisciplinary professions, we are well prepared to think about the built environment from different points of view and to find innovative solutions by integrating those perspectives. We can start by learning from what's already happening across Canada.

The town of Innisfil in Ontario, for example, has inked a deal with Uber to subsidize rides for its citizens within municipal boundaries. The town estimates it is saving $8 million per year in comparison to buying and maintaining buses and operating a similar degree of service. Similarly, large, centralized water treatment plants can cost millions of dollars—but smaller filtration units such as those developed by Zenon Environmental (originally a Canadian company) can provide clean water at a neighbourhood level for far less. The founder of Zenon, Andrew Benedek, who won Singapore's inaugural Lee Kuan Yew Water Prize in 2008, has compared our infrastructure to the evolution of computers. He notes that all computing was centralized and expensive in the era of mainframes and batch processing, but today we have cheap but more powerful machines on our desks and in our pockets. Similarly, our infrastructure now has the potential to become smaller, less expensive and more decentralized.

Water and public transportation aren't the only areas where this could occur. Architects need to consider what will happen when our communities can generate more energy than they consume, purify more water than they pollute, recycle more waste than they produce, grow more food than they need, and sequester more carbon than they emit. It is possible we will be able to do all of these things by 2040. While none of this is written in stone, we do need to explore these possibilities, rather than fixate on massive megastructures that are based on outdated paradigms such as the fossil fuel economy.

To create this new kind of infrastructure, architects need to think outside the building. Many have suggested that our power grid needs to become more like the Internet in terms of flexibility, ubiquity, openness and modularity. To do so, however, requires an easy way to move packets of energy around, just as the Internet moves packets of information. In an idea called Vehicle to Grid, or V2G, the batteries of electric cars are used to move energy from one building to another. As electric, autonomous vehicles mature, the energy needs for neighbourhoods may well be met by a fleet of mobile batteries that constantly moves energy around from where it is created (such as the solar panels on roofs) to where it is needed. On-site storage of energy using stationary batteries may also become a key part of V2G. According to McKinsey, the costs of such storage may drop towards $100 USD per kilowatt-hour by 2020, making it cost-effective for commercial and industrial buildings.

These developments have led some to suggest that we need to re-imagine infrastructure as a "platform." A platform is a fashionable term for a framework or a set of shared tools that allow different people to develop different applications with a reasonable assurance that they will be interoperable because they all share a common development environment. For example, a contemporary building needs applications for energy management, lighting control and performance benchmarking. If these are all developed on the same platform, then they can share information and work together. Moreover, if a new application is needed, such as security, then it can either be purchased from somewhere else or developed cheaply and easily by using the platform tools.

A powerful advantage of the platform approach is that it can be used to efficiently develop applications that we don't even know we need yet. Re-imagining buildings as a platform technology of integrated products and services would transform the idea of architecture. Houses could become their own nano-infrastructure providers, potentially generating energy, information, clean water and even food to share with the micro-infrastructure of their neighbourhood.

This has implications right across the board. As Trevor Butler, principal of Archineers notes, "By designing buildings that are net positive or regenerative from a whole systems perspective, architects and engineers are redefining what it means to be a utility—because these kinds of buildings both give and receive energy, water and other resources. To do so effectively, we need to develop a new kind of infrastructure that can accommodate these bi-directional flows."

If our communities and buildings migrate to localized energy generation and storage, it raises the question: Do we still need elaborate, expensive grids, dams, and the large, corporate utilities that operate them? No matter how this transformation plays out, architecture has an important role to play. As Guy Newsham, a Principal Research Officer at the National Research Council's Construction Research Centre (NRC-CRC) in Ottawa notes, "The building is the natural building block in smart cities."

This is where new technologies collide head-on with the ancient art of placing stone on stone. Just as the Internet revolutionized communications, so may IP (or the Internet Protocol) redefine architecture. This is more than the Internet of Things—but rather, the Internet of Buildings.

Trevor Nightingale, Leader, High Performance Buildings Program, also at the NRC, notes that, "It is now possible to converge all building systems onto a single IP network." Far from being science fiction, such systems have already been implemented in buildings such as the WaterPark Place III building designed by WZMH in downtown Toronto. In this building, lighting, HVAC, fire and security systems are all integrated with PoE (or Power over Ethernet) which eliminates the need for electrical cables and produces significant cost savings. Moreover, these systems will also be able to share data in order to optimize their efficiency.

There are, however, numerous challenges to this work. A year ago, I attended a workshop organized by the NRC on the Future of Cities. There was impressive work being done in major cities across Canada that used data to make their operations more efficient and more economical. And yet, all of these initiatives were being done in isolation from one another. In each case, the wheel was being reinvented at tremendous cost to the economy. In addition, some participants complained that only large cities could afford these innovations, while the rest of the country was falling behind. Having a multitude of incompatible systems—that only serve the few—defeats the entire idea of a platform.

It is also not clear at this point who owns all of the data that buildings and infrastructure will generate, and who will protect it. Everyone needs to be aware that a smart city will be gathering information about individuals and their behaviour, and they may have no control over what is done with the data and who it might be sold to. The privacy concerns of social media and the abuses that have occurred recently are nothing compared to the problems that could result when the built environment can monitor one's every move.

Financing is another critical issue. The federal government has established the Canadian Infrastructure Bank (CIB) as an arm's length Crown Corporation with an initial investment of $35 billion. According to the CIB's website, "The Bank model builds on Canada's mature public-private partnership market. The public-private partnership model is used to transfer certain construction and operating risks to the private sector. The Bank will foster partnerships between the public and private sectors where infrastructure projects are funded primarily by revenue from infrastructure usage."

While the public-private partnership (P3) model may be mature, it is not without its problems. In 2014, the OAA complained in a letter to Ontario's Minister of Infrastructure that under the Alternative Finance and Procurement (AFP) method being used, "Any innovation in design which is presented is not rewarded by offering advantage in the competition, nor is it monetarily compensated, and therefore innovation is not encouraged. The psychology is therefore to trim and not innovate. Once a design scheme has met the requirements of the base program, the low price becomes the focus."

But even low prices can be difficult to achieve in the P3 process, because of the enormous premiums included in the contracts to mitigate the transfer of risk to the private sector. Last June, the Columbia Institute released a report that states, "British Columbia will pay an additional $3.7 billion as a result of contracts signed between 2003 and 2016 to deliver 17 infrastructure projects through public-private partnerships (P3s) rather than traditional procurement."

Alarmingly, the CIB is planning more than just a traditional P3 approach. According to Pierre Lavallée, the President of the CIB, "P3 arrangements typically include payments from the government when an asset becomes available—this model transfers construction and operating risk to private parties. The bank will use a co-investment model that takes the involvement of the private sector a step further to assume risks relating to usage or revenue. The bank's co-investment can mitigate some of the usage and revenue risks for private-sector and institutional investors, or 'inject' capital at key points, making projects more attractive."

The history of P3s in Canada is mixed, but the fact of the matter is that if the private sector invests in our infrastructure, then they will reasonably expect to make a profit. If the model is extended to usage and revenue, then they will continue to expect to generate revenue from that infrastructure long after construction is complete. It is unclear what this means. Beyond road tolls, will it entail additional fees or taxes to send children to schools, or user fees every time someone visits a hospital? As Vivian Manasc, FRAIC, principal of Manasc Isaac Architects, has noted, "A systematic evaluation of all P3 projects in the world, completed in the past 25 years, has yet to be published. Before further large-scale P3 procurement experiments are undertaken, a rigorous analysis would seem to be in order. It would be helpful to identify the costs and benefits, and to whom each accrues."

As architects, we need to understand these procurement issues and prepare intelligent positions regarding them. In other words, the idea of infrastructure as a platform isn't just about a technical framework— it has financial implications as well. Again, this emphasizes the need to think in a holistic manner about the built environment. When we do, it's easy to see that we haven't even begun to plumb the depths of these new opportunities in design and infrastructure.

For instance, how can our buildings go beyond being "smart" to actively being able to learn? What could a skyscraper in Montreal learn from one in Toronto about how to withstand a wind storm? With the sensors of the Internet of Things, this becomes a real possibility. Similarly, our infrastructure needn't just be sustainable; why can't it be regenerative as well? And finally, our infrastructure needs to be more than resilient—it needs to be adaptive, because we cannot predict what new challenges we will face in the future.

To this end, some are proposing radically new perspectives on the built environment. Philip Beesley, of the University of Waterloo, is leading a visionary interdisciplinary team of researchers in the Living Architecture Systems Group (LASG). As he explains it, "Integral to the LASG is the idea that we can create empathic environments in order to establish mutual relationships between individuals and their environments. These environments interact and react to their inhabitants in ways that suggest emotional intelligence and empathy, and that invite emotional responses from those inhabitants."

All of these ideas, from financing to empathic environments, have the potential to revolutionize the built environment—for better or worse. If we are not to be left behind, the profession of architecture needs to play a leadership role in exploiting the opportunities and addressing the challenges of our future infrastructure.

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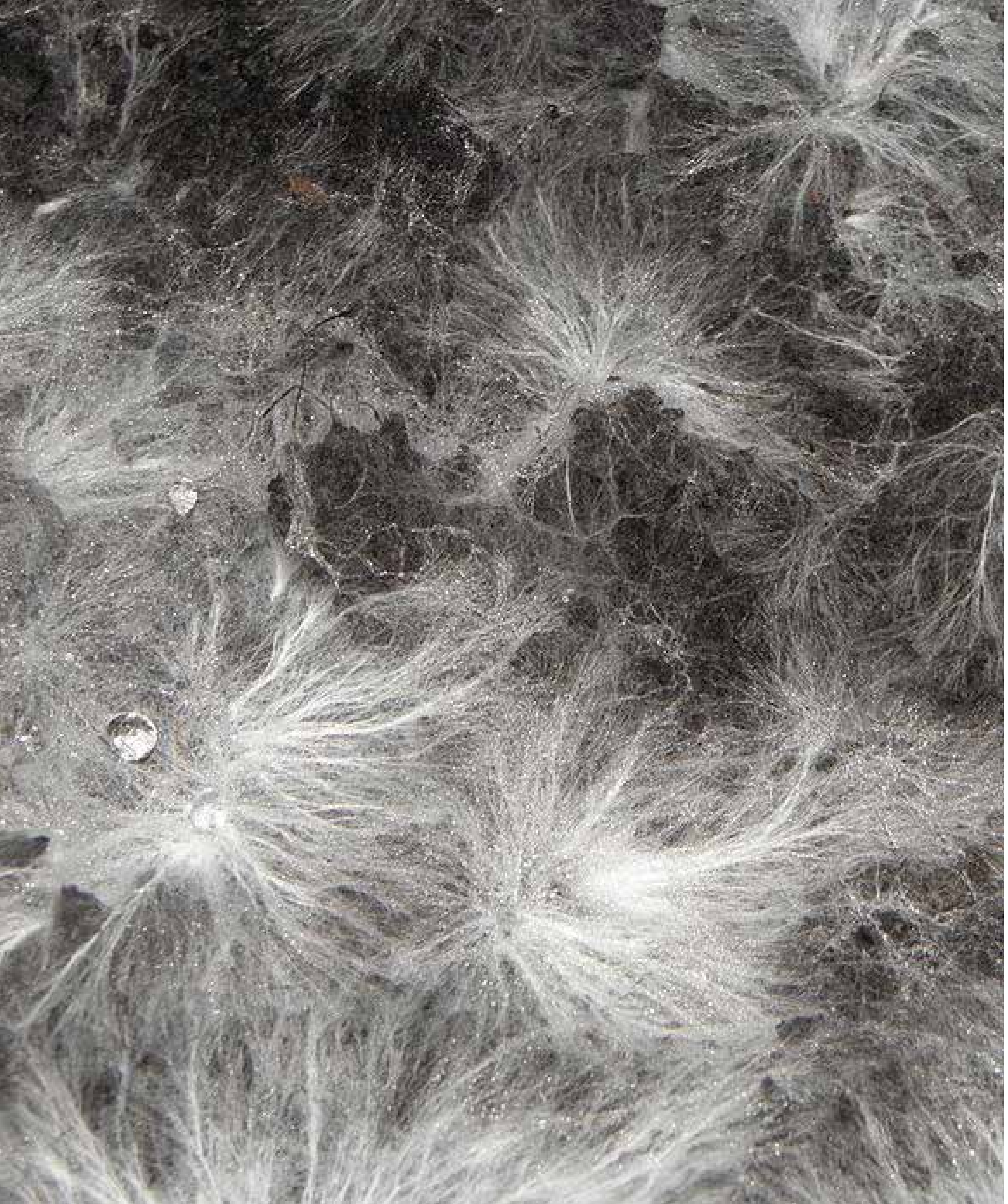
Dr. Douglas MacLeod is the Chair of the RAIC Centre for Architecture at Athabasca University – Canada's first online architecture program. The Centre currently serves over 600 students in 16 countries and continues to enhance the quality of architectural education in Canada.

MacLeod is a registered architect, a contributing editor to Canadian Architect Magazine and the former Executive Director of the Canadian Design Research Network. He is also a former Associate with Barton Myers Associates, Los Angeles.

He led pioneering work in virtual reality at the Banff Centre and is recognized as an expert in e-learning, sustainable design and virtual design. He has degrees in Architecture, Computer Science and Environmental Design and has taught at universities and colleges throughout North America.



The Role of Living Architecture in Regional and Urban Design

An Initial Exploration of Regenerative Assemblages as Innovation Multipliers

J. Eric Mathis
The Institute for Regenerative Design and Innovation

The Institute for Regenerative Design & Innovation, Bio-Regen Coop and SYNC Bioresources along with the Living Architecture Systems Group propose the development of a Bioregional-Innovation Lab or *iLab* for the Great Appalachian Valley with the goal of identifying health centric synergies between traditional and emerging agriculture/energy industries. The iLab will be a user-centered, cooperative-innovation ecosystem specifically tailored for transitioning at-risk communities through public-private-people partnerships. Solutions developed from the "high barrier" context of low-wealth communities will address key shortcomings, limitations, and challenges to transition strategies regionally and nationally. The following are central components to the proposed "multiplier" strategy:[1]

Local Optimization: Living-Lab Platforms
Global Optimization: Bioregional-Innovation Lab
Optimization Network: Cooperative-Innovation Network

1 To learn more about the bioregional "innovation-multiplier" model, please see TEDx Talk entitled "Exploring the Potential Worlds of Living Architecture" by J. Eric Mathis here: https://www.youtube.com/watch?v=FXumceyVPa8

Image 1 Mycelial networks

Introduction

As a team of world class experts collaboratively co-design and deploy projects with communities across the Great Appalachian Valley, it is our hope that the *Bioregional-Innovation Lab* or *iLab* integration strategy will generate key components to fostering sustainable economic, social and environmental transitions throughout our target region and beyond. *Living-Lab Platforms* or "multiplier" will strategically aggregate local knowledge stocks by and through the emerging *Cooperative-Innovation Network* or "iNetwork" and optimize innovation diffusion by and through *Innovation-Multipliers* across the region where the iLab will provide innovative, evidence-based solutions co-designed to optimize the proposed *Bioregional Economic Development* model outlined in *Living Architecture Systems Grouo White Papers 2016* as well as address key market barriers within three industry sectors: 1) health-care, 2) sustainable agriculture and 3) energy optimization. Building from the existing successes of the Living-Lab model that was born within the heart of coal country (Williamson, WV)[2] and the emerging regional iNetwork (originally the Central Appalachian Sustainable Economies or CASE network),[3] the iLab team will collaboratively work with regional stakeholders to optimize innovative strategies and enhance existing projects and infrastructure.[4] Since July 2018, the Institute for Regenerative Design & Innovation ("IRDI"), Bio-Regen Coop ("Bio-Regen"), SYNC Bioresources ("SYNC") and associated partners of both the Forsyth and Alamance County Living-Lab platforms have been working to empower local community stakeholders in North Carolina to identify and build upon cross-county innovations in hopes of launching a multi-state collaboration referred to as the *Bioregional Innovation Cluster*. Building from the iLab's progress to date, IRDI is performing the required due diligence to ensure that the innovation cluster model will generate a replicable regenerative-development strategy that will enable Living-Lab affiliates to spread across the Great Appalachian Valley and beyond. As a central component of the iNetwork, the iLab team will provide resources and technical assistance to support community-driven decisions and implementation processes throughout the target region. The collective goal is to develop a replicable transition model that at-risk/low-wealth communities can implement nationally and internationally. The proposed iLab will help transform the Great Appalachian Valley economy by enriching existing regional networks and building upon what our team refers to as a "nested policy strategy." This synergistic strategy contains the following active components that make up the iLab architecture:

2 For more about the "Lining-Lab Platform" model see Sustainable Williamson http://sustainablewilliamson.com/

3 For more about the "CASE Network" see "2011 CASE Report," Sustainable Williamson http://sustainablewilliamson.com/wp-content/uploads/2017/06/2011-CASE-Convening-Report.pdf

4 Mathis, J. Eric and Tyler Jenkins, "Infrastructure and Platforms as Living Architectures: The Importance of Regenerative Design and Innovation for Bioregional Economic Development," in Living Architecture System Symposium: White Papers, 2016.

iLab Studies: Research Institutions
iLab Convenings: Intervention Strategies
iLab Projects: Innovating Sites
Collaborative Governance Initiative: iLab to Platform-Network Interface
Bioregional Innovation Cluster: Network to Cooperative-Innovation Ecosystem

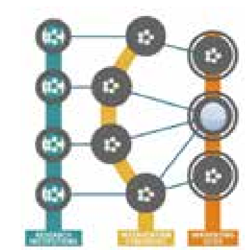


Image 2 iNetwork: Cooperative-Innovation

Image 3 iLab: Platform Network

Innovation Multiplier

A replicable strategy is presently emerging from these successful components and is being nourished by many local, regional, national and international organizations working with IRDI. Serving as Health-Centric *Research Institutions* for the iLab eco-system in Winston Salem, North Carolina, both Wake Forest Baptist Hospital and Novant Health have collectively supported the development of health-centric *Intervention Strategies* as a part of the IRDI's Living-Lab model. This support has been leveraged for the development of the Cooperative-Innovation Network as well as the Living-Lab Platform (see image below) – together forming an oscillatory Network-Platform coupling or "innovation-multiplier" [5] – that is in essence a concrete/real expression of a *regenerative-assemblage* that we generally refer to in this white paper as the iLab. The active role of these research institutions will potentially set the stage for enabling the iLab to implement key economic transition strategies that: (a) support the growth of the iNetwork; (b) demonstrate strong regional, bottom-up support through Living-Lab affiliates; (c) are market-driven; (d) demonstrate high potential for success and sustainability; and closely align with emerging health and wellness development trends. This initiative, collectively referred to as the *iLab*, will optimize the iNetwork of which facilitates economic growth through research and intervention strategies (i.e., community feedback, entrepreneurial advancement, collaborative governance, etc.). To this end, IRDI is presently co-designing several cooperative-innovation ecosystems or Living-Labs that promote entrepreneurial

5 Keller Easterling unpacks the potentials held within multipliers in both Extrastatecraft: The Power of Infrastructure Space. Verso Books, 2014, as well as a wonderfully potent response in a recent interview from a June 12, 2018 issue of Volume entitled Empowering Design. For more of the interview please see: http://volumeproject.org/empowering-design/

ideation, collaboration and knowledge-sharing. The ecosystems will enable community residents, particularly those in low-income/wealth areas, to utilize entrepreneurial/design thinking as a means to improve not only their own circumstances but also of living/regenerative resources including the health and well-being of their neighbors and communities. The development and execution of this dynamic *Regenerative Entrepreneurship* strategy is the crucial role that IRDI situates within the Living-Lab Eco-System.

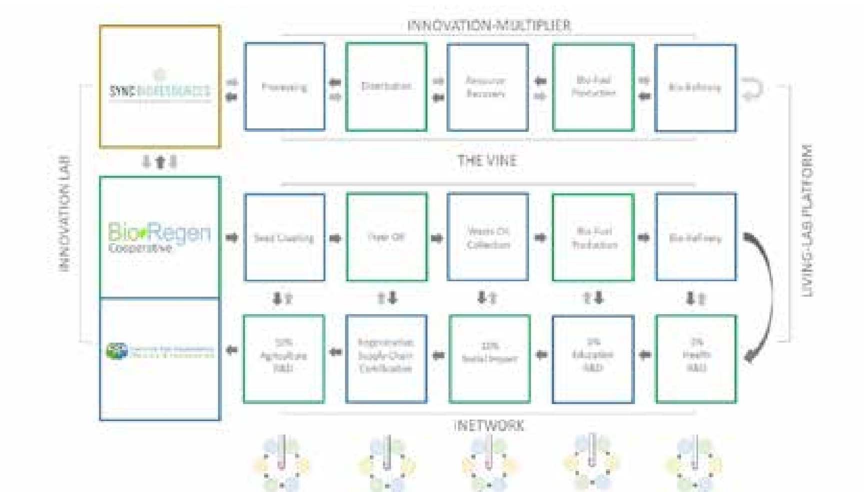
Network Aggregation

The success of the Living-Lab-Platform is highly dependent upon an "informal iNetwork between producers" in parallel with community trust and collaboration (i.e., the "Hidden Layer").[6] IRDI has developed a Network-Platform framework co-designed to successfully connect human and financial resources for the benefit of the health and wellness vision.

6 Mathis, 2016: 7

Entrepreneurial Development

This regenerative-assemblage strategy is the predominant design protocol for our cooperative-innovation model. Using Living-Lab design as an active form, we are developing an integrative platform for populating regional & urban design strategies.



Building upon the creativity of local-residents, the power of local associations, and the supportive functions of local/regional anchor institutions, IRDI draws upon existing community strengths to build stronger, more collaborative networks throughout the target bioregion. Most importantly, by utilizing innovative approaches to soil-regeneration (e.g., biochar, mycelial fungi, etc.) – soil being *The Platform* par excellence – IRDI envisions utilizing these valuable assets as a cornerstone for the development of a regional innovation cluster that systemically addresses multiple scales of degenerative impact as it relates to the present linear economy.[7] A highly integrated Health Innovation design is being explored at several established and emerging Living-Labs with a focus on regenerative-development throughout the region.[8] The proposed process-model (image below) is co-designed from the bottom-up through the deployment of an innovative bio-refinery model that connects directly to user-communities or Living-Lab affiliates nurtured through successful iLab projects. For example, a percentage of the profits generated from bio-fuel production will support the development of IRDI's Curriculum Design (education) initiative that functions by and through community-gardens.

7 Please see forthcoming paper set to be published early 2019: Field-Johnson, Christopher, John H. Fike, John M. Galbraith, Rory O. Maguire, Susan D. Day, Shepard M. Zedaker, J. Eric Mathis. "2018 Pine Sawdust Biochar as a Potential Amendment for Establishing Trees in Appalachian Mine Spoils." Reforesta: International Scientific Journal on Reforestation.

8 For more on innovation districts see both: Katz, Bruce, and Julie Wagner. "The rise of innovation districts: A new geography of innovation in America." Washington: Brookings Institution (2014). Cosgrave, Ellie, Kate Arbuthnot, and Theo Tryfonas. "Living labs, innovation districts and information marketplaces: A systems approach for smart cities." Procedia Computer Science 16 (2013): 668-677.

Ternary Architecture

The above Ternary Architecture (image above)[9] IRDI, BioRegen and SYNC seeks to address what we consider to be a nexus of interconnected socio-economic problems: environmental degeneration, wealth inequality and climate change. It is our belief that these problems synergistically emerge from one single problem: scarcity of resources. In general, this problem is directly related to innovation diffusion such as establishing market linkages between sectors that are typically siloed in present organizational designs – in particular the agriculture, health and energy sectors. This problem continues to persist due to institutional lockins that discourage cooperative-innovation. Crucial to maintaining these degenerative socioeconomic lockins are institutional biases towards linear as opposed to nonlinear processes, whether they be cognitive, social or ecological in their origins. In short: human beings' natural capacity to create/innovate is presently limited. It is for this reason and many others that climate change is perhaps the #1 reason for building our proposed Ternary Architecture with the sole intention of scaling the cooperative-innovation model both nationally and globally through our established networks by and through the deployment of an innovative

9 There are several explorations of ternary or "weighted architectures" (-1,0,1) that provide fruitful insights for generating an optimal innovation-multiplier ecosystem (e.g., chemical, computational, etc.). This article provides some productive insights given its intuitive explorations of fine-tuning what I refer to as the plasticity ratios of a given composition (phase portrait) or tuning an assemblage's morphology of components parts, that is, identifying a virtual-resonance/interference architecture regarding how the components are arranged in clusters akin to Galaxy Filaments found in the Bolshoi-Simulation via Holographic Resonance where synchronization - ability of coupled oscillators to lock to a common frequency - is both isomorphic (frequency locking) and polymorphic (phase locking). In this study, the intensification of differentiation is increased with the "ternary blend" (regenerative-assemblage) as opposed to...

Bio-Refinery model we refer to as "The Vine."[10] By focusing on transitioning from an economy of scarcity (nonrenewable resources) to one of abundance (renewable resources), the primary strategy is to build a Restoration Economy from the soil up, increasing the soil's capacity to capture carbon. Simply: the entire future of establishing a Restorative Economy and absolving barriers within the present Climate Change movement is innovation!

To this end, creativity works best when it is transparent and collaborative. IRDI is executing a three-pronged economic research & development strategy: Regenerative Entrepreneurship, Curriculum Design and Health Innovation. All three components – Agriculture-Education-Health – make up our proven Living-Lab Platform model. Leveraging the power of local research institutions, this ternary model utilizes a triple helix strategy for community development (university, industry, government) with the central focus being health and wellness. Representing industry stakeholders, SYNC's innovation-multiplier model will accelerate the development of technology by and through the regional innovation cluster that is co-designed to optimize agriculture supply chains through Bio-Regen's established farmer/breeder network. Shared Value Creation is central to the proposed ternary model. The premise behind creating shared value is that the competitiveness of our model and the health of local communities are mutually dependent.[11] By taking advantage of these connections between socioeconomic progress, our cooperative-innovation model will potentially unleash the next wave of global growth and redefine how market systems operate and evolve. Our team has developed a unique shared-value model linking farmers, seed breeders and industry leaders as well as universities and local government into a synergistic platform designed to optimize innovation spillovers and in turn increase profit margins.

Success at innovation is dependent on an effective innovation process. While the average innovation success rate is fairly low (17%), it is believed that bio-based products launched using our cooperative-innovation methodology will have a very high success rate due to the unique shared-value creation process. This process is co-designed from the ground up to mitigate the risk of failure through innovative research processes that directly link breeders, farmers and industry leaders to the communities that support them. Through the development of public-private-people partnerships, the iLab will provide private stakeholders with first-hand access to the entire research and development process. This quasi-open access enables

... a "binary blend" (machinic-assemblage) and thus optimization is increased by generating a kind of innovation-multiplier via a deep-parallelism or coupling between Network (photons) and Platform (polymer cell). For more see:

Lin, Yu-Che, Hao-Wen Cheng, Yu-Wei Su, Bo-Hsien Lin, Yi-Ju Lu, Chung-Hao Chen, Hsiu-Cheng Chen, Yang Yang, and Kung-Hwa Wei. "Molecular engineering of side chain architecture of conjugated polymers enhances performance of photovoltaics by tuning ternary blend structures." Nano Energy 43 (2018): 138-148.

For more regarding the role of resonance/interference please see:

Plotnitsky, Arkady. "From Resonance to Interference: The Architecture of Concepts and the Relationships among Philosophy, Art and Science in Deleuze and Deleuze and Guattari." Parallax 18, no. 1 (2012): 19-32.

For more regarding "intuitive explorations of fine-tuning" see Manuel DeLanda's lecture "Virtual Environments as Intuition Synthesizers" here: https://deterritorialinvestigations.wordpress.com/2018/01/22/manuel-de-landa-virtual-environments-as-intuition-syn

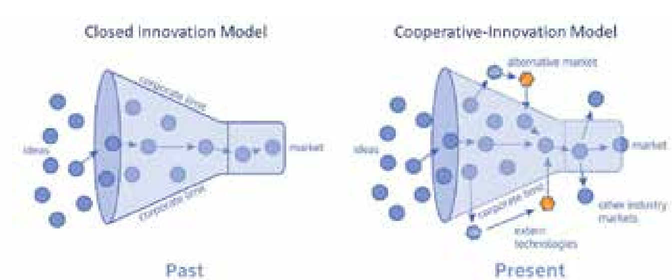
10 The Vine is modeled after this study: Wilson, Noah and Matthew Raker. "A Feasibility Study for a Field-to-Fryer-to-Fuel(F3) Regional Biofuels Production Model." Advantage West Economic Development Group (2014).

11 Porter, Michael E., and Mark R. Kramer. "The Big Idea: Creating Shared Value." (2011).

stakeholders to identify potential markets as they emerge from the earliest stages of the innovation process. It is believed that this novel research and development methodology will provide one of the most cutting-edge innovation strategies for the advanced development, pre-development and development stages of bio-based products, marking a shift from traditional "closed innovation models" to emerging "cooperative-innovation model" specifically tailored for the agriculture, health and energy sectors.

Health Innovation Districts

Central to both IRDI's ternary mission of breeding Regenerative Entrepreneurship by and through a generative-parallel process established between Curriculum Design and Health Innovation and situated within the iNetwork via regional cooperative-innovation cluster strategy, Health Innovation Districts are co-designed to facilitate the emergence of a Restoration Economy across the southeast. The creation of innovation districts is a recent trend in urban planning that has emerged as a new model to stimulate economic growth in cities across the globe. Building from this successful strategy, IRDI is linking emerging innovation district strategies to our Living-Lab model that generate restorative linkages between rural and urban settings. There has been a clear effort over the last 10-15 years to grow North Carolina's economy through the development of innovation districts. Today, innovation districts are present throughout the state, and North Carolina ranked 17th in a 2016 Bloomberg Index of most innovative states.[12] While these districts promote collaboration within a wide-range of industries—local factors frequently determining these industries—the biotech and environmental sciences industries are well represented and promoted in most districts. Our vision is to activate the entire sustainable agriculture supply-chain with the end goal of engaging local, regional and



12 For more see: https://www.massdigitalhealth.org/news/here-are-most-innovative-states-america-2016

global stakeholders in regenerative design and innovation. We strongly believe that North Carolina communities will make the choice to develop *Health Innovation Districts* and retain the investment within local economies, creating well-paying jobs and increasing the local tax base. Diverse participation in the development of Health Innovation Districts will stimulate vital economic growth and improve social conditions including health, wealth and wellbeing.

Key North Carolina Innovation Districts

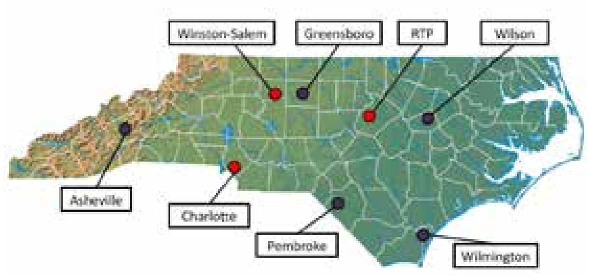


Image 4 Five cities in purple denote cities recently chosen to participate in the "InnovateNC" program, associated with Research Triangle Park (RTP).

iLab Design

With the goal of stimulating the emergence of an agglomerated economy rooted in health-based approaches to transition strategies and resource deployment to local regions, the iLab team will assist Living-Lab affiliate teams with the formulation for locally specific design charrettes led by its *Regional Living-Lab Coordinator*. The planning process for these locally-driven design charrettes will begin with an identification of required inventory data, for example: the local government energy use (e.g., utility bills) as well as identify local research/anchor institutions (K-12 schools, Hospitals, Universities, HUD Housing) for the deployment of community gardens. The analysis of data will be followed by a design charrette led by the iLab team with diverse participants which may include local citizens, city and county officials, local energy generation, transmissions and distribution companies, electric grid managers, transportation fleet managers, health practitioners, local farmers, SMEs and community organizations. These discussions will help prioritize goals and reveal local and regional assets. The Living-Lab affiliates can then leverage them to achieve optimization within the three target sectors, as well as barriers that might hinder viable community development strategies.

Leading the way in developing a health-centric transitional strategy of the iNetwork, IRDI recently launched the annual Grow & Share event in Forsyth County as a concrete example of a locally driven design protocol. The Grow & Share events actively engage residents in establishing crucial Regenerative-Linkages between Soil and Souls that are co-designed to address present degenerative systems related to, for example: chronic homelessness, veteran PTSD and childhood trauma. The IRDI's team is presently working on a circular Waste-to-Soil (composting) and Soil-to-Food (gardening) model as a part of the Curriculum Design program that specially targets future generations beginning with K-12 schools. In collaboration with early adopter teachers across Forsyth County, our team launched the Circular Asset model in spring 2018 in collaboration with Forsyth County Career Center. Our team is presently integrating all participating gardens into a comprehensive experiential STEAM curriculum with a specific focus on Design Thinking (a component of the "Arts"). Specifically, the emerging iLab framework will provide both the initial *iLab process* and serve as the *iLab campus* for developing cooperative-innovation strategies for the surrounding distressed and at-risk communities throughout the Great Appalachian Valley (e.g. opioid epidemic in Central Appalachia). This, in turn, will contribute to the IRDI's health-based strategy for developing an agglomerated regional economy by linking local wealth generation and entrepreneurship.[13]

iLab Process Design[14]

Informed by the European Network of Living Labs (ENoLL) model, the iLab team will develop three synergistic approaches for bottom-up innovation strategies rooted in user-centric innovation:

1. Optimization developed for stakeholders: Stakeholders are consulted, but do not actively participate in the decision-making process.
2. Optimization developed with stakeholders: Products and services are co-designed by iLab team and stakeholders.
3. Optimization developed by stakeholders: With the community-steered context and evaluation context, the stakeholders become the innovators and, to some extent, iLab team and the practitioner become facilitators.

13 Stuart Rosenfeld, Generating Local Wealth, Opportunity, and Sustainability through Rural Clusters (North Carolina: Regional Technology Strategies, Incorporated, 2009):1-53.

14 Mulder, Ingrid, Claire Fahy, Karl Hribernik, Daan Velthausz, Karin Feurstein, Maite Garcia, Hans Schaffers, Anita Mirijamdotter, and A. Stahlbrost. "Towards Harmonized Methods and Tools for Living Labs." Expanding the Knowledge Economy: Issues, Applications, Case Studies 4 (2007): 722-729.

iLab Campus Design

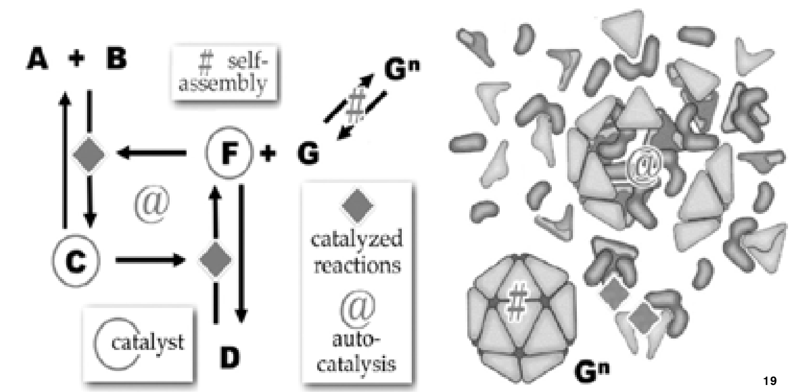
With the Novant Health and Wake Forest Baptist serving as the local research institutions for the proposed iLab, the City of Winston Salem as a whole will serve as the cooperative-innovation campus to experience applied strategies for building community resiliency. Serving as an active participant in the iLab campus, IRDI will supply specific integrator services through a community-driven development process designed to assess Curriculum Design strategies both locally and regionally. The IRDI team is presently collaboratively developing a Living-Lab platform focusing on local wealth generation through a regenerative parallel process established between two gardens: 1) Career Center focused on Curriculum Design and 2) Downtown Health Plaza focused on Health Innovation – both of which breed Regenerative Entrepreneurship over time. The following localized and virtual components are key elements of the iLab campus network that will be fully integrated into the iNetwork:

Research Institution Consortium is a network of educational institutions that are actively participating in the implementation of innovative experiential as well as service learning strategies. Founded upon integrative approaches to community development, the consortium will focus specifically on building community resiliency via service learning.

Open-Resource Library is a collaborative resource platform which will ensure a seamless integration of the Living-Lab innovation strategies into the emerging iNetwork. This library of Curriculum-Modules will provide an open-resource of presentations, videos and articles developed by practitioners involved with co-building the iLab.

Virtual Architecture

Following the proposed "nested policy strategy", the iLab utilizes an integrative Collaborative Governance model that will directly link the iLab with local and state government entities (e.g., sustainability committees) in order to build the necessary consensus required to nourish the long-term sustainability of the regional iNetwork.[15] Collaborative governance will establish a clear path for the expansion of the iNetwork throughout the design, implementation and deployment processes of local design charettes. The regional development of a Living-Lab model will begin with several pilot Living-Lab affiliates – forming a kind of autocatalytic set (see below) where, "when the number of catalyzed reactions *innovations* is about equal to the number of chemical dots *multipliers*, a giant catalyzed reaction web forms, and a collectively autocatalytic system snaps into place."[16] This meets one of two criteria of an assemblage according to Thomas Neil (i.e., Abstract Machine and Concrete Assemblage), that is, once catalyzed by and through the iLab, the Living-Lab affiliate network will form a virtual architecture that is "abtract because it is not a thing or object that exists in the world, but rather something that lays out a set of relations wherein concrete elements and agencies appear."[17] Here, the emerging Living Architecture comes to the forefront where "life emerges as a phase transition" or in the case of the iLab design strategy, the regenerative-assemblage is born.[18]



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Perhaps most importantly, the Collaborative Governance model may provide a diverse regional pool of reflexive and replicable Living-Lab platforms for addressing economic, environmental, social and regulatory challenges in the emergence of a part-to-whole relationship.[20] On the community level of decision making processes, this collaborative approach will build on IRDI's successful stakeholder platforms called "design charettes," which are open-community design meetings that encourage active participation of key stakeholders representing the "collective interests and intelligence of various groups of users: SMEs, innovation agencies, policy makers, local action groups and end-users."[21] In his study *Exploring Business Models for Open Innovation in Rural Living Labs*, Hans Schaffers suggests that these

15 Emerson, Kirk, Tina Nabatchi, and Stephen Balogh. "An integrative framework for collaborative governance." Journal of Public Administration Research and Theory 22, no. 1 (2012): 1-29. Also see Sustainable Williamson's 2011 CASE Convening Report http://sustainablewilliamson.com/wp-content/uploads/2017/06/2011-CASE-Convening-Report.pdf

16 Kauffman, Stuart. At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Oxford University Press, 1996: 63.

17 Nail, Thomas. "What is an Assemblage?" SubStance 46, no. 1 (2017): 24.

18 Kaufmann, 1996. 62

19 *Image 5* The reaction network of a simple autogenic process. Right: Idealized depiction of an autogenic complex in formation. An autogen is formed when a reciprocally autocatalytic set of molecules (C and F) modifies available substrate molecules (A, B & D) to produce (along with additional Cs and Fs) a side product (G) that tends to self-assemble (#) into an impermeable container (a process analogous to the formation of a virus capsule). Such a system will tend to reconstitute itself if disrupted and reproduce duplicate systems if sufficiently disrupted. Taken from: https://www.researchgate.net/figure/Left-The-reaction-network-of-a-simple-autogenic-process-Right-Idealized-depiction-of_fig3_284532156

20 Van Wezemael, Joris. "The contribution of assemblage theory and minor politics for democratic network governance." Planning Theory 7, no. 2 (2008): 165-185.

21 Guzman, Javier Garcia, Hans Schaffers, VilmosBilicki, Christian Merz, and Monica Valenzuela."Living labs Fostering Open Innovation and Rural Development: Methodology and Results." In Proceedings of the 14th International Conference on Concurrent Enterprising, Lisbon, Portugal, June, 2008: 25.

participatory stakeholder platforms are "an important enabler of open-innovation and Living-Labs business models."[22] The value of this long-term strategy of economic development from the perspective of regional and urban design "is to promote a focus on decentralized systems of innovation which at the same time *will* need a context of regional clusters and collaborative networks to be effective and sustainable."[23]

When coupling the iLab design strategies and the proposed Collaborative Governance model with national trends of pursuing 100% Renewable Energy by 2025 of local municipalities, the iLab team is presented with an exciting opportunity for deploying an Energy Optimization "Stack" where the initial Living-Lab platform that is rooted in the bio-refinery model begins grafting additional renewable energy layers upon the established bio-fuel component (e.g., demand-response integrated into municipal buildings).[24] Another way of conceptualizing the proposed Stack is the SEED-SCALE development model where biofuels become the SEED within the soils of the cooperative-innovation ecosystem for achieving SCALE, that is, 100% renewable energy goal.[25] Emerging from this Stack, an innovative approach to renewable energy integration can be generated to target residential, commercial and industrial applications in an emergent, part-to-whole economic development strategy.[26] Building from the IRDI's innovative model for promoting a Culture of Health by and through linking healthcare and economic development into community-design, the cooperative-innovation component of the iLab will provide an ideal context for identifying synergies between RE business services as well as demand-response technologies to optimize an energy optimization ecosystem via an augmented Virtual Power Plant (VPP) deployment strategy. Akin to the "platform" role that VPPs play in the larger power-grid network, the iLab will function as a bio-centric – built from the soil up – catalyst within the iNetwork, providing a vibrant stakeholder-driven or Living-Lab platform for establishing partnerships and programs that enable a sustainable innovation cluster to emerge throughout the Great Appalachian Valley. Linking all three of the proposed "outcomes" (i.e., iLab Campus, iLab Process Design and iNetwork) of the Local-to-Regional/Urban-to-Rural (vertical/horizontal axis) network, the proposed iNetwork will achieve these goals by exploring network optimization opportunities – identify gaps, synergies, redundancies and aligning services – and co-developing bottom-up integration strategies beginning with bio-fuel production and distribution.

22 Ibid.

23 Schaffers, Hans, Mariluz Guerrero Cordoba, PatriziaHongisto, TündeKallai, Christian Merz, and Johann Van Rensburg. "Exploring Business Models for Open Innovation in Rural Living Labs." (2007): 3.

24 For more about "Stack" architecture see both: "The Stack to Come: On Benjamin Bratton's The Stack" by McKenzie Wark and Bratton, Benjamin H. The stack: On Software and Sovereignty. MIT press, 2016.

25 Taylor, Daniel C., Carl E. Taylor, and Jesse O. Taylor. Empowerment on an unstable planet: From seeds of human energy to a scale of global change. Oxford University Press, 2011.

26 For more regarding the 100% RE by 2025 please visit: https://www.sierraclub.org/ready-for-100/commitments

Mats Eriksson (et al.) defines Living-Labs as an R&D methodology, whereby innovations, such as services, products and application enhancements, are created and validated in collaborative, multi-contextual, empirical real-world settings. In the augmented VPP model, community stakeholders, solar integrators, bio-fuel producers and public entities are mutually entangled sources of innovation, and not merely inert/independent objects for testing and validating a given energy optimization strategy.[27] Inherent in the proposed Living-Lab strategy is the assumption that a Curriculum Design strategy should be carried out in real-world settings that provide non-traditional barriers to technology development. Bringing real-world components of innovation to the forefront, the proposed iLab will provide a robust curriculum design strategy in a high barrier context (e.g., health disparities, low electricity costs, fossil-fuel based economy, poverty, etc.). The strategy is rooted in the emerging theory that socio-economic limitations necessitate and often catalyze innovation.[28] Specifically, the proposed Living-Lab's adaptive/reflexive qualities (among others) present an invaluable regional case study for understanding the socio-economic parameters of pedagogical inclusivity, and, in turn, capacity for optimizing transition strategies nationally.[29] Ultimately, *transition-innovation* must "survive a *social* rather than simply methodological falsificationism."[30]

The local stakeholder strategies will focus on the development of several novel programmatic approaches to regional innovation that target residential, commercial and industrial applications in an emergent part-to-whole deployment strategy. To further explain this innovation strategy, Sustainable Williamson's Living-Lab Platform produced an "Energy Optimization" video which specifically unpacks Integrated Energy Parks and how they relate to developing an augmented VPP deployment strategy in coal country co-designed to accelerate the United States transition to a post-fossil fuel economy.[31] Serving as a concrete example of virtual architecture, traditional VPPs are clusters of distributed generation installations (such as micro-CHP, solar panels, small hydro, natural gas generation facilities, etc.) which are collectively run by a central control entity – a similar role that the iLab plays, albeit it functions more like a "probe-head or guidance device" than a central control entity.[32] The concerted operational mode delivers benefits, such as the ability to deliver peak load electricity or load-aware power generation at short notice. Such a VPP can replace a conventional centralized power plant while providing higher effciency and more flexibility. Because of their flexibility, efficiency and capacity to provide crucial information on supply

27 Tatnall, Arthur, and Anthony Gilding. "Actor-Network Theory in Information Systems Research," (2005): 42-46.

28 This theory is presently being developed by J. Eric Mathis and has been the primary topic of many of his presentations including his lecture at MIT which discussed the merits of "failed-successes" that were produced by the "One Lap Top Per Child" program citing the transflective screen as a successful innovation that emerged from limitations found in developing countries such as lack of infrastructure.

29 Kathleen M. Eisenhardt, and Behnam N. Tabrizi, "Accelerating Adaptive Processes: Product Innovation in the Global Computer Industry," Administrative Science Quarterly (1995): 84-110.

30 Andrew Webster, "A Sociological Commentary on Reflexive Innovation," International Journal of Technology Assessment in Health Care 20, no. 1 (2004): 65.

31 See video here under "Energy Optimization": http://sustainablewilliamson.org/ Here the VPP component functions as the Platform component of the Platform-Network architecture. According to Jane Bennet, "the electrical power grid offers a good example of an assemblage. It is a material cluster of charged parts that have indeed affiliated, remaining in sufficient proximity and coordination to produce distinctive effects. The elements of the assemblage work together, although their ...

and demand, VPPs are the perfect model for shared-solar resource projects to reduce costs while enhancing innovative capacity for the communities in which they are deployed.

The key component to this aspect of the strategy is virtual net-metering. Within a virtual net-metering system, multiple electric meters are collected into one inflow-outflow “virtual” mechanism so that more than one consumer may benefit from a single, remote solar array. An offsite solar array can be monitored for both the energy fed into the grid (outflow) and the energy required on the opposite side of the system when solar does not satisfy demand (inflow) – this virtual architecture (outflow/inflow) can be utilized for redesigning broader production flows within the proposed biorefinery model. Net generation credits can be passed on to the virtual net-metering participants, further incentivizing investment through long-term stabilization of energy prices. Virtual net-metering, a primary integration strategy for traditional VPP development, offers a viable avenue for augmenting the iLab Design protocol to accelerate innovation in all three sectors (Agriculture-Energy-Health) as the United States continues its integration of sustainable energy resources over the coming years. Importantly, the iLab team will encourage deployment in areas most likely to succeed, through soft assets like community engagement through local biofuel production and hard assets like adequate solar insolation values and proximity to transmission or distribution grids.

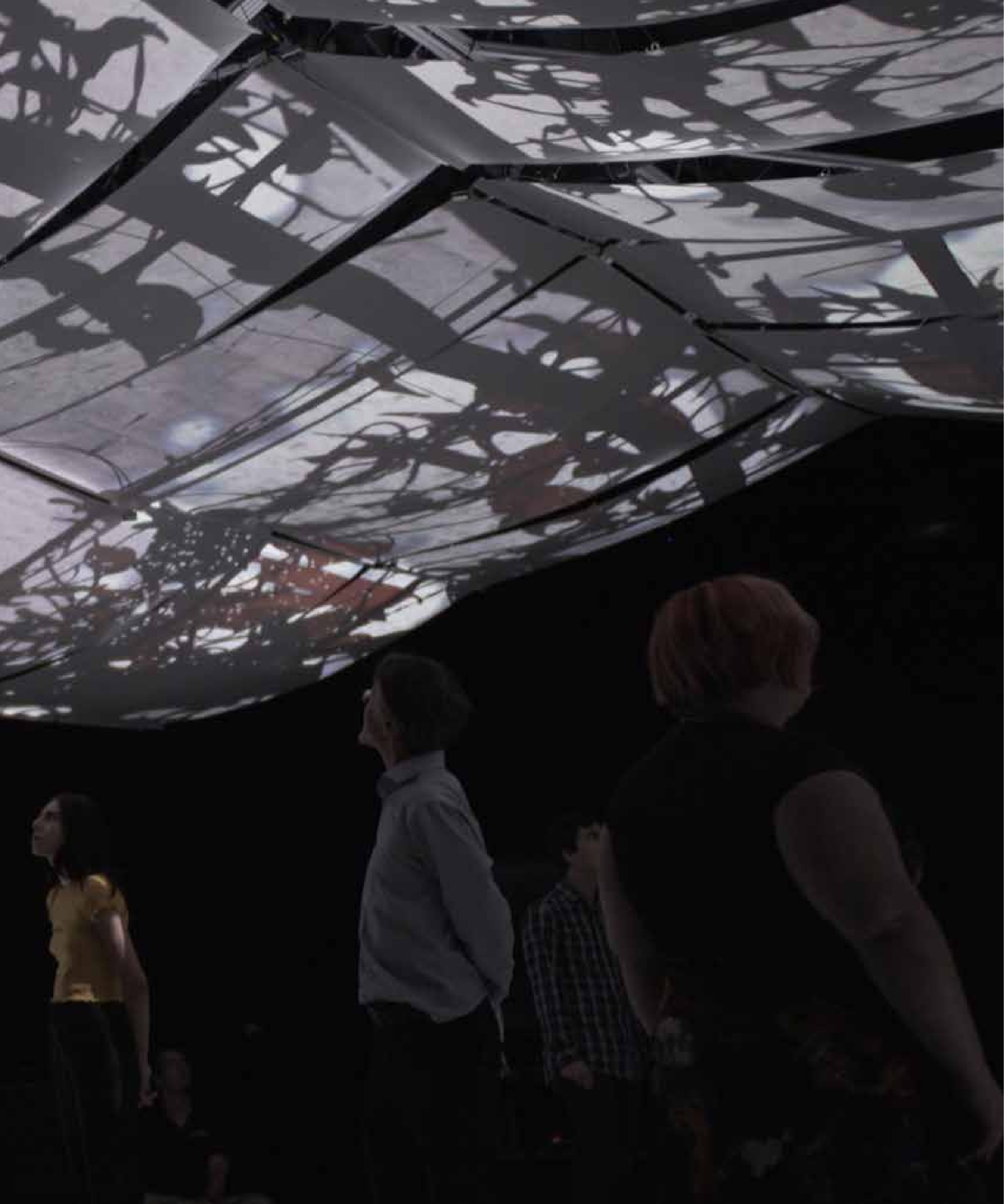
By linking all three focus sectors to both IT infrastructure and novel materials within the emerging field of bio-regenerative design (e.g., industrial hemp), it is our hope that this project will increase measurable job creation and innovative capacity while improving environmental and health outcomes through a regionally integrated “open-source” platform for accelerating regional transition. The key to this health-based strategy is to link local wealth generation and entrepreneurial development. The proposed iLab model recognizes the substantial economic and community development opportunities that will result from an integrated regional approach: 1) identifying key innovation gaps and developing critical regional infrastructure to ensure the continued expansion of the three focus sectors; 2) clearly packaging and delivering existing resources in a coordinated fashion to accelerate community-driven innovation through the comprehensive deployment of regional cooperative-innovation strategies by and through the iNetwork that is made up of Living-Lab affiliates; and 3) in line with the White House Rural Council, this project will proactively cultivate linkages between rural and urban settings to ensure that quality job creation is achieved regionally. The project will be a collaborative effort across the Great Appalachian Valley cooperatively nurtured by and through the iNetwork. The strategy will include the following:

1. Community Mentorship with iLab and other emerging Living-Labs;
2. Local Design Charrettes modeled after iLab’s Living-Lab platform;
3. Community-Driven Innovation will be developed in collaboration with the iLab team;
4. Entrepreneurial Training for all aspects of the open-design and deployment processes;
5. Technical Assistance for all established and emerging Living-Labs; and
6. Living-Lab Pipeline for expanding Living-Lab affiliates.

... coordination does not rise to the level of the organism this is where VPP comes in. Rather, its jelling endures alongside energies and factions that fly out from it and disturb it from within. And, most important for my purposes, the elements of this assemblage, while they include humans and their (social, legal, linguistic) constructions, also include some very attractive and powerful nonhumans: electrons, trees, wind, fire, electromagnetic fields.” Bennett, Jane. Vibrant matter: A Political Ecology of Things. Duke University Press, 2009: 24. Bracketed comment my own.

32 Deleuze, Gilles, and Felix Guattari. “A Thousand Plateaus, trans. Brian Massumi.” London: continuum (1987): 454

Making a name for himself by spearheading what is considered by many one of the most advanced coal transition strategies in the United States along with being a part of the core team that successfully launched the hemp industry across the United States through the 2014 Farm Bill, J. Eric Mathis has been at the forefront of Regional & Urban Design strategies throughout the Southeast with a specific focus on regenerative design and innovation. Serving as the Co-Director of the Institute for Regenerative Design & Innovation and building from his experience in both regional & urban planning in central Appalachia, Mr. Mathis is presently co-designing a regionally focused design-protocol referred to as a Living-Lab Platform. These platforms are engineered to breed both local and regional “circular-assets” within the energy and agriculture sectors – collectively forming a comprehensive Bio-Regional Development model rooted in an ag/energy nexus strategy. Deemed the “City of Arts and Innovation,” Mr. Mathis strongly believes that his home city of Winston Salem is poised to become one of the world’s most advanced Regenerative City models – incubating a Bio-Regional Innovation Lab or iLab through the strategic deployment of a novel health-centric ecosystem that merges both Resilient Communities and Living-Lab Innovation design protocols into one comprehensive development platform, called a Health Innovation District. His most recent social enterprises, both Bio-Regen Coop and SYNC Bio-Resources, play a central role in the development of this bio-regional strategy.



SC: *A Modular Software Suite for Composing Continuously-Evolving Responsive Environments*

Brandon Mechtley, Todd Ingalls, Julian Stein,
Connor Rawls & Sha Xin Wei
Arizona State University, Tempe, USA

1 Hendricks, Barbara E. 2001. Designing for Play (Design and the Built Environment Series). Farnham: Ashgate Publishing

Xin Wei, Sha. 2013. Poiesis and Enchantment in Topological Matter. Cambridge, MA: MIT Press

Image 1 **SERRA Vegetal Life installation, 2018** Oana Suteu Khintirian, Todd Ingalls, Sha Xin Wei + Synthesis @ ASU

SC is a modular suite of software designed to allow designers to compose the behavior of a responsive media environment evolving in concert with contingent activity in a physical space. The media can be rich and fairly eccentric: projected video, spatialized audio, theatrical lighting — generally fields of structured time-varying light and sound, as well as water, mist, animated objects etc. The behavior of the responsive environment evolves according to prior design as well as contingent activity.[1] A key condition is that everything happens in real-time, in concert with the activity of the inhabitants of the responsive environment. SC supports rich and thick experiences with poetic, symbolic, and scientific effects.

Introduction

A responsive environment is a physical space in which the media — light, sound, or some other material — can vary in concert with the activity of people and things inside the common space.[2] A key condition for composing these environments lies in the leverage of the affordances of analog media and the relations among living bodies in a live event. Responsive media are fields of structured light, sound, or some other computationally-modulated distribution of matter or energy that vary accordingly to movement or gesture. Typically, responsive media are continuous in time and space from the point of view of human. Their palpable, real-time, continuous coupling to movement affords rich, painterly, calligraphic, gestural expression with arbitrary, improvisatory nuance; discrete change, modulated by Boolean procedural logic, is a special case.

To facilitate the creation of responsive media environments, we have written a structured set of software abstractions — SC — that simplify the physical sensing of environments and control of media instruments within them. It is intended to allow modular design that enables designers to rapidly pass signals between sensors, data transformations, and media; manipulation and production of dense, continuous media that produce a rich palette of possible media states; continuous evolution of media that can facilitate production of dynamic, responsive, rather than static or repetitive media environments; and designing at the level of metaphor that focuses the attention of developers on the intended effect of media states rather than underlying mathematical representations.

SC is designed to be used by event composers or installation artists who are not software engineers. The scripting language Max/MSP/Jitter, the lingua franca for live media scripting, permits the blending of decades of toolkits for live media processing from developers worldwide, such as cv.jit computer vision; MuBu multibuffer audio signal processing, SPAT spatialized audio; Wekinator machine learning.[3]

We have used SC and its precursors in various installations, media sculptures, and events. For a sampling see the following videos: immersive enactive cloud simulation (vimeo.com/synthesiscenter/clouds), or day in the life (vimeo.com/synthesiscenter/slsa2).

2 Bullivant, Lucy. 2006. Responsive Environments: Architecture, Art and Design. Victoria and Albert Museum

Xin Wei, Sha. 2000. "M3 / T-Garden," In SIGGRAPH 2000.

http://www.siggraph.org/artdesign/gallery/S00/interactive/thumbnail18.html. acc July 16 2018.

3 3 Pelletier, Jean-Marc. cv.jit | Computer Vision for Jitter. https://jmpelletier.com/cvjit/. acc. July 16 2018.

Schnell, Norbet, Axel Röbel, Diemo Schwarz, Geoffry Peeters and Riccardo Borghesi. 2009. "MuBu & Friends - Assembling Tools for Content Based Real-Time Interactive Audio Processing in Max/MSP." International Computer Music Conference (ICMC), Montreal 2009

Carpentier, Thibaut, Markus Noisternig, Olivier Warusfel. 2015 "Twenty Years of IRCAM SPAT: Looking Back, Looking Forward." In 41st International Computer Music Conference (ICMC), Sep 2015, Denton, TX. 270 – 277.

Fiebrink, Rebecca. "Software for real-time, interactive machine learning." Wekinator

http://www.wekinator.org. Acc. July 16 2018.

The SC Responsive Media Library

The SC software frameworks are built around *media instruments*: code that transforms a media stream (typically sound, video, or light) into another media stream at real-time rates under the threshold of perceptible latency.

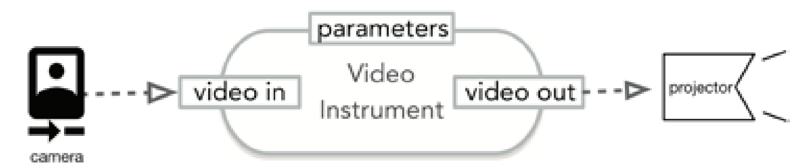
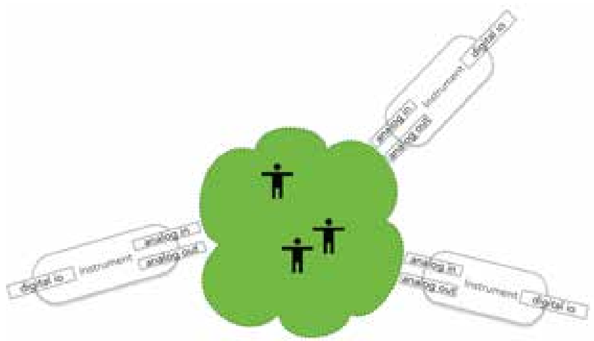
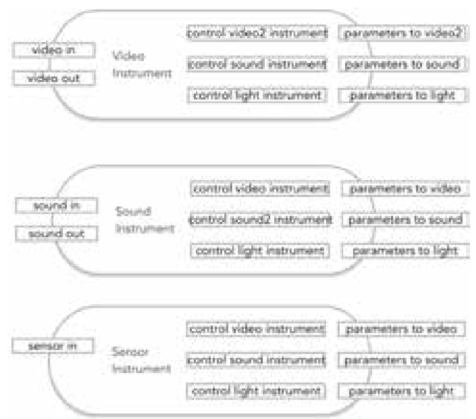


Image 2 A media instrument transforms a stream of media into another stream in real-time, modulated by public parameters.

Media instruments are redefined continuously by parameters that are functions of features derived from sensor inputs, internal conditions, or the metaphorical state of the event (see *Image 2*). In a typical responsive environment, a suite of instruments process the time-based field media by mapping streams to streams as illustrated in *Images 3* and *4*

Within the SC framework, nearly 300 utilities and instruments have been created to compose responsive environments, consisting of physical sensing and actuators, acoustic sensing and multi-channel audio, lighting arrays, and streaming video capture and visual projections. SC supports working between real-time media formats by using a standardized modular architecture whereby messages, including real-time streams of manipulated media as well as statistical calculations are passed between components. In this way, media can be easily interchanged or transcoded. To support this style of development, SC has been implemented in the real-time media programming environment Max/MSP/Jitter to make all layers of control legible in a common scripting language accessible to composers who are not software engineers and wish to work across all computational media types. In the following sections we will describe a few example objects from each category: audio, video, lighting, physical, and intermediate complex systems. In addition to the media instruments, SC provides utilities for manipulating data streams, including objects for scaling, easing, mapping, interpolating, and ramping signals as well tools for event detection, time-series analysis, and tools for producing sequences of data, such as Markov random processes and physical models.





Audio Instruments

SC's extensive collection of audio utilities includes several modules for audio effects and filtering, and reverberation effects to simulate different acoustic environments, granular synthesis, synthesis of parameter trajectories and sequences for pitches and frequency bands, a multi-band filterbank instrument that allows movement within a dense stream of video to manipulate audio streams, and several utilities for producing audio in different multi-channel setups aided by IRCAM's Spat audio spatialization package.[4]

Image 3 Media instruments modulating time-based media in an environment.

Image 4 "Solipsistic" instruments tend to require redundant and combinatorially complicated logic.

4 Jot, Jean-Marc. 1999. "Real-time spatial processing of sounds for music, multimedia and interactive human-computer interfaces." Multimedia Systems, 7 no.1:55-69.

Video instruments

The collection of video utilities and instruments encompass everything from grabbing video from different sources to computer vision algorithms for feature extraction and post-processing of graphical output. SC has abstractions that wrap methods of reading data from cameras, files, and the Syphon[5] framework. A cornerstone of the SC package is the array of computer vision abstractions. These patches cover methods of background subtraction, edge detection, optical flow, and presence detection. All of these techniques have been built as GLSL fragment shaders to allow for higher resolution tracking while still increasing performance in comparison to traditional CPU-based versions.

5 Syphon, by Tom Butterworth & Anton Marini http://syphon.v002.info/

In addition to methods of quantifying video inputs, SC is also capable of visualizing the results from complex system simulations. Two notable methods are through the use of particle systems and vector fields. The particles can either act as tracers, being guided by the output field of a complex system, or behave as agents, feeding data back into the system that is moving them. Vector fields reveal trends of change within a complex system's output by drawing poles pointing in the direction of the current delta.

SC also provides methods of modifying visualizations through post-processing effects. The list includes blooms, blurs, palette-based recoloring, and temporal shifts. Most notably, the "time-space" effect produces an image consisting of delays on a per-pixel basis. The system stores incoming frames of video into a buffer, and uses a mask to determine where in the buffer to sample for each individual pixel. This temporal processing method allows for a visual history of any video stream and also opens up opportunities for artistic use of delays.

Lighting instruments

SC's lighting abstractions rationalize accessing and controlling DMX lights or other hardware via a common messaging protocol. Pre-built abstractions handle everything from scaling incoming data along the response curve of individual lights to communicating the correct DMX address with the chosen interface. This allows composers to blend in a state-of-the-art professional theatrical lighting to produce the highest quality visual qualia.

Physical sensors and actuators

The library of physical sensing patches supplies methods of reading and parsing data from different sensor configurations and controlling physical media. It includes modules for communicating with a network of WiFi-enabled development boards that control arrays of ultrasonic atomizers, interface with a custom bend-sensing glove interface, and parse data from x-io Technologies XOSC[6] I/O board, which transmits IMU data and the state of up to ten additional sensors wirelessly via UDP bundled in the Open Sound Control protocol.[7]

6 "x-OSC" x-io Technologies http://x-io.co.uk/x-osc/

7 (REFERENCE Freed et al)

Complex systems simulations

To produce rich behaviors governed by dense, complex dynamical processes, a core component of the SC system is a set of simulations for complex dynamical systems models of physical material systems, ranging from Navier-Stokes[8] and lattice Boltzmann fluid dynamics[9], Gray-Scott reaction-diffusion chemical systems[10], to more specific systems, such as a charged body simulation (by Rawls) and our Experiential Model of the Atmosphere.[11]

In the charged body simulation, gradients of electrical charge can be used to manipulate video. Bodies are assigned initial positive or negative charges upon entering a physical space, which can be controlled by the designer. As objects or bodies move within the video, their charges interact based upon the values held by neighboring objects. The resulting charge gradients can be used to assign properties to different pixels within a video stream. A previous use of this system determined how attractive or repulsive an object was to virtual particles within a fluid simulation.

EMA is a real-time, steerable simulation of warm cloud physics that allows media developers to move between virtual states of dry air, water vapor, and condensed liquid water under the influence of atmospheric dynamics.[12]

The SC state engine: continuously evolving media

To produce continuously evolving behaviors within responsive environments using the SC instruments, we have created a state engine utility that allows designers to determine how the environment will evolve in response to the sensed state of the environment and current state of the media instruments or underlying simulations. The purpose is to meaningfully evolve the behavior of the entire ensemble of rich media instruments suggested by a *continuous* model of state evolution. We use a continuous dynamical system[13] in place of boolean, procedural, or stochastic (probabilistic) logics that are commonly implemented using finite state machines to provide rich behavior that responds to arbitrary fine nuance, and evolves robustly to arbitrary, even unanticipated, activity.

This continuous state evolution model is not a finite state machine because the formalism admits continuous ranges of change and unbounded continua of possible states: *a state can be the formal combination of any number of ingredient states*. The state engine does not describe the state of component code or physical devices, which we call *parameterization* or presets. Rather, in our terminology, a *state* refers to a metaphorical description of the event as experienced by the inhabitants in the environment during a live event. For example the state of an event could be characterized by terms such as “the beginning,” “nighttime dormancy,” “people are bored,” or “stormy,” which are nominally associated by the composer to combinations of features that can be derived from sensors (cameras, microphones, photocells, piezoelectric sensors, etc.). This interpolation of a state evolution layer in between the sensor data and the parameters controlling the software/hardware media instruments allows the composer to design rich behavior while at the same time freeing her/him from locking that behavior design into particular technology or particular technical instantiations.

It is also important to emphasize that the behavior is *neither* a fixed sequence (fixed tree of locally determined linear sequences of action) nor random (stochastic). More profoundly, the designer does not determine what actually happens, but rather the way the environment will *tend* to evolve in response to *any* activity. Thus the state evolution acts on the space of *potential*, not actual activity. Nonetheless, the designer can condition the behavior as precisely and narrowly as desired. In practice, this system is best for medium to coarse qualitative changes in the behavior of arbitrarily rich complex environments, whereas specific action-response logics can be written using conventional ad-hoc code.

In practice, SC’s state engine is implemented as an interface where designers can a) define a number of states, b) assign nominal sensor values to each state, and c) bind parameters of the media instruments to these states. The designers can then arrange the states in a simplicial complex, allowing for both linear movement between “fundamental” states and more complex regions in the potential state space where the current state may be a combination of many fundamental states. (There is nothing sacred about which states are fundamental and which are (convex) sums of fundamental states.)

The system’s state evolves as a function of both the incoming sensor features and an intrinsic dynamic based on minimizing an energy functional.

8 Stam, Jos. 2003. “Real-Time Fluid Dynamics for Games.” Game Developers Conference.

9 Bao, Yuanxun Bill, and Justin Meskas. 2011. “Lattice Boltzmann method for fluid simulations.” Department of Mathematics, Courant Institute of Mathematical Sciences, New York University

10 Pearson, John E. 1993. “Complex patterns in a simple system.” Science 261, no. 5118: 189 – 192.

11 Mechtley, Brandon, Christopher Roberts, Julian Stein, Ben Nandin and Sha Xin Wei. 2018. “Enactive Steering of an Experiential Model of the Atmosphere.” In International Conference on Virtual, Augmented and Mixed Reality 126 – 144.

12 More details about EMA can be found in Brandon Mechtley. “An Experiential Model of the Atmosphere.” Synthesis Center http://synthesiscenter.net/projects/ema/. acc. July 16 2018.

13 We exploit Max’s powerful pattr abstractions for saving and restoring the settings of any object’s parameters, and have implemented a design pattern for application programming that leverages either pattr or odot.

MacCallum, John, Rama Gottfried, Ilya Rostovtsev, Jean Bresson and Adrian Freed. 2015. “Dynamic Message-Oriented Middleware with Open Sound Control and Odot.” In ICMC 2015 58 – 64.

The vector distance of current sensor data from the nominal sensor vectors assigned to each fundamental state is computed. It contributes to the energy of the current state of the environment. The physical model then evolves so as to minimize this energy by adjusting the position of the player state. In addition, several parameters allow designers to give each state a certain amount of static energy to fine-tune the contribution of the state to the movement of the player state. An example state topology leading an environment through different times of day and seasons is shown in *Image 5*.

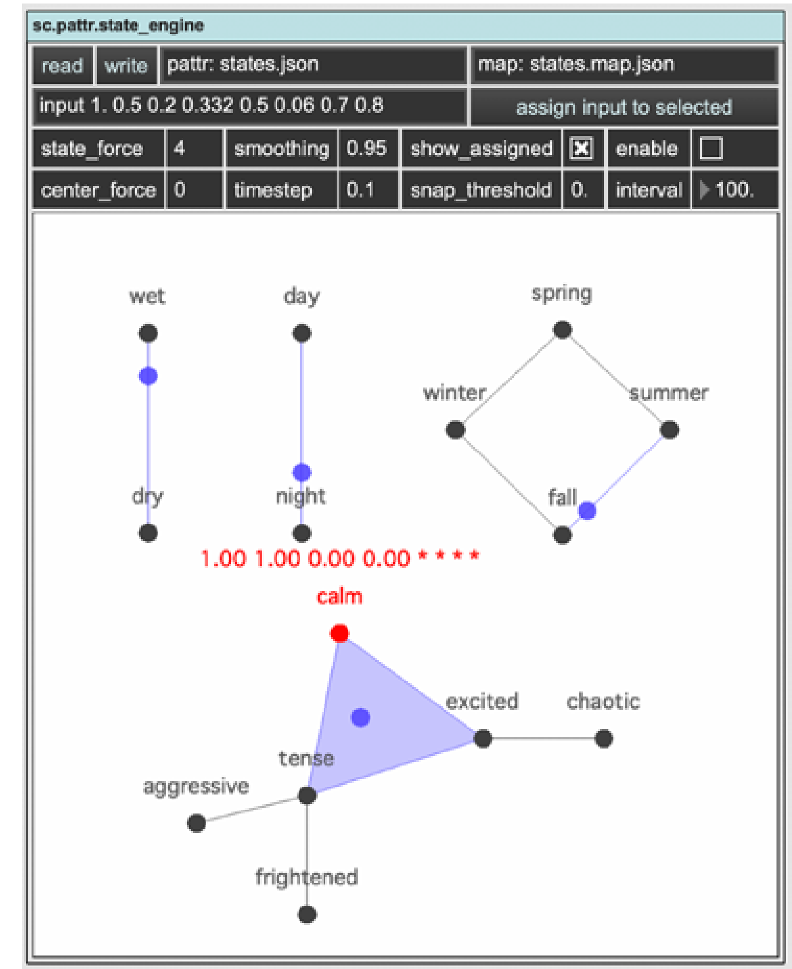
In this topology, the state of the media environment can move between several metaphorical states associated with different seasons of the year and times of day. Within each season, the system state can evolve continuously between the different times of day, but significant seasonal state transitions will only occur overnight. In this image, the media environment is experiencing an overnight transition between summer and fall. If this topology were to drive EMA, for example, each state could be associated with different physical variables, such as average ground temperature or humidity, associated with different seasonal climates. The state engine is implemented in a graphical interface that makes it easy for designers to arrange the state topology, name states, and assign sensor data values and media parameters to each state.

Conclusion

We have outlined a software framework usable to designers to compose behaviors for responsive environments. The system's key features include:

1. Rich robust evolution of behavior in concert with arbitrary, improvised activity by inhabitants;
2. Evolution of state based on continuous dynamical system rather than discrete finite state model;
3. Real-time media stream processing instruments created by time-based media artists for aesthetic and experiential impact;
4. Implementation in lingua franca for real-time media processing;
5. Transcoding.

Image 5 An example state topology using sc.pattr.state_engine.]



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Xin Wei, Sha. 2011. ed. "Poetic and Speculative Architectures in Public Space." AI & Society 26.2. London: Springer-Verlag

Xin Wei, Sha, Michael Fortin, Navid Navab and Timothy Sutton. 2010 "Ozone: A Continuous State-Based Approach to Media Choreography." ACM Multimedia. Montréal: Topological Media Lab, Concordia University

Stam, Jos. 1999. "Stable Fluids." In SIGGRAPH '99 Proceedings of the 26th annual conference on Computer graphics and interactive techniques, New York, 1999. 121 – 128.

Synthesis at Arizona State University provides a place for experimentally inventing and fusing fresh practices of understanding and enriching how the world works with fresh practices of making meaning. Sha Xin Wei founded this atelier for fusion research in 2014 with colleague research faculty Todd Ingalls and Brandon Mechtley to extend and expand on 15 years of prior work in the domains of responsive environments and live event / movement-based research creation at the Topological Media Lab / Concordia / Montreal, and at Arts, Media + Engineering / ASU.

Affective Atmospheres
Ambient Feedback Ecology

Nima Navab, *Topological Media Lab, Montreal, Canada*
Desiree Foerster, *Institute for Arts & Media, Potsdam, Germany*

1 Frost, Samantha. 2016. Biocultural Creatures: Toward a New Theory of the Human. Durham: Duke University Press.

Image 1 angibleFlux plenumorphic chaosmosis microcosm no.2 plenumélliptique périgée Navab, 2018

Encompassing a series of experiments with atmospheric scenography, the following paper maps out the relationships between different materials and energetic flows as part of a spatial design. These investigations emanate from the basis that poetic relationships between material and immaterial processes can induce new meaning to the ways we inhabit our environment. In diffusing the boundaries between states of matter in the environment and the perceiver, the unfolding atmospheric processes enacted here function as perceptual amplifiers for transformations on scales that are usually not sensually accessible. The focus shifts from the concrete to the in-between. The visualization and enaction of flows that make up our surroundings suggest a greater involvement of oneself with the environment.[1] Through these experiments we demonstrate 1) how spatial continuity can be achieved in relating attributes of dynamic behavior of water, vapor, air, sound, and light to significances in space; 2) that the indifferent role of the human perceiver is challenged in making their impact and responsiveness to the environment part of the spatial composition itself; and 3) how the expressive qualities of atmospheric variables can be used to experience layers of meaning in spaces that are usually not comprehensible (such as ecological dimensions of water use).

Introduction

Discussions about climate change, scarcity of resources and the lack of distributive justice often point towards a phenomenological problem. People in Western industrial nations, who mainly live in urban areas, generally have little direct reliance on natural processes and therefore lack a sense for the direct significance of local consumption of resources and global consequences.[2] Instead, digital networks regulate the climatic well-being of residents and consumers, car drivers or passengers. This is juxtaposed with the utopia of the off-the-gridder, people who invest their own physical energy to energy flows in their homes or early techniques and instruments of observation and navigation of natural phenomena that testify to human involvement in natural processes—which is contrasted by the navigation app. That being said, one can state that a direct perception of water and other energy cycles plays a little role in the everyday life of most people in the industrialized nations. The interdisciplinary projects presented here aim to explore the phenomenology of energy cycles and flow dynamics beyond scientific-technical approaches and to design poetic suggestions for new sensual milieus involving humans in a new, digital-analogue way.

2 Peter Rudiak-Gould. 2013. "We have seen it with our own eyes. Why we disagree on climate change visibility." Weather Climate Society, 5:120 – 132.

In this paper, we investigate the use of ambient feedback to amplify qualities of usually unperceivable processes and relate them to the felt experience of space. How does the flow of particles in the air and ambient eco-feedback relate to our physical presence and actions in a meaningful way?

The first project to be outlined here explores the development and integration of two ambient eco-feedback displays that were integrated into the kitchen and courtyard spaces of a residential dwelling. The displays were created by Nima Navab with The Topological Media Lab. The house itself was built and exhibited by Team Montréal, a competitor in the 2018 Solar

Image 2 Liquid Light
Photo by Nima Navab.

Decathlon competition in Dezhou, China. The collaborative effort intertwined a manifold of disciplines around situated concerns of sustainable living and passive building strategies. The second project takes its point of departure from the process and outcome of an interdisciplinary workshop series on responsive atmospheres. The project involves researchers and students from the Topological Media Lab, Synthesis Centre and the Institute for Arts and Media, bridging Philosophy, Architecture, Speculative Design, Arts and Media Technologies.

Image 3 Liquid Light integrated in the kitchen. Photo by Nima Navab.

Ambient Feedback Ecology: Solar Decathlon's 'Performative Dwelling'

The first project covers two responsive lighting installations that were integrated into a house and courtyard in order to create a visually stimulating and experiential environment while raising awareness of consumption, performance, and behavior relative to use of water and energy resources.

The first installation is a lighting fixture embedded into the kitchen cabinets. By being installed in place where it visually connects the performed action of the residents in real time with the overall consumption of water, an experiential dimension of scales usually not accessible is added to everyday action. This communication of the relation of the amount of water used for washing the dishes or drinking water to resource consumption is purposefully mediated in an aesthetically pleasant way: water droplets are released inside the fixtures' fluid chamber according to consumption trends, animated by light from the top of the chamber. This way the eco-feedback display gains an ambient quality that merges with the everyday activities. Ambient feedback thus has an advantage over other forms of data visualization, which are mostly abstract or oriented towards the deficits of the actions. Whereas charts or digital measure units quickly move to the background of our awareness, ambient feedback displays are capable of producing intuitive, bodily

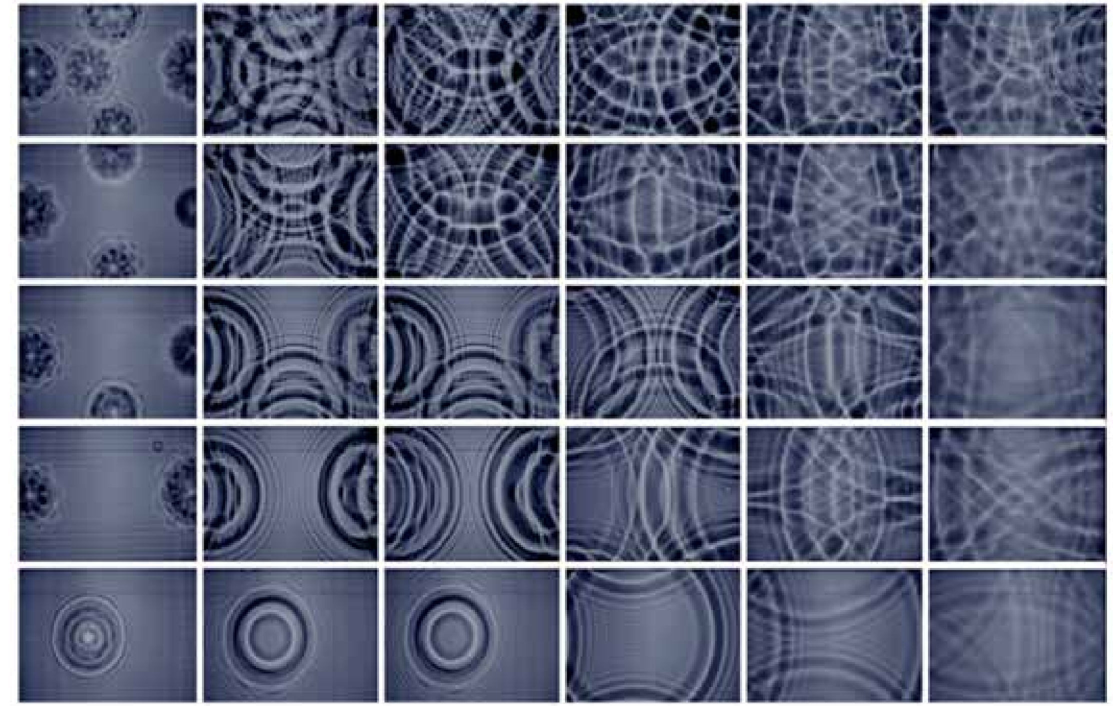

Image 4 Liquid Light snapshots displaying gradient of textures. Photo by Nima Navab.

knowledge about the relationships between situational actions and overall consumption.[3]

While the light fixture that is embedded into the kitchen cabinets communicates through manipulation of liquid textures overall trends in consumption of water over time, the awning integrated into the courtyard of the house represents the overall balance of energy in using different light structures that animates shadows of plants. Shadows disperse and overlap, becoming more diffused as the energy consumption starts to outweigh solar energy gained during the day. Thereby the invisible interrelationship of occupants and their home expressed in the continuous flow of energy, water and other resources becomes present and can be experienced in its processual nature throughout time.

The aim of the project was to investigate if eco-feedback technology integrated in such a way can sensitize for the impact of individual and collective

3 Browning, William and Catherine Ryan. 2014. 14 Patterns of Biophilic Design New York: Terrapin Bright Green llc. 1.

4 Froehlich, Jon, Leah Findlater and James Landay. 2010. "The Design of Eco-Feedback Technology" In CHI '10 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Georgia, 2010 2: ACM.

5 Rogers, Johnny and Lynn Bartram. 2011. "Exploring Ambient and Artistic Visualization for Residential Energy Use Feedback" In IEEE Transactions on Visualization and Computer Graphics 17 no. 12: 2489 – 2497.

6 Xin Wei, Sha. 2013. Poesis and Enchantment in Topological Matter Cambridge: MIT Press, 20.

behaviors on the environment.[4] It was found that material interfaces of Sense and Fluid are helpful in highlighting which activities residents can target to reduce water and energy demands, while the media installations evoke a sense of care by poetically engaging the residents with the matter to raise curiosity about consumer behavior in the first place.

Atmospheric media such as light and water have been found rich materials to serve in such a design context: they allow to express the subtle and gradual ambient shifts of the environment.[5] These observations, perceptible in atmospheric relations, such as sunlight's illumination of interior spaces or the sound of rain hitting the glass of window panes, became a way for us to map the dynamic and complex energy flows of our environment and their subsequent impact on the built world. Through the exploration of material agencies translated through temporal and textural properties of water and light, occupants attune to the rhythm of cumulative patterns of consumption. The quality of light, to signify changes gradually detailed and aesthetically rich, allows to relate abstract data to one's own experience of space by making them perceptible and tangible through the slow and gradual composition. In sum, this project uses interactive and immersive technologies to enable design solutions for fluid lighting automation and communication of environmental data while paying close attention to everyday behavior in domestic space.[6] Thereby, media installations that revolve around the concept of a performative dwelling and make use of architecture as an interface, directly relate and engage with internal and external flow dynamics of material and immaterial processes.

Caustic Scenography: Responsive Cloud Formation

The starting point of the second investigation is an installation to explore ephemeral fields of light, water, air, sound, and temperature as a trigger of pre-reflective, embodied ways of relating to environments by shifting boundaries between human agents and their environment. The installation creates mist and clouds of different textures and simultaneously intensifies and augments the movement and transformations of matter and their response to the exterior conditions.

Image 5 Shadow Play courtyard awning garden. Photo by Nima Navab

At the core of the platform, a bed of ultrasonic atomizers is submersed in a pool of water. Variable ultrasonic power is converted to high frequencies driving piezoelectric transducers. Through distributed continuous modulation of frequencies, atomizers vibrate particles at a rapid pace, in effect, allowing for the creation of low to high density cloud structures, while spreading water droplets around its periphery. For humidification purposes the droplets are considered a nuisance, but in the installation, they become instrumentalized, orchestrating subtle to dramatic undulations within the bounds of this reflective pool. A multi-directional embedded light design projects these wave patterns through reflection and refraction, creating a caustic scenography around the installation. The material computation makes physically and metaphorically felt the co-dependencies of immediate to remote actors in play within its spatial setting. In effect, performative qualities of transformative states of matter are amplified through caustic experimentations.

The experimental work runs parallel to philosophical investigations, with practice and theory constantly stimulating each other. Spatially, performative qualities are explored in a series of etudes ranging from participatory flow dynamics and gestural interaction, affecting airflow through movement and respiration, to compositions based on real-time atmospheric models and biophilic rhythmic compositions.

The questions that guided the project encompassed philosophical as well as design strategic inquiries. The philosophical questions are primarily related to phenomenology and the perceiving subject and how it emerges in encountering atmospheric processes. The authors wanted to understand what modes of perception it takes to recognize an event within diffusive processes, to recognize a meaningful referentiality between the elements at play. What kind of perceiver-subject emerges when the center of engagement is not a solid object but ambient conditions that can be experienced and embodied through their effects on multiple scales? Atmospheres envelop the perceiver in space. Consequently, we not only explored the relation between the perceiver-subject and the atmospheric surroundings in the act of observation, but also in what way embodied actions can lead to engagement with the clouds that become meaningful over time. What is idiosyncratic about atmospheric media such as clouds is that they change shape, take on form and dissolve on layers barely visible. Clouds are no solid objects, they are processual in nature. The leading question therefore was, how the perception of intermediate states instead of fixed objects can be extended in time and allow for meaningful bodily engagement. To approach this question, we investigated the patterns of cloud-formation

Image 6 Cloud Chamber 1.0 Atmospheres Workshop, Synthesis Center, Tempe, Arizona (2018) Photo by Elsa Alonso.

and transformation and ways to re-pattern them through movement. At the intersection of philosophy and design we wanted to find out if these novel engagements with atmospheric surroundings can push the relationship of observing or mapping environments towards being in environments, to suggest bodily rich and meaningful ways of dwelling. To approach these questions, we took into account the semantically rich meanings of atmospheres when constructing the installation. In the following the installation will be described in more detail and related back to the outlined research interests.

Atmospheres can mediate moods, they can affect the perceiving subject in the way she feels. This emotional-affective quality of atmospheres is expressed in the installation by way of dramatic structured lighting, which suggests natural phenomena that are already charged with a certain mood, such as sunsets or sunrises, the reflection of sunlight on a water surface at the horizon. In re-creating these phenomena at arm's length from the perceiver, she becomes corporeally affected. Memories of familiar phenomena merge with the felt significance of testimony. Being in space thereby is loaded with meaning and emotionally intensified. Besides the emotional charge of atmospheres, atmospheres in the climatic sense of the word also mediate weather phenomena, in being the sum of the parameters that constitute weather: air temperature, atmospheric pressure, humidity, precipitation, solar radiation and wind. We cannot experience climate in its complexity, but we do know weather phenomena and we experience their impacts. In our installation, these familiar phenomena are made tangible: the multiple phases that constitute the formation of dense clouds, their dissipation and transformation into water droplets, the impact of wind and pressure on the movement of clouds and mist, is laid out in a sensually accessible and bodily experienceable way. These effects are both applied within the installation as well as in the space that surrounds it through the digitally controllable matrix of the platform - the dynamics of processual phenomena can be empathized. In blowing into the cloud formations, using the hands or objects to touch or move the clouds, one's own body can become part of the internal dynamics of the system. In using fans of different sizes and angles as well as heat plates, the impact of temperature change and airflow is used to extend the clouds towards space. The heat plates are installed above the water level and move the mist upwards. Fans installed on the edges can form a vortex in the middle of the platform, fans connected to a pipe suck the mist upwards and release a thick stream of vapor into the air. Each of these different movements and ways to create, transform and dissipate clouds allows for bodily engagement on different layers.

One can blow into the mist, touch it, move it, increase the impact of the airflow or heat or try to weaken it. This way, atmospheres create a context in which one's own body becomes the medium for experience and the way sensory experience is structured—as part of processes that are related to something known in order to become meaningful—relates the perceiver to the everchanging surroundings. Turning towards atmospheres in this way, means to enrich the experience of the in-between: the multi-relational zone between bodies in space, between objects, between the perceiving subject and its environment. Thereby, we argue, atmospheric media can induce new meaning to the ways we inhabit our environments. By seeing and feeling how our bodies and the surrounding atmosphere interrelate, we begin to focus our attention in a new way and become aware of the processes and relationships that normally only form the background of our perception.

Conclusion

In both projects, the unfolding of material and energetic processes that enact both space and its inhabitants are moved from the background of experience to the foreground. The visualization and enaction of these flows not only offer a greater understanding of a place and its microclimatic conditions—it also offers new affordances to act in this space and thereby suggests a greater involvement with the environment. This involvement impacts the sense of agency: When solid boundaries are replaced with processes of transition, exchange and transformation of matter, one's own impact and responsiveness to the environment must be mediated in a new way in order to gain meaning. The projects show how the implementation of atmospheric phenomena into space discloses layers of interaction and relation, thereby creating a space that affords multiple layers of engagement. The layers that compose a space can encompass multiple dimensions of experience such as social and ethical—such as the water use of a household - or physical - in the ways our bodies participate in metabolic processes that our surroundings are made of, in sharing the air we breathe, the energy we take in and the wastes we release back into our environment. If these layers become meaningful for an experiencing subject, its own actions as well as the actions of others can be experienced as relevant in novel ways. We have shown that the expression of different, formerly invisible layers of a site can enable new ways of engaging with a space as well as with others. A further investigation would have to show if this experience and a more continuous engagement with different layers of spaces can impact a lasting change of habits as well.

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Lab Directors:
Michael Montanaro, TML, Concordia University.
Sha Xin Wei, Synthesis Center, AME.

Main Collaborators:
Nima Navab, Desiree Foerster, Thierry Dumont, Tatev Yesayan, Thierry Syriani, Emiddio Vasquez and Brendon Mechtley.

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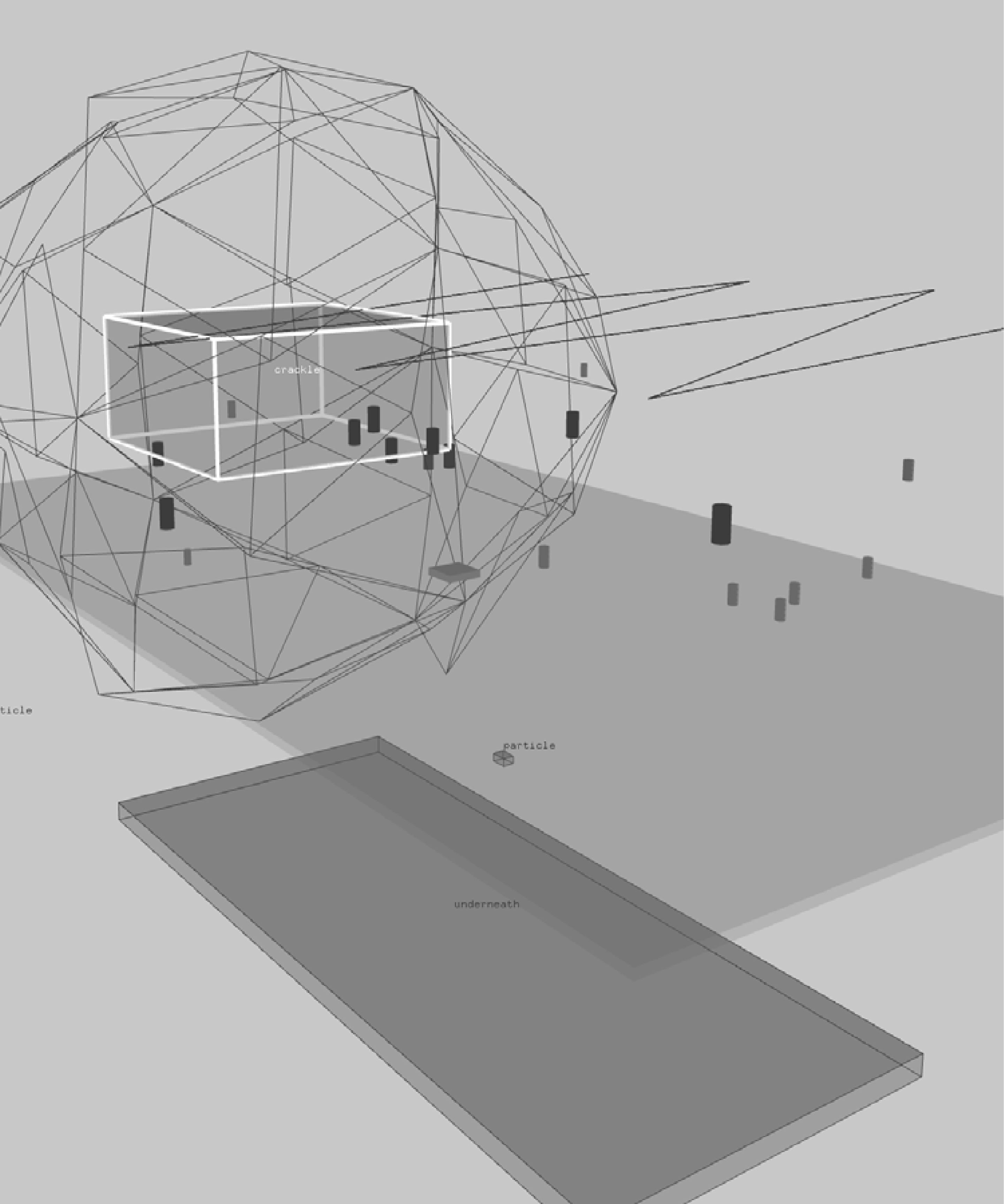
Since his years at OCAD studying Environmental Design, Nima Navab has become increasingly focused on spatial design, and more specifically, examining the role of art and technology in enhancing both intimate and large-scale public interactions. Through a variety of mediums and means, Nima investigates the various roles humans play in shaping both the ecological, political and sensorial landscapes of our built environment. His increased attention to everyday spatial interactions has brought to light the importance of field research, discussion and collaboration with those occupying the space as well as the space itself, highlighting the importance of spatial experience and theoretical research, both which continue to form the basis of his creative process. He is a research associate at the Topological Media Lab.

Desiree Foerster's research revolves around the study of embodied aesthetics. Her goal is to incorporate additional sensory modalities into the current aesthetic frameworks, such as thermoception, interoception, chemoception. Taking on the perspective of process philosophy and mediaesthetics, she investigates the role that liminal experiences play in situating the human subject apart from a conscious reference to the world. Her PhD thesis asks questions such as: in how far can aesthetic framework inspired by metabolism (and process philosophy) provide new understandings to the emergence of subjectivity? She is a PhD candidate at the University of Potsdam, where she is advised by Birgit Schneider (Potsdam) and Sha Xin Wei (ASU).



Integrating Sound in Living Architecture Systems

Application of 4DSOUND in Kinetic Sculpture and Architectural Design

Poul Holleman, Salvador Breed & Paul Oomen
4DSOUND, Amsterdam, Netherlands

Image 1 Royal Ontario Museum mapping, 4D Visualization Still.

Summary

We elaborate on results of our collaborations with the Living Architecture Systems Group (LASG) over the past year. Instead of additional layers of material, spatial sound interweaves meaningful fabric to sculptural form and living architecture. An architectural design now can be embedded within a sonic field (exterior), or spatial sound can form itself inside sculptural objects (interior). 4DSOUND has evolved in implementing irregular speaker setups to enhance sound projection and create applied instrumental possibilities of composing with spatial sound in the sculptural realm. We will further discuss developments regarding the integration of the 4DSOUND Engine to control other media like light, kinetics, and sensor interfaces. The paper will conclude with future research and objectives.

Projects

Astrocyte, DX EDIT, Toronto, Canada - fall 2017
Amatria, Indiana University, Bloomington, Indiana, USA - spring 2018
Noosphere | Aegis, Royal Ontario Museum, Toronto, Canada - summer 2018

Introduction

Sound is an essential medium in understanding space, expressing emotions, and abstracting organic and artificial phenomena like growth and electronic textures. When a physical sculpture is present within the soundscape, the spatial and physical relations between sculpture and sound requires a clearer definition. The in-depth collaboration with the LASG has challenged 4DSOUND to extend the control of sound beyond an empty space that hosts sound objects to a world where the virtual is seamlessly integrated with the actual.

The 4DSOUND paradigm considers sound by its sculptural and architectural qualities. Sounds are objects that can be sculpted with dimensions, construed sub particles, and applied properties through sound design. These objects are subsequently placed in a (virtually) infinite space where they can move following particular trajectories or according to a certain behaviour. The setup allows sound to become intimate, as close as almost touching the body, or to move like a flock of birds on a distant horizon. Inside this virtual environment, sounds are embedded with acoustic reflections to model the flexibility of sonic experience from inside a small room to a vast space. The flexibility affords the virtual environment to take on surreal forms, creating otherworldly textures and gestures that evoke imagination beyond the recognizable.

4DSOUND is an instrument, a set of tools that enables composing and performing intuitively with spatial sound in great sculptural detail. In the context of the :LASG, the challenge has been multiple. Not only do we need to create a virtual sound space - virtual sound sources that live in a 3D space which manifest through a range of speakers - that can be explored, but to integrate this sound world inside a sculpture, giving it a voice and allowing its compartments to be meaningful actors within a designed physical environment. Three R&D topics have been central in achieving these goals:

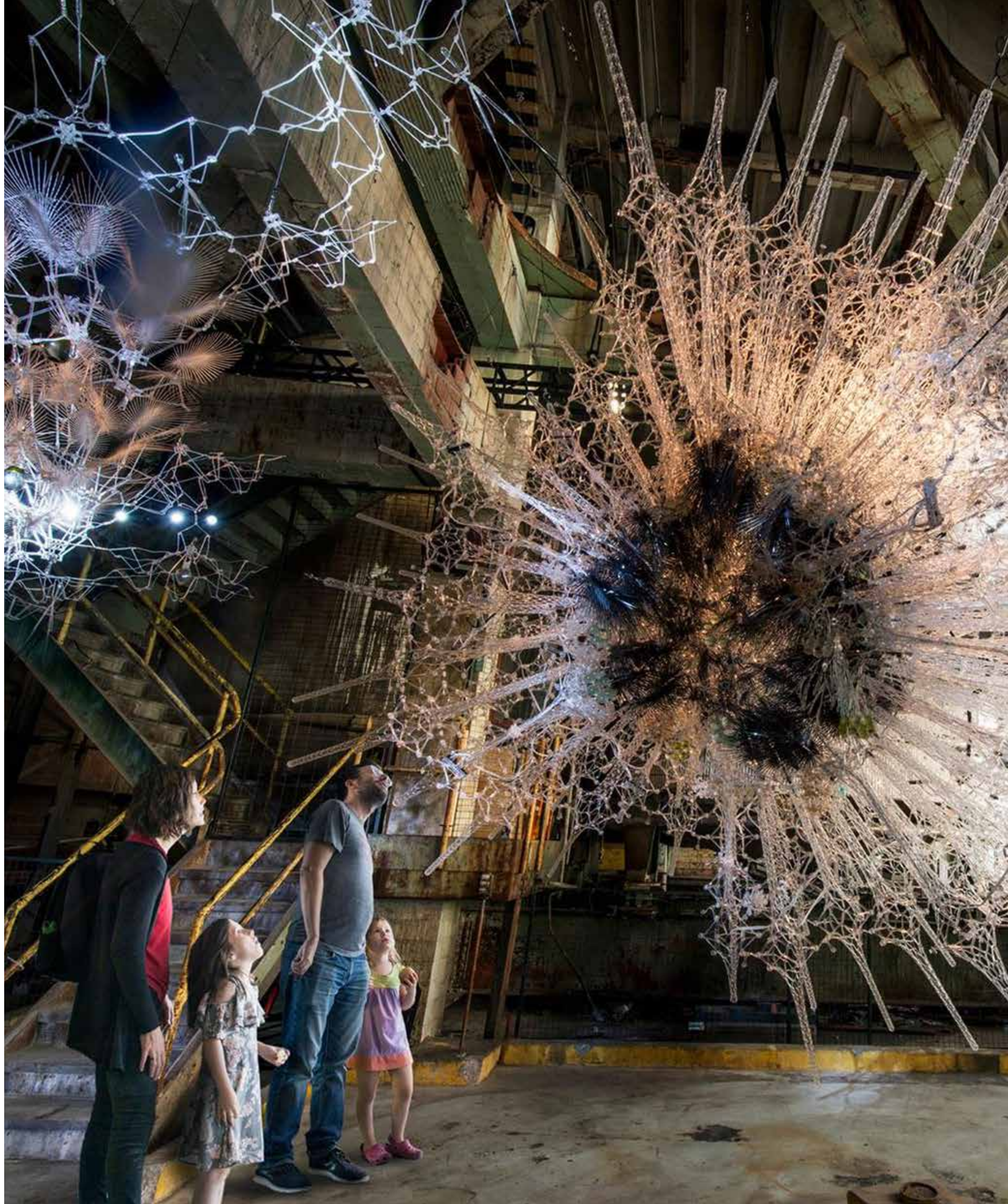


Image 2 The large sphere of Astrocyte – the inner semi-sphere contains ten speakers. DX EDIT, Toronto, 2017

1. Categorizing speaker constellations in type and function to gain control over precise sound projection.
2. Introducing irregular speaker configurations to cater to irregular sculptural configuration.
3. Making virtual sound objects, actuators, and sensor interfaces part of the same virtual space and enabling integrated interaction.

Exterior and Interior

Embedding a distributed network of speakers within the sculpture required a redefinition of the 4DSOUND panning algorithms. The new algorithms expand sound spatialization within a singular omnidirectional grid, hence a distinction between exterior and interior speakers was necessary.

A field of exterior speakers can be considered similar to 4DSOUND's regular layout. It covers the omnidirectional field of the actual space and virtually extends this field beyond the actual space to infinity by adding spatial sound synthesis. 4DSOUND's equally distributed grid system provides a social listening area that is not concentrated into just one sweet spot.[1] The listeners are empowered to move around to self-compose experiential perspective and orientation.

1 Oomen, Paul, Paul Holleman, Leo de Klerk: "A New Approach to Spatial Sound Reproduction and Synthesis." In Living Architecture Systems Group White Papers 2016, ed. Philip Beesley (Toronto: Riverside Architectural Press, 2016).

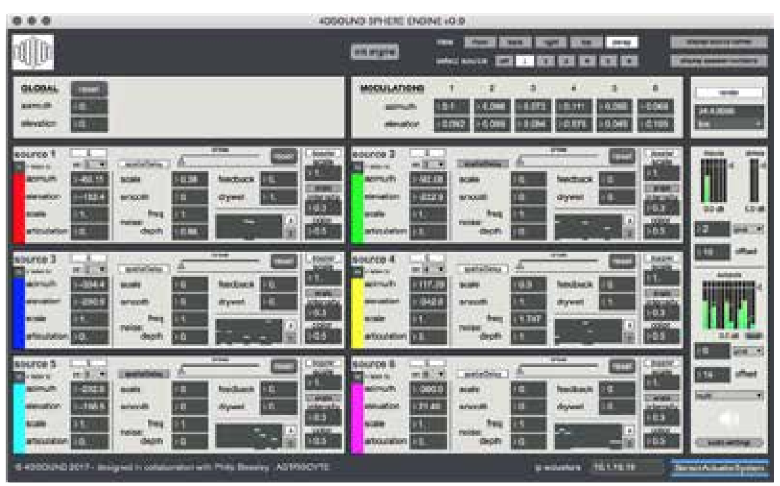


Image 3 User interface of the Sphere Engine developed for *Astrocyte*

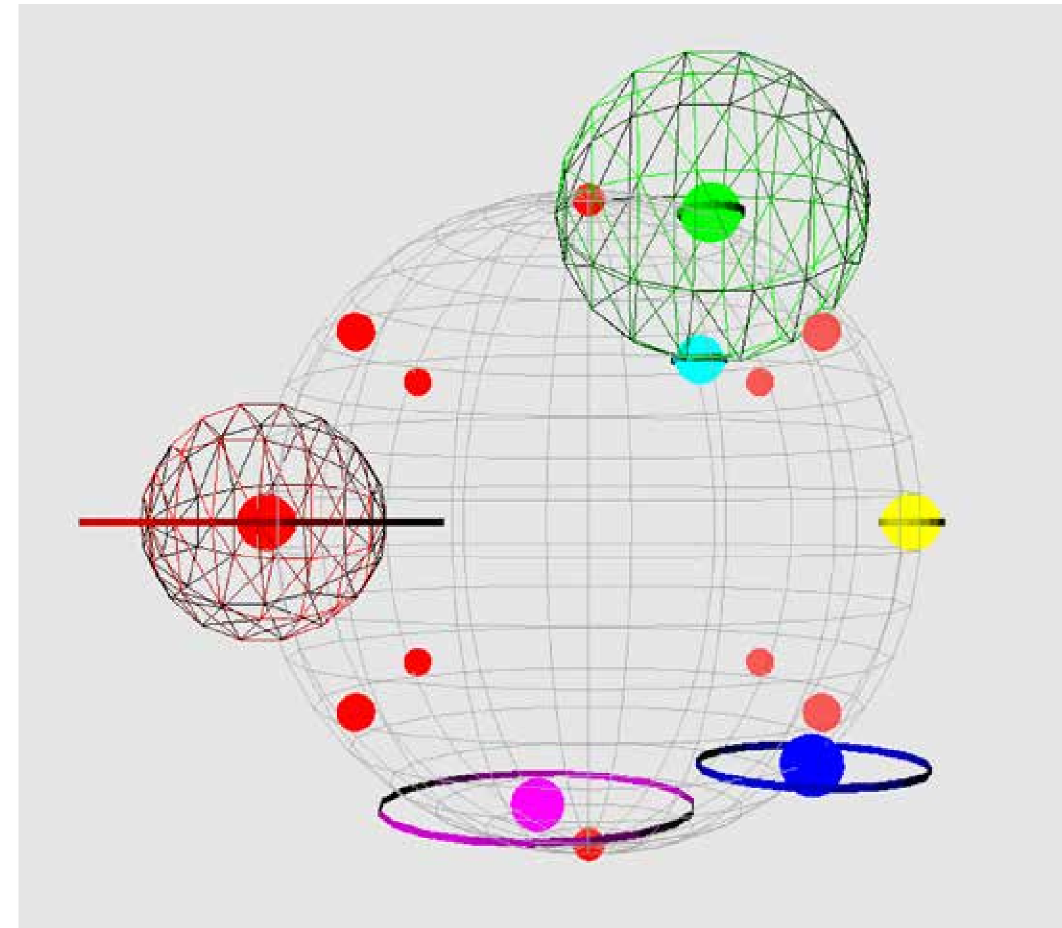


Image 4 3D visualization of the Sphere Engine spatialization developed for *Astrocyte*

The interior speakers are the voice of the sculpture. The configuration of the sculpture's components and their spatial relations impact how the 4DSOUND interior speakers are set up and run as internal constellations. In projects that have been realized to date, we have successfully generated sounds that behave like a dense crackling neural network, or the omnipresence of smaller objects within the sculpture - like electronic birds in a tree.

For the most part, sounds in either one or both of the fields share the same extensive set of controllable parameters to form movement, physics and perception of sounds in space. In terms of control, this added sonic versatility to

Image 5 *Amatria*
LASG and Philip Beesley, Indiana University, Bloomington, USA. 2018.

cover both the internal and external fields of different sculptures' components requires only a minor expansion in parameters. A simple matrix interface allows one to route sound sources to the desired speaker constellations. Sounds that live within the one sculptural composition can easily be transferred to or spread over other components. Indirect connections are also possible, like external reflections as responses to sounds that originate from inside can potentially create echoes that seem to come from spaces that are beyond the one that the listeners are in.

For the installation *Astrocyte* (2017) we introduced the Sphere Engine, a prototype application that complemented the regular 4DSOUND Engine. The Sphere Engine was designed to drive ten speakers inside the large sphere that created the central constellation of the installation. The speakers were spread almost equally across the central semi-sphere, which was slightly tilted and raised above the heads of the listeners. The result was a defined focal listening point within the expanded space of the sculpture. This centralization, together with the gentle directional quality of the speakers and granular sound design, evoked a sensation of proximity and a feeling of intimacy with this large, radiating object.

We found that the results of technical sound tests - such as exposure to continuous noise and a variety of waveform pulses to different spatial projection onto the sphere - offered a broad palette of characters and

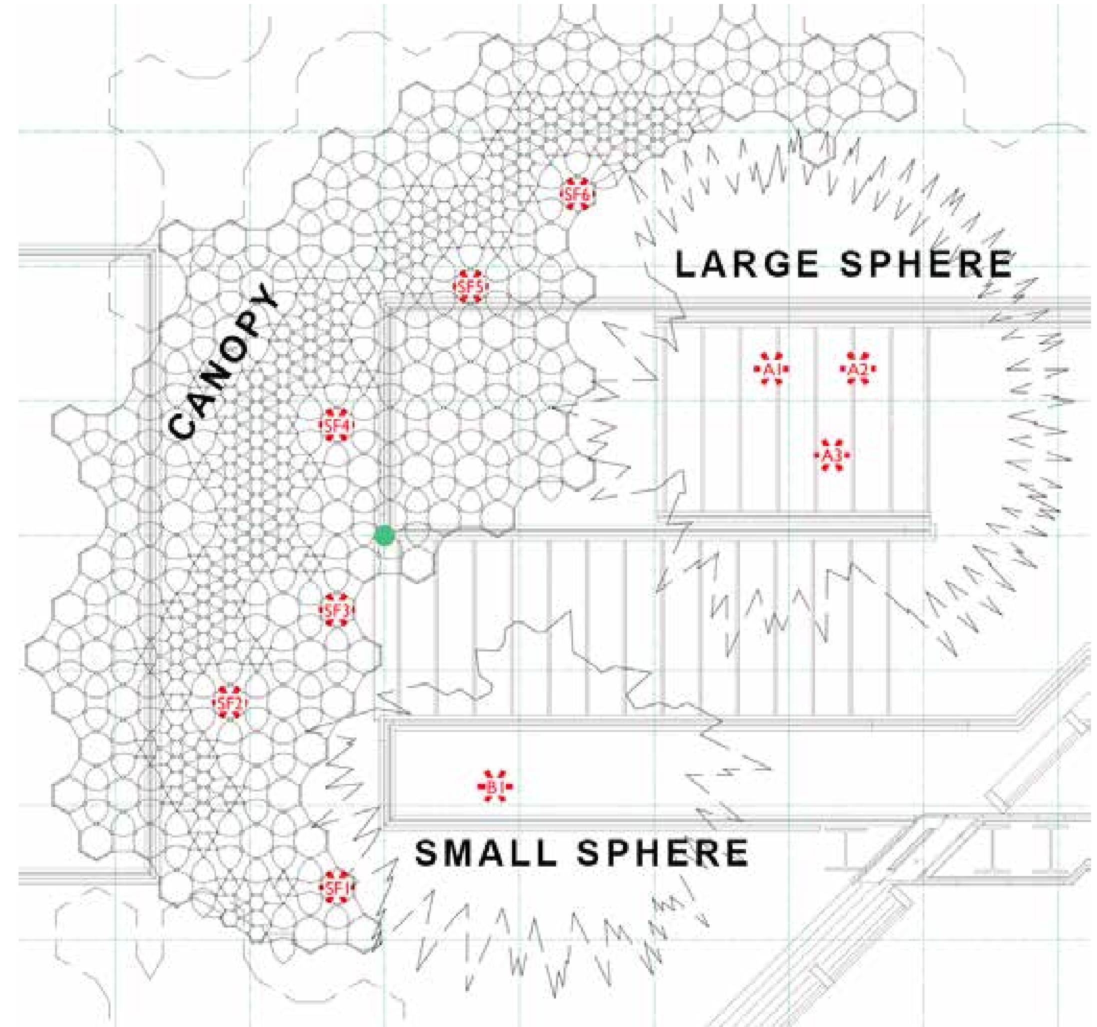


Image 6 Irregular speaker configuration of *Amatria*

abstract associations. For example, synchronised pulses can accentuate the shape of the sphere as a whole, where diffracted sounds dissect its parts and reveal the granularity of inner processes within the sphere. As a result of high speaker density the perception of small, moving sound objects became extremely clear. Altogether, the sphere created a 'sonic painting' with a broad palette onto a tightly focused frame.

Irregular Speaker Configurations

4d.pan, the proprietary panning algorithm developed by 4DSOUND, was initially limited to symmetrical rectangular speaker grids. To provide asymmetrical sculptures with varying densities of interior speakers, we expanded the 4d.pan algorithm to support irregular setups of varying sizes and shapes. The principle remains to position exterior field speakers as equally spaced as possible to assure balanced sound projection and refined continuous spatial definition in all directions. For the interior, all configurations are allowed in order to support any artistic or acoustic tasks and to create more irregular grids. A combination of an equally spaced exterior field with an irregularly spaced interior determined by the sculpture can deliver a convincing and powerful soundscape with explicit control over the sonic presence in the space.

Any given constellation of speakers can be divided into subsets to allow extremely detailed control in spatial sound design. The setup differentiates speaker groups (areas) for sound sources to exist within. The internal structure of the sculpture divides interior speakers in ways that mimic its components. This results in an almost organic design where the sonic and material interpretation of the sculpture dictates the speaker configuration, instead of the other way around. We are excited that backend complexities can realize an elegant frontend for an intuitive system handling and sound design.

The permanent environment *Amatria* (2018) at Indiana University is a follow up on the *Astrocyte* installation (2017). The environment consists of ten speakers distributed throughout the larger part of the sculpture. We identified the Large Sphere (speakers A1-A3), the Small Sphere (speaker B1), and the Canopy (speakers SF1-SF6). By defining three sub constellations we were able to develop the spatial sound design around two actor objects (the Spheres), and a more diffracted area (the Canopy).

As the protagonist, the Large Sphere is equipped with three speakers, while the Small Sphere has only one. The differentiation made possible by using a triad configuration creates a spatial depth and dimensional perception of the sounds that are projected onto the field. The single speaker in the Small Sphere is timid compared to its neighbours, but the sharp contrast in sonic magnitude and its distinctive character makes it a focal point within the shared space.

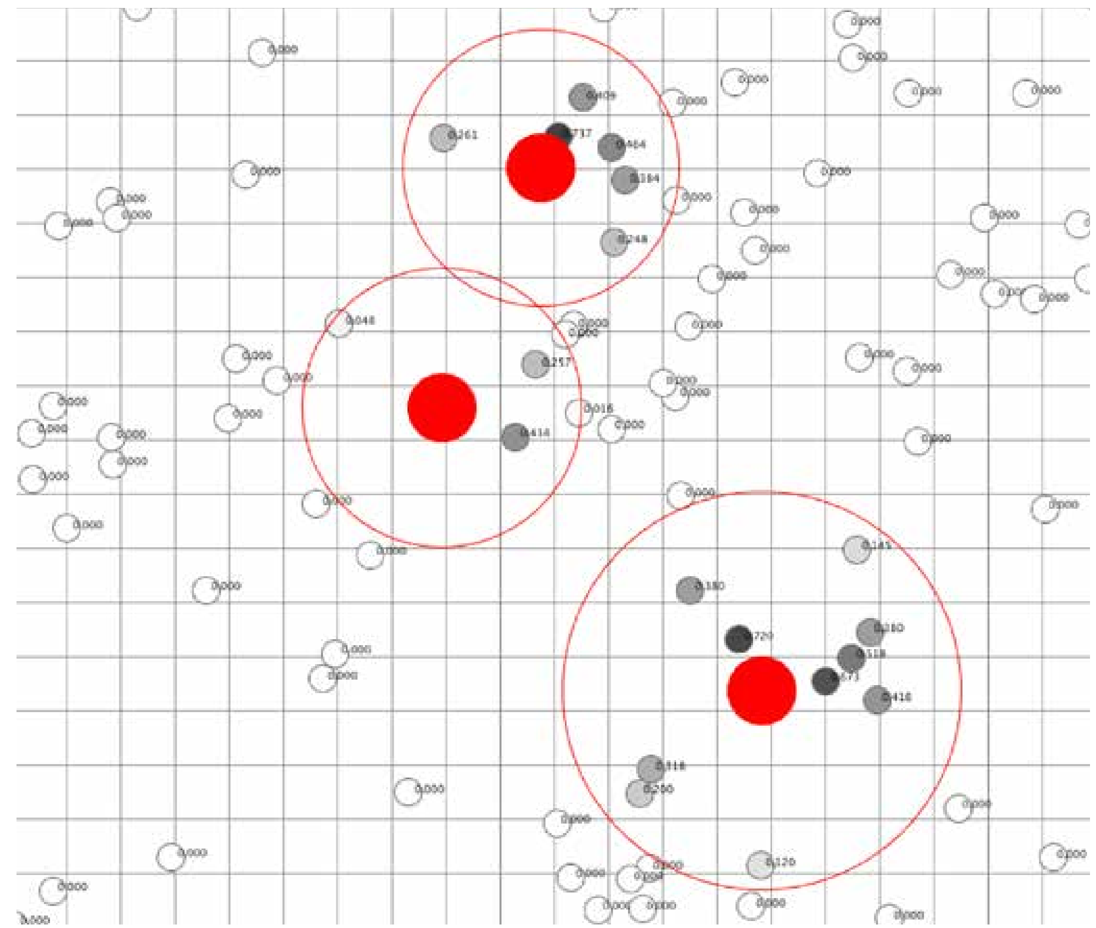


Image 7 Excitor Objects and their distance-based relationships to actuators present in a sculptural environment.

While designing the spatial sound for the installation, we experimented with unique assignment for each character in the sculptures. For example, 'breathing' spheres would have subtle reflections on the canopy with patterns resembling textures of dense fog, light raindrops or breaking glass. The flexibility of the system in filling the entire space or carefully occupying specific areas proved to be essential in constructing the integration of sculpture and sound.

Shared Worlds: Merging the Virtual and the Actual

Another important R&D goal has been the integration of sound spatialization with other kinds of actuators in the sculpture such as granular light, kinetic mechanisms and sensor interfaces. To create meaningful integrated interaction, we developed the prototype Distance Based Interaction Engine (DBIE) in collaboration with LASH collaborators Philip Beesley, Rob Gorbet and Adam Francey. The DBIE is a simplified interpretation of the spatialization algorithms that already exist within 4DSOUND. In the 4DSOUND Engine, spatial properties of virtual sound objects are mapped to speaker amplitudes and audio signal processing (spatial synthesis). Meanwhile, the DBIE maps basic spatial properties of an 'Excitor Object' like position, size, and force to lights, kinetic objects, or any type of actuator.

The basic principle of Distance Based Interaction is the intensity of an actuator (e.g. the brightness of a light, or the speed of a motor), which is determined by its distance to a virtual object. Every actuator holds position properties that match their actual locations relatively within the sculpture. The virtual Excitor Objects also live inside this 3D map where their presence can excite the actuators by moving closer and further away. An excitor can be an infinitely small point, or of any spherical size. An increase in scale means it covers more virtual space and effectively comes closer to more actuators resulting in more actuators being excited. The final parameter is Force, a multiplier of Distance Intensity acting as the upper limit of excitation. With scale and force combined, one can create a large but weak excitor, or a small and strong one.

Sensor systems are integrated in the same Cartesian space as the sound objects. Their positions in an infinite continuum of space are defined by XYZ-positions.[2] Infrared modules register the presence of visitors and their positions inside the sculpture, as well as their hand gestures. Virtual sound objects and excitors can react consistently and immediately in attractive or repulsive reflexes triggered by infrared sensors. There is a subtle balance between direct basic responsiveness (e.g. triggering short samples on the location of the sensor) and more complex movements that evolve over time (e.g. ripple effects in the surrounding actuators, or the progression of the sound composition on a higher level). The correlation of sound events in space and actuation triggered by movement and behaviour enhances the immersive experience between the visitors and the sculpture.

2 Ibid.

Image 8 Human input as excitation for kinetic sound, light and movement within *Noosphere.* LASG and Philip Beesley, Toronto, 2018

In this setup, virtual sound objects, virtual excitors, speakers, actuators, and sensors all share the same environment, and can interact accordingly. This produces a versatile and intuitive interface to design coherent movements and behaviour. Background behaviour can be small excitors, moving fast and slowly, emerging and vanishing like snowflakes or a soft breeze through the woods. Bigger excitors could be phantom creatures, or abstract magnetic forces beating through space. The technical essence is that single indexed actuators are no longer considered in artistic design, instead, the interface is elevated to a higher level of control where conceptual translation becomes more immediate and inspirational.

The first implementation of the DBIE was in *Noosphere* and *Aegis* (2018) at the Royal Ontario Museum in Toronto, Canada. Background behaviour was generated by small, semi-random excitations throughout the sculpture. In the larger sphere *Noosphere*, an excitor was active with transformational size, force, and trajectory. They marked the first modest but profound step in unifying algorithms for behaviour in sound, light, and movement, and in interaction with human input through sensor interfaces.

Future Research

In future research we will refine panning algorithms, explore the characteristics of different kinds and combinations of speakers, and continue stretching the flexibility of sound spatialization using varied speaker configurations. The divide between exterior and interior sound may be further contrasted to enhance depth of field. At the same time, the differentiation will also invite explorations in the coherence between the perception of diffusion field and focused objects, emerging from the same technological principles in hardware and software.

A shared origin with all technological disciplines in the same spatial interaction paradigm will be further developed in an even more integrated software reality. A right balance between utilising processing power of a personal computer and performing algorithms on the distributed network of microprocessors that are not necessarily aware of structural properties, can enable each sculptural character to act more like individual agents within the network.

Other objectives are designing an offline prototyping environment to develop interactive algorithms and behaviours that can develop independently from a hardware testbed. Since all virtual properties will share the same physical environment, they should be included in a shared virtual environment. An extensive 3D visualization of all activity will complement the possibilities to exploit spaces as an instrument and provide insightful feedback. The tool will allow detailed preparatory work, stimulate creative design of the space as a whole, and increase efficiency during the final phases of installing the sculpture on site.

4DSOUND was founded in 2007 by composer Paul Oomen and technologists Poul Holleman, Luc van Weelden and Salvador Breed to further the development of new processing software and control interfaces for spatial sound. In the same year, audio engineer Leo de Klerk published his patented application for omnidirectional loudspeakers that enable the production of phantom sound images independent of the place of the listener. Since 2010, Oomen and de Klerk have worked together on the development of the system.

4DSOUND is a fully omnidirectional sound environment where the listener can experience sound in an unlimited spatial continuum. Sound can move infinitely far away or come intimately close: it moves around, as well as above, beneath, in between or right through you. Led by your ears, you're encouraged to explore the space. You can move between blocks of sound, touch lines of sound and walk through walls of sound. 4DSOUND enables vivid sonic environments that blur the boundaries between the real and the imagined: the world of sound we know, and a world beyond.

Soft Kinetics

Integrating Soft Robotics into Architectural Assemblies

Vera Parlac
University of Calgary, Canada

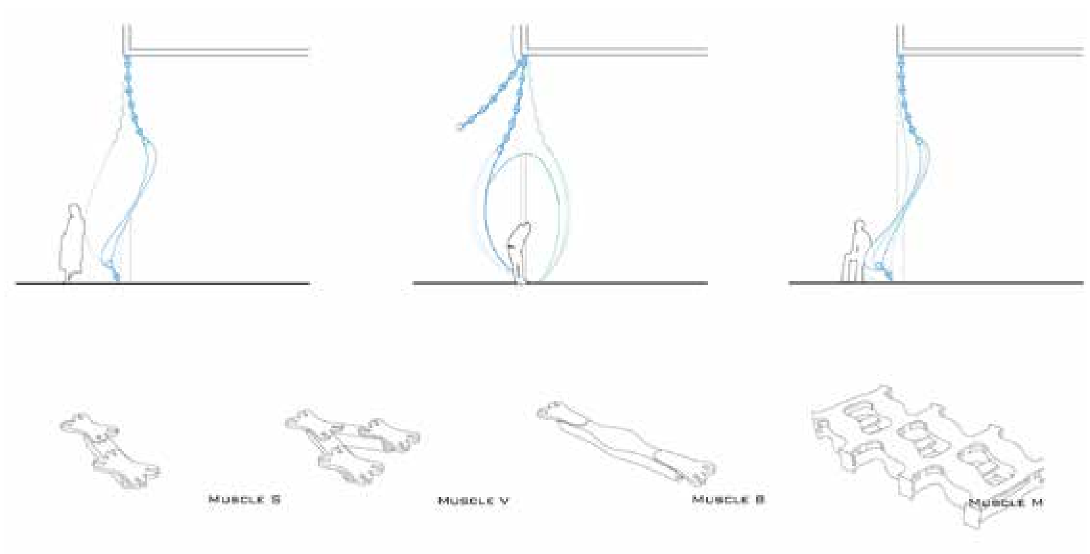


Image 1 "Programmable" architectural modular system simultaneously addressing stability, dynamics and adaptability of a material system

The project described in this paper explores the integration of custom-made soft robotic muscles into a component-based surface. This project is part of a broader research that focuses on new material behaviors and their capacity to produce adaptive and dynamic material systems. The paper discusses the use of a pneumatic system as a form of material-based actuation. It presents the ongoing research into the capacity of integrated *pneu* structures to generate kinetic movement within a component-based assembly to produce a responsive and "programmable" architectural skin. This is a prototype-based exploration that demonstrates different kinds of movement achieved by different silicone muscle types and proposes a light modular construct, its components, and patterns of aggregation that work in unison with the silicone muscles to produce a dynamic architectural skin. The project is informed by a history of pneumatic structures, the technology of soft robotics, and a kit-of-parts design strategy.

Introduction

Pneu is a primary form of living nature, an effective structural system as well as an instrument of form giving.[1] Every cell is a *pneu* structure.[2] An elastic membrane that delineates *pneu* structures responds dynamically to the change in pressure by changing its mass. The change in pressure or mass can cause considerable physical transformation of the structure. This transformation enables a *pneu* structure to produce a kinetic effect in its own structure and also in structures that are attached to it. In engineering, rigid materials are employed to fabricate precise and predictable dynamic systems, but natural systems often exceed this performance with soft and flexible bodies.[3]

In soft robotics, the *pneu*-like capacity is used to design robots that move or handle fragile objects by manipulating the inflation and deflation patterns. Their bodies are capable of large-scale deformation and high level of compliance.[4] Some of these robots are able to move around obstacles or squeeze under them.

The research by Harvard's Biodesign Lab and soft robot fabrication techniques, described by Andrew D. Marchese et al.,[5] provided a starting point for the initial studies of *pneu* elements in this project. Other relevant studies that informed the project were related to the movement of soft actuators and their motion patterns,[6] and the complexity of this movement.[7] The capacity of soft robotic components to affect larger structures in which they are incorporated is of key importance for this project.

The project attempts to address two challenges present in designing dynamic and adaptive surfaces: actuation system and surface tectonics. Therefore, on one hand, it explores a capacity of *pneu* structures to induce kinetic movement, and on the other, it articulates a component-based tectonic assembly that can integrate such movement. The main premise of the project is that the integration of elastic inflatable pneumatic components into a component-based structure will influence the structure dynamically and support a variety of movements. This project is informed by a history of pneumatic structures, the technology of soft robotics, and a kit-of-parts design strategy (*Image 2*).

1 Otto, Frei. 1995. "Pneus in Living Nature." in IL35 Pneu and Bone, Stuttgart: Institute for Lightweight Structures (IL). 56 – 63.

2 Helmcke, Johann-Gerhard. 1977. "The Biological Pneu." in IL9 Pneus in Nature and Engineering, Stuttgart: Institute for Lightweight Structures (IL). 138 – 150.

3 Rus, Daniela, and Michael T Tolley. 2015. "Design, Fabrication and Control of Soft Robots." Nature 521 no.7553: 467 – 475.

4 Marchese, Andrew D., Robert K. Katzschmann and Daniela Rus. 2015. "A Recipe for Soft Fluidic Elastomer Robots." Soft Robotics 2 no.1: 7 – 25.

5 Ibid.

6 Bishop-Moser, Joshua, Girish Krishnan, Charles Kim and Sridhar Kota. Oct. 2012. "Design of soft robotic actuators using fluid-filled fiber-reinforced elastomeric enclosures in parallel combinations," In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE. 4264 – 4269.

7 Connolly, Fionnuala, Conor J. Walsh and Katia Bertoldi. Oct. 2016. "Using Analytical Modeling to Design Customized Fiber-Reinforced Soft Actuators." In Society of Engineering Science 53rd Annual Technical Meeting (SES 2016).

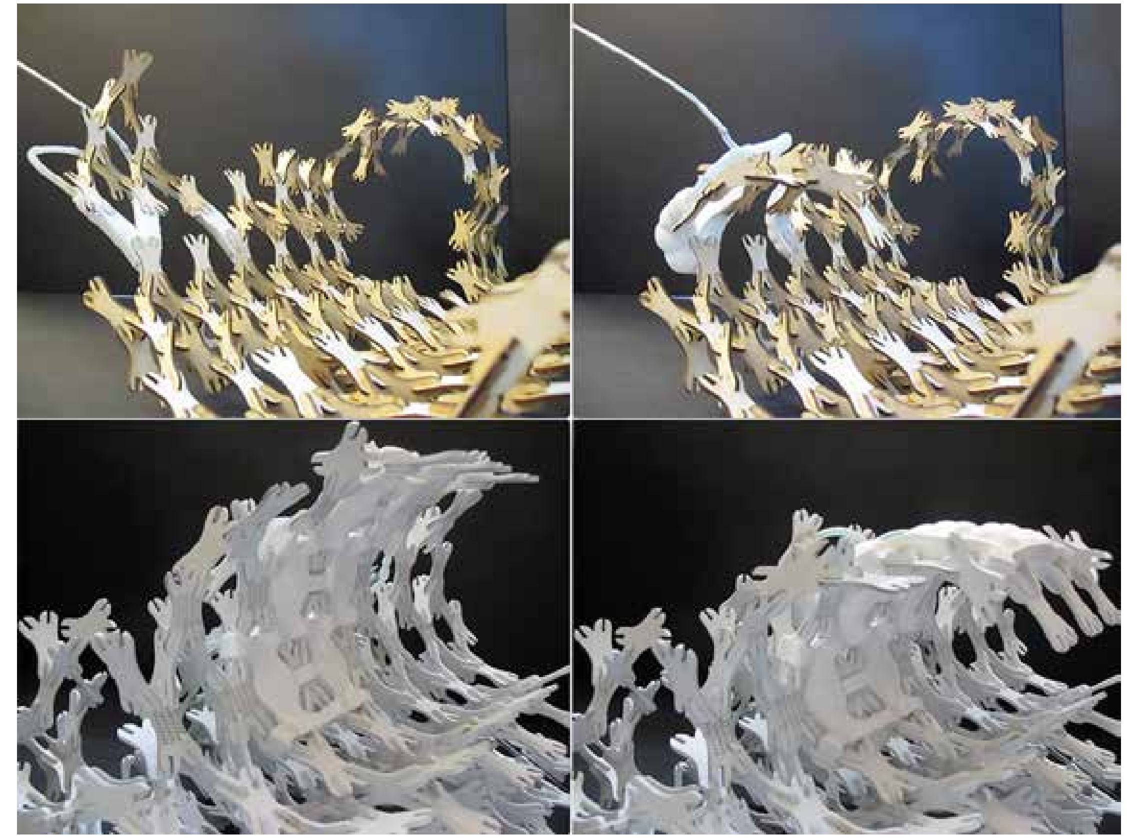


Image 2. Active pneumatic muscles move part of the structure

Background

Inflatable or pneumatic structures have been used in architecture primarily for their lightness in relation to the structural span. Between 1940s and 1970s these structures underwent a significant evolution. One of the first fully inflatable structures was a radome developed by Walter Bird in the late 1940s. The exploration of air-supported structures quickly grew beyond their use as shelters for equipment or supplies. In 1960s and 1970s they were used in a variety of experimental projects in architecture. For example, the Fuji Group Pavilion, designed by Yutaka Murata for the 1970 World Expo in Osaka, was built using a series of attached air-inflated vinyl tubes that were bound together to form a larger structure, with the necessary air pressure maintained by the constant supply of air flowing through the tubes. The shift from a single inflated volume (radome) to the aggregation of inflated tubes presented an innovative moment in building large span pressurized structures. But besides their inherent self-supporting structural capacity, inflatable structures offered a potential to design soft and transformable spaces with new formal (and dynamic) qualities. Experiments by Coop Himmelb(l)au and Haus-Rucker-Co created structures at the scale of a human body utilizing their soft and temporal qualities. A new kind of architectural space emerged that operated as an extension of the immediate body space. Coop Himmelb(l)au's Villa Rosa, for example, even allowed for a change in volume by inflation. These mobile and mostly temporary structures were acknowledging the transformational potential of inflatable form. They brought into architecture the notions of a dynamic, changeable and soft space with boundaries no longer defined exclusively by rigid material enclosures. Today researchers are experimenting with even smaller scale inflatables that could be integrated into architectural surfaces and components, i.e. into tectonics of a material system itself. Current experiments with elastic inflatable elements influenced by soft robotics are suggesting new trajectories in exploring dynamic spatial boundaries.

Soft robotics is concerned with the development of actuators made from "soft" materials. Materials such as shape memory alloy, electroactive polymers or silicone elastomers are used for these purposes. From the design point of view, soft actuators produce "soft" deformations and life-like movements offering a large degree of freedom when conceptualizing adaptive building systems.[8]

8 Rossi, Dino, Zoltán Nagy and Arno Schlueter. 2014. "Soft Robotics for Architects: Integrating Soft Robotics Education in an Architectural Context." Soft Robotics 1 (2): 147-153.

Several experimental research projects point to a new potential that these structures might have in designing responsive and adaptive architectural surfaces and structures. The *PneumaKnit* by Sean Ahlquist, McGee and Sharmin explores motion and geometric articulation of inflatable components using knitted constraints. Instead of relying on the shape of the actuator to produce specific motion, knitted constraints regulate the expansion of the actuator and, therefore, its motion. The emphasis is on the material structure of the knitted constraint, which, through a density of its weaves, produces the surface transformation. This work is concerned not only with the actuator itself but also with the integrated system, where an actuator and its constricting surface work in unison to produce the desired effect. The material integration between the inflatable and knitted elements is a step forward in rethinking the assembly of a material system in which constituent parts are dynamic, and perform synergistically. On the other hand, in the *Pneuma-Technics,*[9] the focus is on the shape of the actuator itself. The differences in its size, shape and the geometry of its internal channels produce variations in its elasticity and therefore its directional deformation. This project offers a surface made of soft pneumatic components that can respond and adapt to modulate passage of light, air or view. The result is a soft panelized surface that can open and close through its inflation and deflation patterns. This is similar to Park's *Modular Pneu-Façade System*, which was imagined as "a dynamic pneumatic interface which can be used in building applications including responsive façade, ceiling, floor and interior screen, etc."[10] But, while *Pneuma-Technics* is responding to environmental stimuli, the *Modular Pneu-Façade System* is sensitive to human touch. Its surface utilizes capacitive sensors and conductive gel, which make it conductive to touch. This layer of soft inflatable elements can be integrated into building skins to make them transformable and active. The strong analogy of this system to the cardiovascular system in a body and other biological systems like muscular-hydrostats brings forward architects' fascination with "living" and sentient systems, and the desire to tap into their potential for adaptation.

9 Fougere, Daniel, Ryan Goold and Kathy Velikov. 2015. "Pneuma-Technics: Methods for Soft Adaptive Environments." In ACADIA 2015: Computational Ecologies: Design in the Anthropocene, Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture, edited by L. Combs and C. Perry, Cincinnati: ACADIA. 274 – 283.

10 Park, Daekwon and Martin Bechthold. 2013. "Designing Biologically-Inspired Smart Building Systems: Processes and Guidelines." International Journal of Architectural Computing 11 no.4: 437 – 464.

The *Soft Kinetics* project, described in this paper, utilizes elastic pneumatic muscles to explore the integration of soft and hard elements (or layers). Its aim was to produce a dynamic material system that is self-supporting, pliable and kinetic with behavior depending on the configuration of modular components and the position and concentration of pneumatic elements. As such, it could be developed as a stand-alone "programmable" building skin system. The goal of the project was to exploit transformational capacity of these active structures (inflatable muscles) as ingredients in space making.

Methods

The *Soft Kinetics* project brings together two strategies for designing adaptive architectural skins. One is concerned with the combinatorial variability of a light structure built by aggregating small self-similar components. The other one focuses on the integration and distribution of pneumatic muscles within an aggregated structure. The proposed system reflects a deep interest in the development of a component-based material system whose properties range from rigid/stable (self-supporting) to pliable/active (dynamic). To achieve these variable properties, a particular emphasis was placed on the system's morphology that emerged by integrating self-similar rigid and pliable components with pneumatic muscles. This process produced a "programmable" surface that can open, close or alter its basic form.

Light Modular Structure

The light modular structure is built using self-similar elements with a non-orthogonal alignment. It is aggregated through slot-friction connections and can be organized in a number of different configurations. The configuration of the construct is governed by the requirements for stability (self-support) and kinetics; both of these criteria are equally important to support dynamic transformations. Stability is achieved in two ways: by interlocking the components through simple slot-friction connections and by the patterns of aggregation. The kinetic behavior is enabled by a system of pneumatic muscles, their full integration with the patterns of aggregation, and the capacity of the modular structure to allow for disruptions in pattern continuity without compromising the construct's stability. The redundancy in connections and elements provides a structural resiliency.

By utilizing a kit-of-parts design strategy, the structure can be built in a variety of configurations and adapted to a variety of spaces. Due to the self-similar unit shape and the standardized connection between the units, there is a great combinatorial potential for a structure assembly. On a more local scale, however, the combinatorial potential is driven by the assembly pattern that is contingent on the shape of the unit and the angle of its connections.

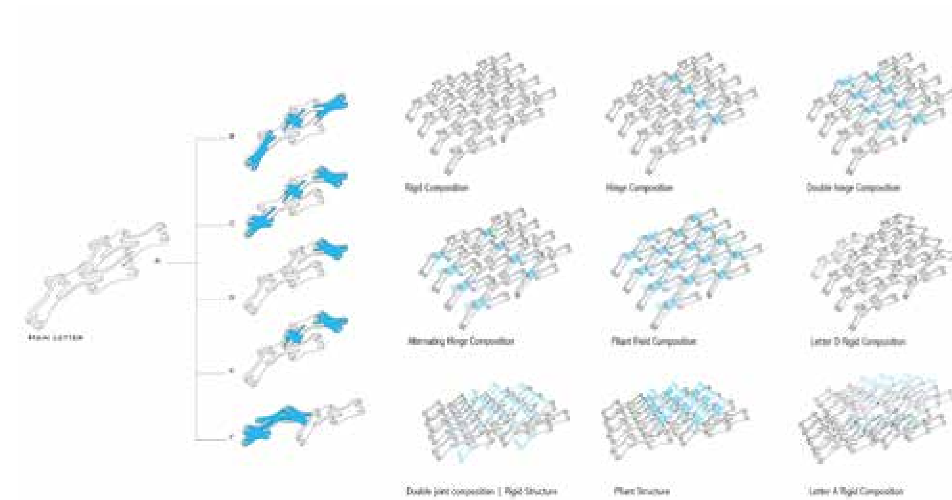
Image 3 Rigid and pliant configuration; Integration of bendable component

Following the assembly pattern, two main configuration trajectories emerged: rigid (self-supporting) and pliant (flexible) (*Image 3*).

Individual components can form any number of permutations, but discrete assemblies, used to govern the form of a larger construct, were generated to support change in functionality, directionality and form. These discrete assemblies were then combined into larger formations, and their tectonic and spatial capacities were examined. However, the system itself remains open and able to adjust to a variety of spatial/contextual conditions as well as to support part replacement. In this way, recalibration of the construct can be maintained since its parts could be reconImaged in a variety of ways (*Image 4*).

The component shape was chosen for its capacity to produce a significant number of different combinations while maintaining the pattern that generates rigid and pliant versions. These configurations were then modeled digitally and tested physically for their behaviour. The tests resulted in a design of a new bendable component that was positioned adjacent to pneumatic muscles to facilitate bending of the regions surrounding the muscles. Ultimately, the modular structure can negotiate a change in direction (straight, angled, curved), change in thickness by smoothly transitioning from single to multiple layers (from a surface to a three-dimensional construct) and change in structural capacity (from self-supporting to bendable).

Image 4 Combinatorial Potential



Pneumatic Muscles

The soft body of the *Soft Kinetics* project is imagined as a continuous and interrelated network of pneumatic muscles integrated into an assembly pattern of the modular structure. It consists of clusters of interconnected soft inflatable pneumatic muscles. They are linked by silicone tubes that allow passage of air through a number of muscles, inflating and deflating them in a sequence. When inflated or deflated, these clusters move entire regions of the modular structure, producing opening and closing apertures (*Image 6*).

The movement of pneumatic muscles depends on the flexibility of the elastic material, and the volume of internal chambers and their geometry.[11] Andrew Marchese et al[12] list three soft robot morphologies differentiated by their internal channel structure: ribbed, cylindrical and pleated.[13] The soft body (actuation system) of the *Soft Kinetics* project is developed using a ribbed morphology, but its internal channels are produced using two different techniques: the lost wax casting, and a combination of the lamination casting and the soft lithography fabrication method. As a result, two types of muscles are produced: the central channel muscles (S, B and V) and the distributed channel muscle (M) (*Image 6*). The fabrication technique is important in achieving consistent properties of the muscles as they get reproduced; it plays an important role in achieving consistent elasticity and inner channel geometry.

The behavior of designed pneumatic muscles was explored through prototyping and iterative design and their performance observed as they were activated within a modular structure. The central channel muscles produced

11 Bishop-Moser, 2012.
12 Marchese, 2015.
13 Ibid.

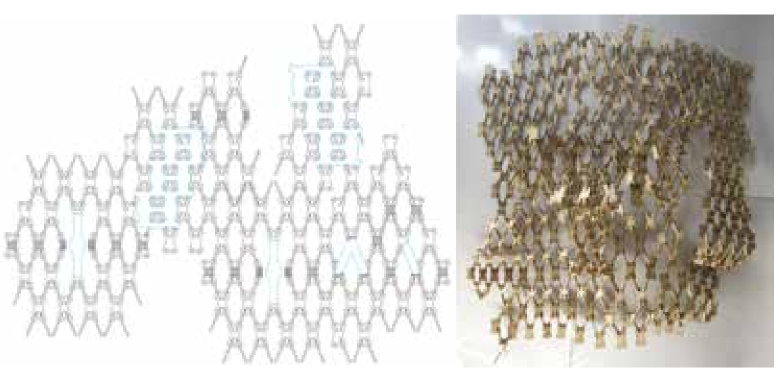


Image 6 Assembly pattern and surface deformation

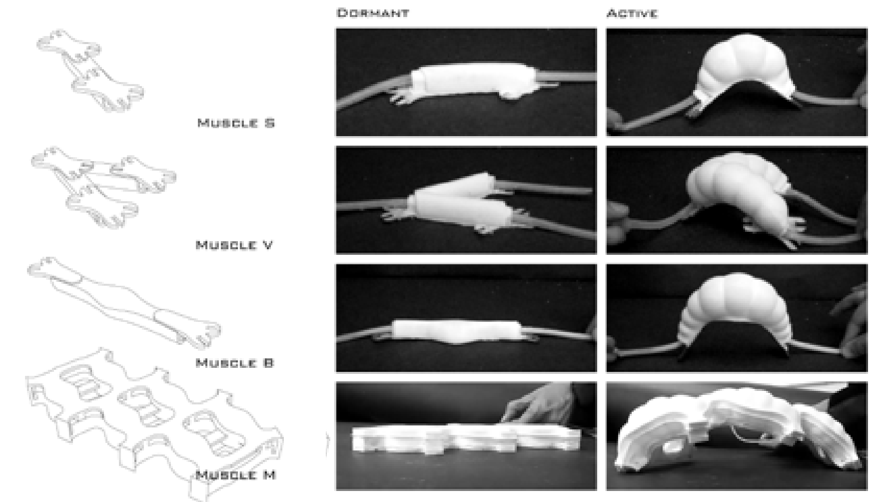


Image 7 Muscle types and their performance

using the lost wax technique were resilient and durable (by not being cast in laminated fashion). Compared to the distributed channel muscle it achieved significant bending. In general the lost wax technique allows for a great variety of cavity forms since the muscle was made as a solid body and was designed that way, not in layers. The proposed central channel muscles underwent several modifications to achieve maximum bending after inflation.

The muscles were conceived as modular elements of the structure and as such could be integrated into the structure interchangeably; two muscles (S and V) were designed to integrate into the assembly grid pattern while the other two (B and M) to nest within the voids of the grid. In terms of their behavior, the central channel type muscles (S, B, V) act as linear actuators while the distributed channel muscle (M) acts as a folding hinge (*Image 6*).

The muscle morphology and geometry were designed to balance the wall thickness and the volume of air channels. These two different types of muscles required different approaches to mold production. The central channel muscle molds were CNC milled, while the distributed channel mold was produced by layering laser-cut acrylic material. Both muscle types were made from silicon rubber. To direct their motion, one side was fabric-reinforced. Soft elastomer pneumatic muscles are capable of continuous deformation; but the challenge is to isolate a particular bending movement within its length.[14] For that reason, the pneumatic muscles used in this project were

14 Ahlquist, Sean, Wes McGee and Shahida Sharmin. 2017. "PneumaKnit: Actuated Architectures Through Wale- and Course-Wise Tubular Knit-Constrained Pneumatic Systems" In ACADIA 2017:Disciplines and Disruptions, Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture, edited by T. Nagakura. Cambridge: ACADIA. 38 – 51.

short and compliant with the grid pattern of the modular structure (*Image 6*). Their length and cluster organization, however, will be further explored in the next phase of the project, to produce asymmetrical shifts within the fabric of the modular structure.

Integration and Prototypes

The "soft" body of pneumatic muscles could easily be integrated with the "hard" body of the light modular structure. The connection was achieved by embedding the modular component within the central channel muscles or by weaving the components through the openings in the distributed channel muscle (*Image 7*).

The central channel muscles were integrated into the hard body of the structure by a slip joint, just like any other modular component of the system. Therefore, the soft pneumatic muscles could be positioned to displace the "hard" parts of the modular structure, working as an active connective tissue while the overall assembly pattern was maintained. This strategy allows muscles to be asymmetrically distributed throughout the structure, concentrated in some areas or placed sporadically in others. This is seen as a very promising direction that will be further explored in the next phase of the project. For example, larger segments of the modular structure could be dynamically altered to open and close apertures of varying sizes and shapes (*Image 8*).

Several small prototypes were constructed to test various ways and combinations of muscle integration. It is in the prototypes that the clustering of muscles was explored. The clusters, consisting of three to five pneumatic muscles, were inflated in sequence. Solenoid valves controlled the inflation and deflation pattern (supply and exhaust) and their work was regulated through an Arduino microcontroller. The rate and duration of valve opening and closing was set to allow all linked muscles to inflate in a sequence; the pressure was controlled through a sensor to prevent over-inflation and damage to the muscles. Muscles linked in a cluster worked as a group, affecting dynamically a designated region of the structure. The work of the "soft" body could be controlled through proximity sensors to reveal a clear view out or in, or could be regulated by light sensors to serve as a functioning shading device (*Image 9*).

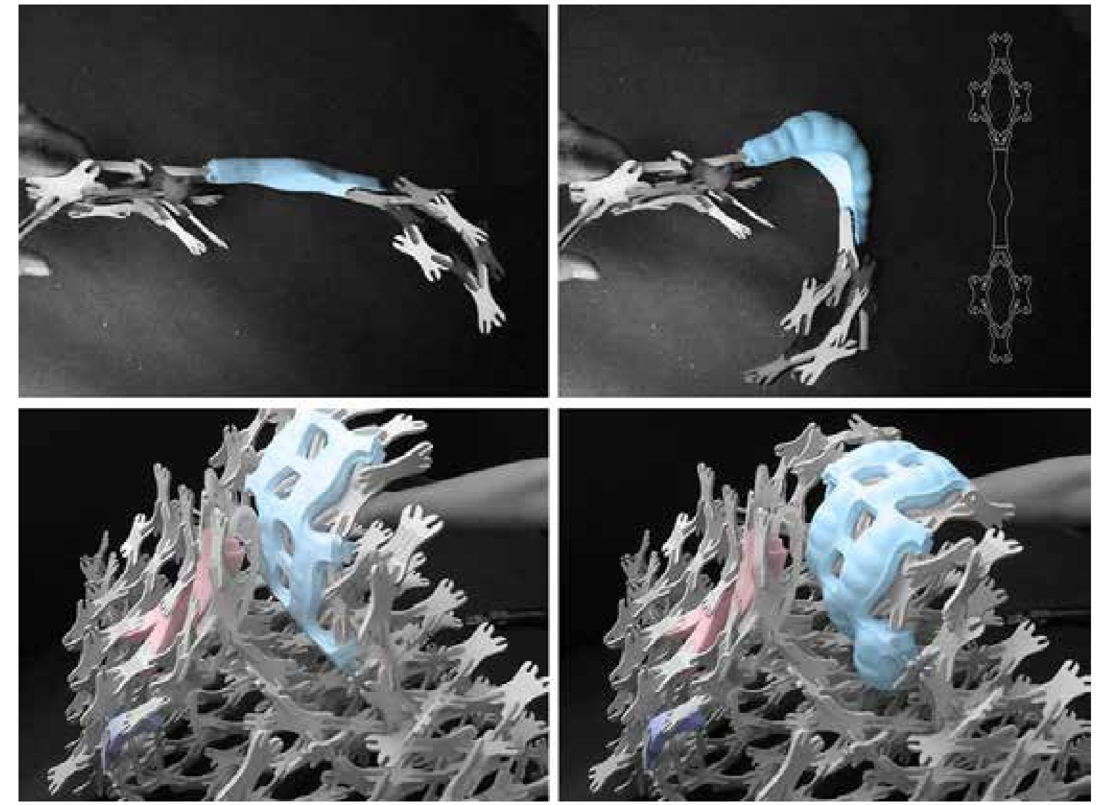


Image 7 Testing the connection and movement of the muscle; dormant and active muscles

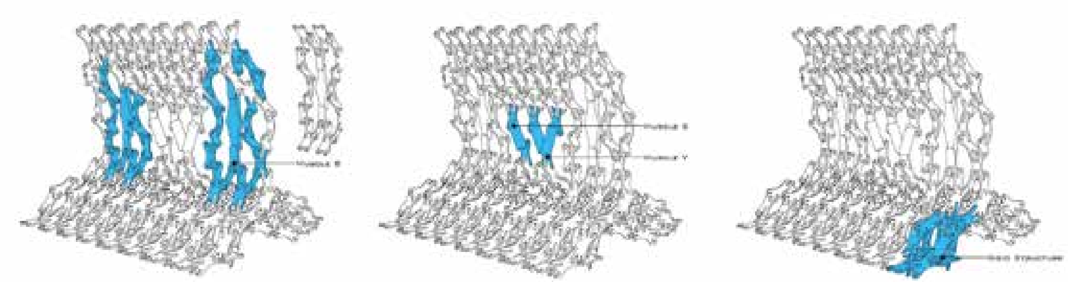
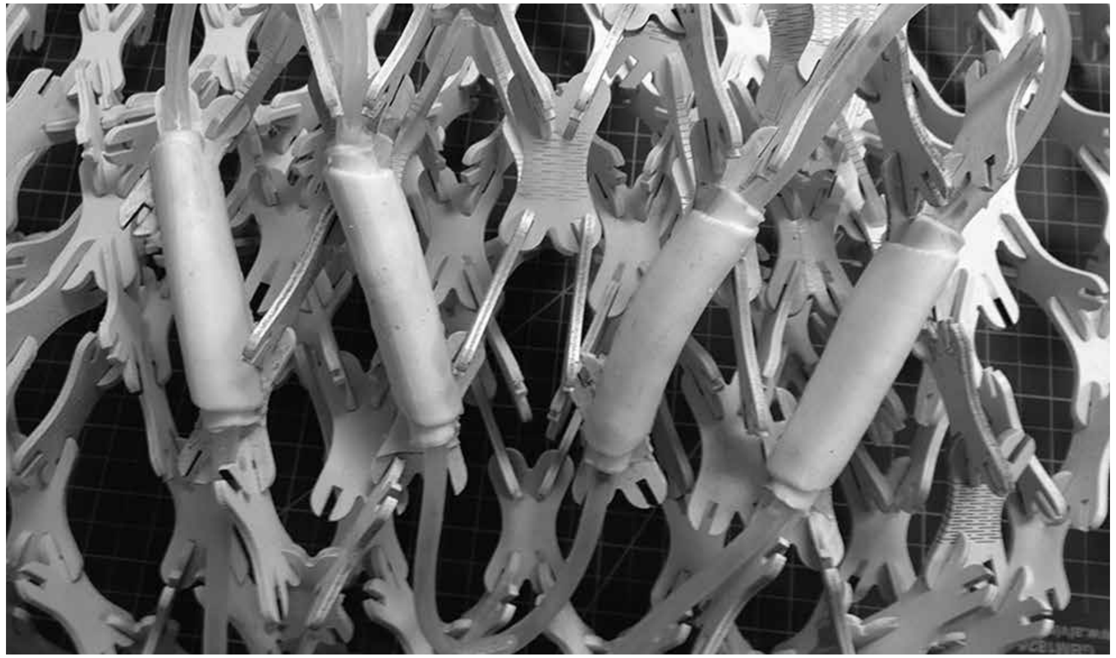


Image 8 Illustration of muscle integration



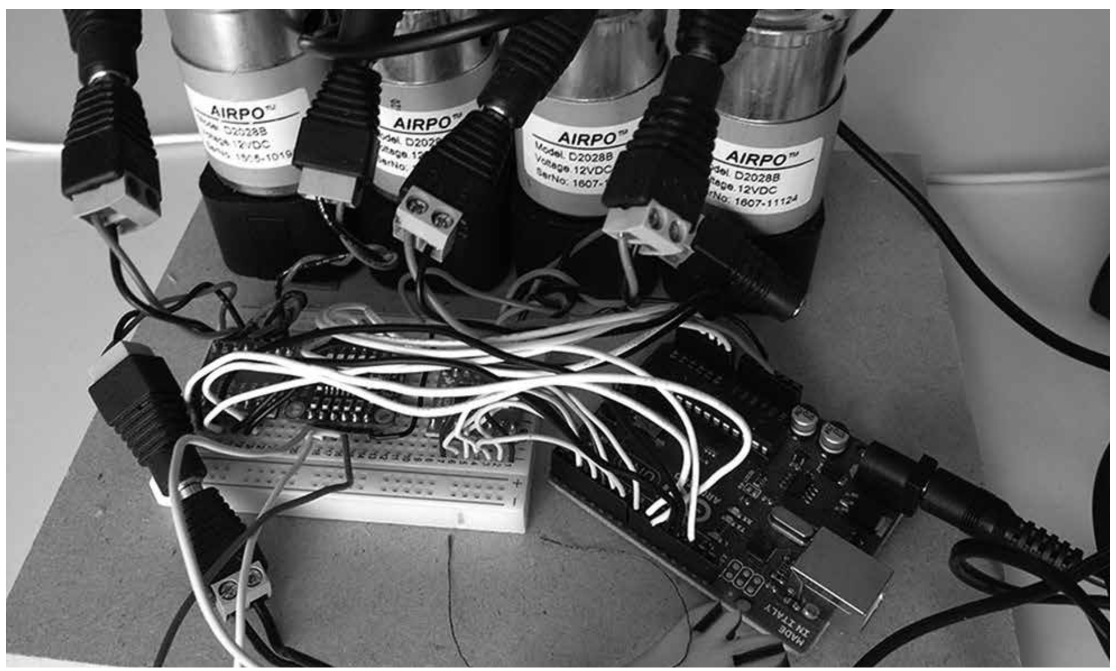


Image 9 Air pumps and pneumatic clusters

Results and Discussion

The research shows a promising way of integrating an active pneumatic layer within a light modular structure. An important aspect of this project is the smooth transitioning between fixed and dynamic regions of an aggregated structure. Additional components that would facilitate that transition or compensate for motion were not necessary. This is achieved by using self-similar components and by designing some of those as bendable. Other essential features are the slot-friction connections, consistent aggregation patterns and modular pneumatic components that integrate seamlessly into the designed patterns. The transitions between dynamic and static regions are achieved through carefully designed (and tested) component distribution patterns and varying densities of pneumatic muscle components within the aggregated construct. Some parts of the resulting structure are self-supporting, providing structural stability, while other parts permit different levels of movement without compromising the structural integrity. This variation in performance is achieved by a variable density of the assembly pattern and its extensive combinatorial capacity.

The *Soft Kinetics* project utilizes small-scale pneumatic components and weaves together soft, hard and pliable elements to create a material system that can behave dynamically in a variety of ways and transition seamlessly between them. The design of pneumatic muscles builds on projects such as the *Adaptive Pneumatic Frameworks* and the *Modular Pneu-Façade System*, but strives to seamlessly integrate soft and hard layers into a composite system using the same aggregation patterns. The key feature of *Soft Kinetics* is an actuating system that is embedded through the geometry of its components into the overall structural pattern of the construct, while simultaneously making the regions of that construct dynamic. This is achieved through the modularity and the use of slot friction connection for all components in the assembly, including the pneumatic muscles. In nature, functionality and materiality of the material systems are blended and integrated. This project attempts to integrate those capacities within an architectural assembly, by integrating functionality and materiality of soft/dynamic and hard/structural layers to produce dynamic architectural assemblies.

Conclusion and Future Work

The main motivation for the development of this system of soft actuation was to produce a uniform material system that can be built in a variety of configurations and reduce a presence of complex mechanical systems in dynamic architectural assemblies (such as dynamic building facades). The primary advantage of this mode of actuation is in its lightness, as well as the possible degree of movement control that it can offer.

The weight of the structure is an important factor; therefore more research is required to define the "blended" materiality of the modular structure as well as the durability and weight of the embedded pneumatic components. Current composite structure is made of plywood, but the use of aluminum and plastic will be explored in future iterations.

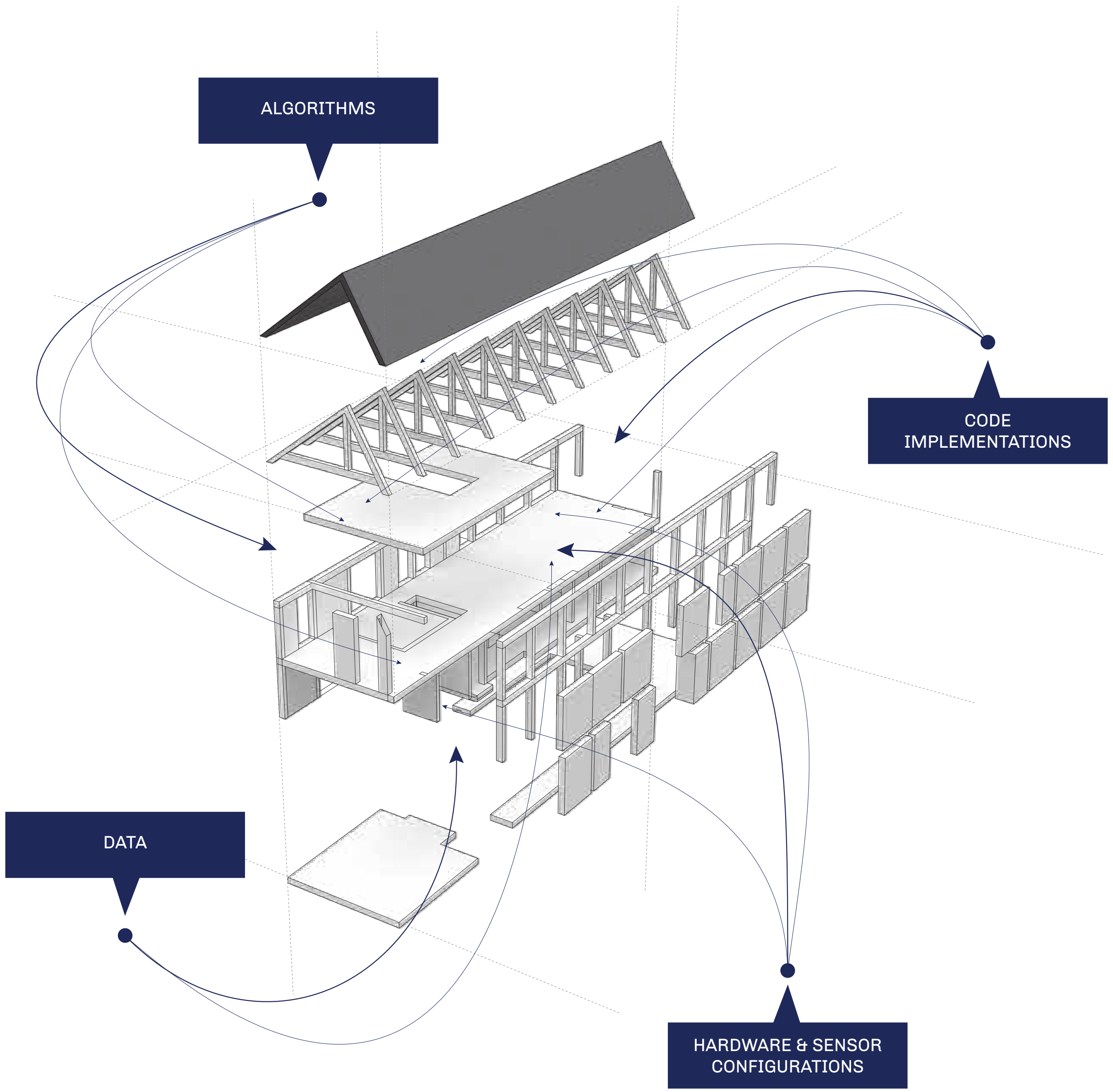
The integration of the actuators within the aggregation pattern of the structure enables movement of its regions. The current study examines behavior of small clusters of actuators, but their distribution and density (within a larger structure) need further study to fully understand the potential of this system to move larger regions of a structure. New computational tools for simulation of complex non-elastic behaviour will be employed to quickly test alternative designs. Future research will also focus on the design of alternative aggregation patterns to further experiment with range and amplitude of motions.

In his seminal article on Resilience and Stability of Ecological Systems, C. S. Holling points out different ways we see the behavior of a system. Engineered systems or devices that perform specific tasks under predicable external conditions have their performance immediately adjusted if the variation in performance is observed. They are concerned with constancy of performance and lean towards stability. Natural systems that are constantly confronted with unpredictable external changes are less concerned with constancy and more with persistence of the relationships.[15] An equilibrium-centered view of a system is static and does not offer the flexibility necessary for systems with transient behavior. The project presented here is an exploration into how to incorporate variability in performance (from stable/structural to dynamic), and how those variable conditions integrate and interface with each other.

15 Holling, C S., 1973. "Resilience And Stability Of Ecological Systems." in Annual Review of Ecology and Systematics, Annual Reviews, 4: 1 – 23.

When designing active and adaptive artificial environments, whether they are intelligent facades or built environments that interface with natural ecologies, we want to establish a flow of information and energy. The adaptive synthetic built environment should behave similarly to natural systems. Therefore, when designing them, we might be less interested in stability as an on/off condition, and more in the zone of stability, its gradient and ability to perform under constant changes.

Vera Parlac is a registered architect in Pennsylvania, USA and an assistant professor at the Faculty of Environmental Design at the University of Calgary. She received a Diploma Engineer in Architecture degree from University of Belgrade and a Master's degree in design from UCLA. Vera Parlac is one of the founding co-directors of the Laboratory for Integrative Design (LID), a design research laboratory where design is engaged as a broadly integrative endeavor by fluidly navigating across different disciplinary territories. Vera's current design and research is focused on responsive material systems and informed by contemporary models in biology, material science research, and mechatronic systems. Prior to her appointment in Calgary, she taught design and other subjects at several universities in North America, most recently at Temple University and in Hong Kong. Vera has worked in architectural firms in Philadelphia, Toronto, Boston, Miami and Los Angeles including Carlos Zapata Design Studio and Kieran Timberlake Associates.



Soft Materials

Exploring Data Quality in Data-Integrated Design

Maya Przybylski
University of Waterloo, Canada

Introduction – Soft Materials

The increasing availability of real-world data is having a profound effect on the practice of architecture. The integration of data-driven computational methods into design processes has transformed the way architects work across all project phases – from design and planning to execution and operation.[1]

This integration presents new modes of engagement for architects and designers in allied fields whereby they play the role of producers of digital technologies – developing custom computational processes that are embedded as agents in the design phases and beyond. This practice, labelled here as *software embedded design* (SED), supports wide-ranging work: supporting undertakings such as form generation, automated analysis, advanced visualizations, and interaction and responsiveness. Often, these custom

1 Tamke, Martin, Mine Özkar, Bige Tunçer, Nataly Gattegno, and Brady Peters. 2017. "IJAC 2017: Special ACADIA Edited Issue." International Journal of Architectural Computing 15 (1): 3-5.

Image 1 How do our relationships with data, code implementations, hardware configurations and algorithms change when we consider them as part of a project's material assembly?

computational processes remain in the studio; the code is active while the project is in development, and when complete, its output is disconnected from the computational apparatus when deployed in the physical world. Yet, increasingly these processes go beyond the pre-deployment phases to include scenarios where the components remain online and continue to actively mediate project outcomes and behaviors through time as space – post deployment, in the real-world. By embedding software as an active element, a *soft material*, charged with mediating function and performance over time, designers are effectively adding computational components to their project's material assemblies.

As software is embedded in this way, a new set of responsibilities emerges for its producer – in this case, the architect. The increasing links between computational elements, material elements and project performance and behaviors adds complexity to how we assess project impacts and outcomes. We can consider a broad range of issues in this regard including things like technical performance, spatial effect and programmatic support. However, as part of the material assembly, we argue that the data and algorithms defining *soft materials* need to be understood also as playing a direct role in shaping the socio-cultural outcomes of the design work.

This argument is supported by key offerings from the field of Software Studies which position software – its actual lines of code and data, not just its effects – as a material practice with both social and spatial outcomes. Software Studies seeks to crack open the prevalent representations of software as a black box and to understand its inner workings with respect to instructing technologies how to act,[2] and work done in this arena has successfully demonstrated that software is a social-material production with profound influence on everyday life.[3]

2 Software Studies: A Lexicon. Ed. Matthew Fuller. Cambridge Massachusetts: The MIT Press, 2008.

3 Kitchin, Rob and Martin Dodge. 2011. Code/Space: Software and Everyday Life Mit Press.

These perspectives support a reconceptualization of ethical literacy in *software embedded design*; by including *soft materials*, such as data and algorithms, in our conception of a project's material assembly they implicitly become a part of the matrix defining the works' ethical dimensions. Thus, an expansion of knowledge and methods to support a more complete engagement with computational components embedded in such work is necessary. As producers of the material assemblages constituting our design work, we need to be literate and possess agency with respect to the social, cultural and political effects across the entire assembly – and this includes not only the material outside the computer, but the material inside the machine, and the connection between the two. Specifically, what are the necessary methodologies to support these a socio-cultural understanding of the softer materials of design work? How do we understand software's agency as a spatial agent? How should we shape designers' relationship with custom software to ensure its spatial agency is acknowledged, managed and leveraged towards the most ethical outcomes?

This is particularly important as a maturing SED field is on the cusp of moving from test-spaces with relatively minimal risks, to real-world applications with potentially more serious outcomes.[4] This transition demands that designers assess their capacity to engage fully with adopted extra-disciplinary techniques. As SED projects move to consider seriously their social and cultural consequences, designers need to exercise the same criticality they have shown the physical project components towards the virtual project components operating inside the computer and the relationship between the two.[5] The data we integrate and the algorithms we code need to be understood and examined as designed project elements with agency over project outcomes – not only from a technical perspective, but also with respect to social and cultural impacts.

4 Shepard, Mark. 2011. Sentient City: Ubiquitous Computing, Architecture, and the Future of Urban Space The MIT press.

5 De Monchaux, Nicholas. 2016. Local Code - 3,659 Proposals about Data, Design & the Nature of Cities. New York: Princeton Architectural Press.

Specifically, designers need to integrate questions and criticality around data sources, data format and selection, algorithm design and coding culture in order to confront the spatial and sociocultural agency of their data-driven works[6]. As we enter new frontiers in computational design, it is no longer enough to only have methods that *integrate* data in design projects but new methods are needed that *engage with it critically* throughout the design process and beyond.

6 Kitchin and Dodge, 2011

Finn, Ed. 2017. What Algorithms Want: Imagination in the Age of Computing MIT Press.

Data Quality & Terrain Nominal as Key Concepts to Better Understand Soft Materials

This paper focuses on the discovery and articulation of methods aimed at expanding the degree to which designers relate specifically to the data components of soft materials (algorithms and coding culture will be tackled in future work). It presents the key concept of *data quality* (DQ) as described in disciplines with more established histories of valuing data-literacy, such as information science, geography and other social sciences, and goes on to examine the potential for DQ assessment in SED work.

Data Quality: A Multi-dimensional Problem

Thinking about data in terms of its *quality* offers an entry point for forming a critical assessment of data consumed and produced in SED work. The details of such a process, such as first identifying the characteristics that should be evaluated and then carrying out the assessment, is an active research front rooted in the information sciences but also present in other disciplines such as geography, sociology and computer science. DQ is often presented as a multi-dimensional concept emphasizing a varying set of characteristics depending on it assessors' perspective.[7] Thus, fitness-for-use is widely adopted as a core principle in DQ[8] implying that data quality is relative: its assessment depends on its use and data appropriate for one use may not be appropriate for another.[9]

Numerous researchers across various fields have developed DQ frameworks which identify and group various data attributes which constitute holistic pictures of 'quality'. Knight and Burn[10] offer an extensive examination of the twelve most widely accepted DQ frameworks. They review the literature and enumerate the DQ dimensions listed in the studied frameworks and account

DIMENSION	DEFINITIONS
Accuracy	extent to which data are correct, reliable and certified free of error
Consistency	extent to which information is presented in the same format and compatible with previous data
Security	extent to which access to information is restricted appropriately to maintain its security
Timeliness	extent to which the information is sufficiently up-to-date for the task at hand
Completeness	extent to which information is not missing and is of sufficient breadth and depth for the task at hand
Concise	extent to which information is compactly represented without being overwhelming
Reliability	extent to which information is correct and reliable
Understandability	extent to which data are clear without ambiguity and easily comprehended
Accessibility	extent to which information is available, or easily and quickly retrievable
Objectivity	extent to which information is unbiased, unprejudiced and impartial
Relevancy / Usefulness	extent to which information is applicable and helpful for the task at hand
Usability	extent to which information is clear and easily used
Amount of Data	extent to which the quantity or volume of available data is appropriate
Believability	extent to which information is regarded as true and credible
Navigation	extent to which data are easily found and linked to
Reputation	extent to which information is highly regarded in terms of source or content
Efficiency	extent to which data are able to meet the information needs for the task at hand
Value-Added	extent to which information is beneficial, provides advantage from its use

Image 2 The Common Dimensions of DQ in widely accepted frameworks, presented in ranked order based on frequency of occurrence. (Adapted from Knight and Burns).

7 Klein, Barbara D. 2001. "User Perceptions of Data Quality: Internet and Traditional Text Sources." Journal of Computer Information Systems 41 (4): 9-15.

8 Wang, Richard Y. and Diane M. Strong. 1996. "Beyond Accuracy: What Data Quality Means to Data Consumers." Journal of Management Information Systems 12 (4): 5-33.

9 Tayi, Giri Kumar and Donald P. Ballou. 1998. "Examining Data Quality." Communications of the ACM 41 (2): 54-57.

10 Knight, Shirlee-ann and Janice M. Burn. 2005. "Developing a Framework for Assessing Information Quality on the World Wide Web." Informing Science: International Journal of an Emerging Transdiscipline 8 (5): 159-172.

for how often they appear (*Image 2*). This list is useful as it exposes a preliminary longlist of concerns to be incorporated in forming critical relationships with data consumption.

Of the twelve presented by Knight and Burn, the framework created by Wang and Strong (WS) entitled "A Conceptual Framework for Data Quality"[11] is selected here for closer examination. The WS framework is refined to address four key categories (Image 2). 1.) *Intrinsic DQ* addresses the extent to which data values are in conformance with actual or true values. This category includes *accuracy*, the extent to which data are correct, but also includes *objectivity*, the extent to which information is unbiased, unprejudiced and impartial. 2.) *Context DQ* deals with the extent to which data are applicable to the task. Key components of this category include *value-added*, the extent to which information is beneficial, provides advantages from its use, and *relevancy*, the extent to which information is applicable and helpful for the task at hand. 3.) *Representational DQ* addresses the extent to which data are presented in an intelligible and clear manner. 4.) *Accessibility DQ* concentrates on the extent to which data are available and obtainable.

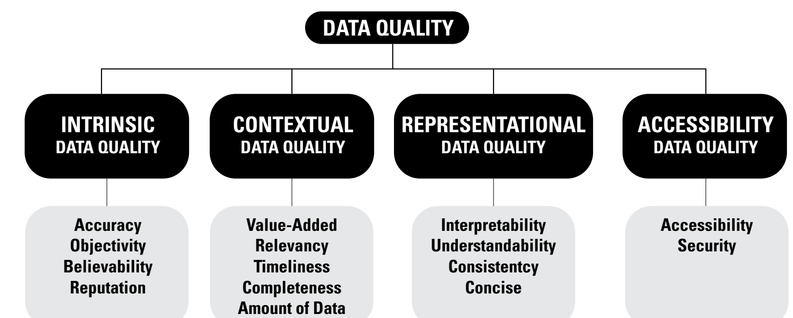


Image 2 Wang & Strong's Hierarchical Conceptual Framework for Data Quality. (1996)

We posit that the WS framework is well suited to serve as a starting point in developing a preliminary framework for DQ in SED. First, the WS framework departs from previous approaches by focusing on DQ from the perspective of the data consumer, not the producer[12]. Further, the WS framework's top-level categorization aligns well with familiar design considerations such as performance, form, context, and representation. Finally, the WS framework has successfully served as a foundation for more refined frameworks

11 Wang and Strong, 1996.

12 Klein, 2001.

13 Knight and Burn, 2005.

developed for specific domains.[13] The WS framework offers a structured guide to organizing dimensions against which designers can form critical relationships with data. The framework's core concerns are familiar enough to designers to offer a familiar point of entry yet broad enough to support the integration of SED specific concerns.

Terrain Nominal

The conceptual organization and terms provided by DQ frameworks facilitate a more critical engagement with data integrated in design projects. By exposing the multidimensional quality of data, frameworks identify some of the questions designers need to ask of the data being consumed in their projects.

In order to satisfy a given dimension of a DQ framework, the data must be understood by the extent to which it fulfills the specific dimension. This terminology reminds us that DQ is relative: the *extent or degree* to which a dimension needs to be met must be specified by the designer. It is only when the designer specifies the *degree to which the data needs* to be accurate (or relevant, objective, timely, concise…) that DQ assessment can take place. The sum of these specifications defines the *terrain nominal* which declares, implicitly and explicitly, the required level of abstraction and generalization relative to the real-world phenomena the data attempts to capture.[14] *Terrain nominal*, accepts that there is no objective reality or essential truth the data must capture and instead focuses on establishing a specification corresponding to a perspective of the phenomena which is tuned to the task at hand.[15] In some cases, data is known to be subjective, incomplete, or inexact; by accepting 'shortfalls' such as these in the conceptual model the data may still be fit-for-use and meaningful to the project.[16] Thus, to judge fitness-for-use, the designer needs to not only assess the data against the specification, but also consider the effectiveness and limitations of the conceptual model itself.[17] (Image 3).

Terrain Nominal is also a direct reminder of the inherent subjectivity captured in software systems. Software can be understood as "a form of subjectivity – the software constructs sensoriums, that each piece of software constructs ways of seeing, knowing and doing in the world that at once contain a model of that part of the world it ostensibly pertains to and that also shape it every time it is used."[18]

14 Veregin, Howard. 1999. "Data Quality Parameters." Geographical Information Systems 1: 177-189.

15 Chrisman, Nicholas. 2010. "Development in the Treatment of Spatial Data Quality." In Fundamentals of Spatial Data Quality, edited by Rodolphe Devillers and Robert Jeansoulin, 21-30. London: John Wiley & Sons.

16 Veregin, 1999

17 Veregin, 1999

18 Fuller, Matthew. Behind the Blip: Essays on the Culture of Software. New York: Autonomedia, 2003: 19.

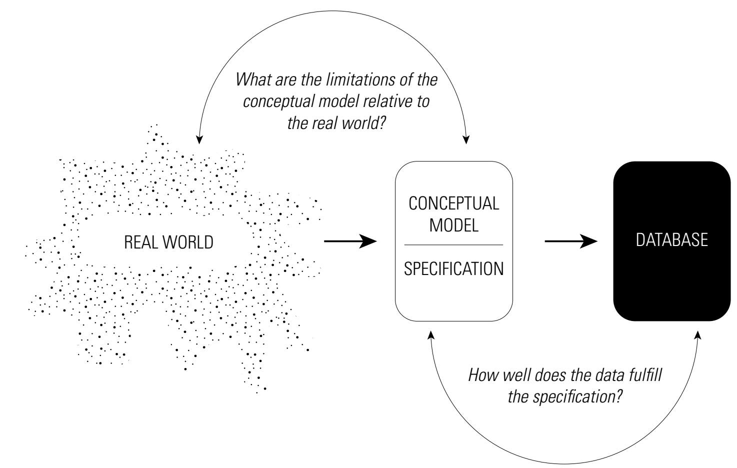


Image 4 Terrain Nominal. A Conceptual Model as a bridge between the real world and its data-based representation

Towards a Preliminary DQ Framework for Data-Integrated Design

In order to make some of these thoughts more concrete, we use an existing SED project and carry out a post-mortem reflection on how its DQ assessment may transpire. Specifically, an initial mapping of these extra disciplinary understandings of DQ into the design domain is tested through the proposal of a preliminary framework for assessing data quality in a project entitled *OnTheLine* (project credits omitted for blind review).

OnTheLine was conceived as an exhibition which converts a transit line into a gallery connecting transit riders with the rich collection of destinations located along the route. The project team created a suite of physical installations and digital interfaces aimed at shaping and presenting a collective identity of the region. Utilizing bus shelters, buses, a centralized project display, an interactive website, and a mobile app as media for information transmission, *OnTheLine* both distributes and collects information about activities, events, and destinations along the transit corridor (Image 4).

Two complementary sets of data contribute to the unified presentation of destinations: first, the project presents a *curated* and centralized set of local cultural destinations and activities that has been pre-assembled

by the project team from a suite of local information resources; second, an *emergent* set of destinations submitted by the public, via social media mechanisms such as twitter hashtags, augments the list of presented destinations (Image 5). This hybrid data set constitutes a growing directory of local information, engaging a diverse range of participants as project collaborators. The project's various sites, its collection and use of data, and its supporting media and technologies, are combined into a comprehensive framework for enabling the city as a site of participation, thereby offering a mechanism by which to sense the city and enable its strategic development and management.

Image 5 OnTheLine: Conceived as an exhibition which converts a transit line into a gallery connecting transit riders with the rich collection of destinations located along the route, the project offers a comprehensive framework for enabling the city as a site of participation, thereby offering a mechanism by which to sense the city.

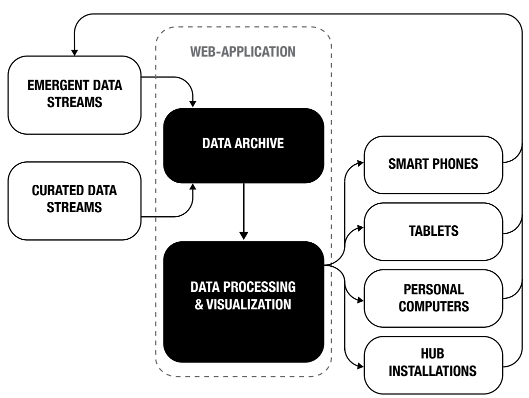


Image 6 The OnTheLine's Datascape: two primary data streams, curated and emergent, are combined into a suite of physical installations and digital interfaces.

Taking lessons from the DQ assessment context established above the following steps are outlined for conducting a high-level assessment of the DQ used in *OnTheLine*:

1. Establish *OnTheLine's* socio-cultural and technical objectives in order to establish the terrain-nominal.
2. Identify the DQ dimensions to be assessed.
3. Prioritize selected DQ dimensions.
4. Develop specific assessment techniques for prioritized dimensions.

The literature identifies three approaches to studying DQ: intuitive, theoretical, and empirical.[19] The *intuitive* approach is taken when the selection of DQ attributes is based on the assessor's experience or intuitive understanding about which characteristics are "important".[20] While this approach has some shortfalls – the assessment is limited to the DQ knowledge existing within a specific project by not integrating DQ concerns held by external parties – it does allow for a quicker identification of relevant DQ attributes. By being relatively easy to formulate, the intuitive approach also allows for each study to select its own set of attributes most relevant to its particular goals.

19 Wang and Strong, 1996

20 Wang and Strong, 1996

The intuitive approach has been selected to develop a preliminary DQ framework for *OnTheLine*. An exhaustive DQ assessment of the project is beyond the scope of this paper. Instead a subset of the project's data is strategically culled to highlight the diverse set of questions and analytical outcomes across the several datasets used in the project.

Results & Discussion

Image 6 presents a summary of Steps 1 – 3 outlined above. A sampling of specifications driving the key technical and socio-cultural objectives of the project is offered (left) to establish a conceptual model of the phenomena that the data is meant to capture – namely the name and location of notable sites along the transit line. These specifications establish the key considerations informing the prioritization of the Wang & Strong DQ attributes (center). Connecting lines are drawn to communicate which specification relates to which DQ attribute. A Preliminary intuitive ranking of attributes is also provided.

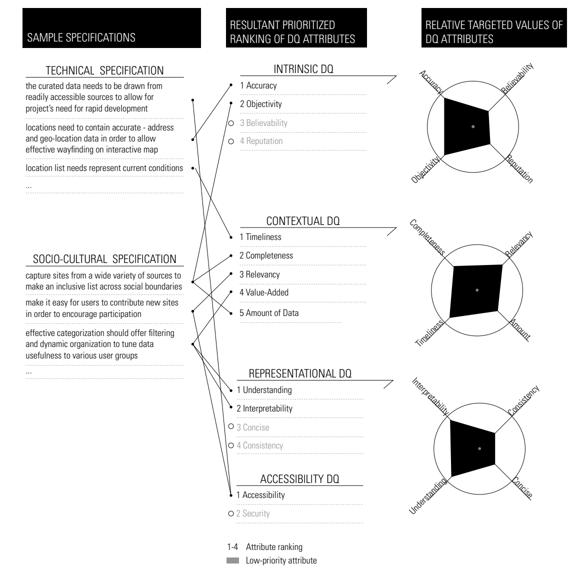
Step 4 demands specific assessment techniques to be developed. During these early stages of this research, Radial Coordinate Maps are used to create multivariate representations of the data's quality in an accessible way[21]. A total of three sets of Radial Maps are produced. The first set, presented in Image 6, establishes target values for DQ Attributes based on the projects stated objectives. The two subsequent sets of maps are produced as part of Step 4. Image 7 presents the differential between Curated Data and target values according to the DQ framework's three main categories. The final set of maps (Image 8) examines the quality of Accuracy as a single attribute in more detail.

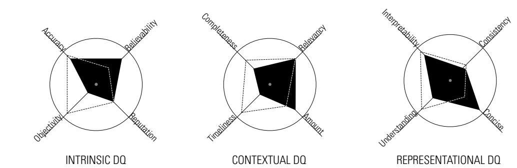
21 Wortmann, Thomas. 2017. "Surveying Design Spaces with Performance Maps: A Multivariate Visualization Method for Parametric Design and Architectural Design Optimization." International Journal of Architectural Computing 15 (1): 38-53.

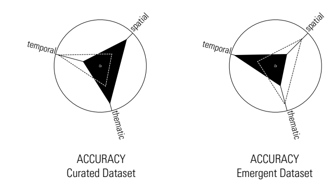
Image 7 presents a high-level intuitive assessment of *OnTheLine's* Curated Data, assembled by the project team from a variety of community-level sources, such as the Ontario Heritage Trust and Waterloo Regional Tourism group, and subjected to manual processing, verification and selection. Processing steps, such as cross-referencing municipal addresses with geocoding results, increased ratings for accuracy and believability. The timeliness attributes received a low rating as some data sources were dated over one year prior to the project implementation and thus increased the probability of venue being closed or otherwise out-of-date. Objectivity was also scored relatively low: the selection process behind the data's inclusion (immediate availability was a key driver and less available sources were excluded) did little to ensure an unbiased and impartial dataset.

Image 8 presents a more detailed comparison of the Accuracy attribute across the Curated (CData) and Emergent (EData) data sets used in the *OnTheLine*. Here, due to the data's geospatial nature, accuracy is unpacked to include three additional dimensions by which to better understand its quality: temporal accuracy, spatial accuracy and thematic accuracy.[22] Independent examination of each of these sub-properties exposes discrepancies between the two datasets. On the one hand, the real-time features of the EData overcame some of the timeliness issues of the CData discussed above. On the other hand, EData was more susceptible to lower levels of relevance and higher probabilities for mis-categorization, resulting in a lower rating for thematic accuracy. Further, users' smartphone location settings caused the precision of spatial information to vary widely across EData entries. Meanwhile, the CData was subject to spatial accuracy verification which ensured highly precise spatial data.

22 Veregin, 1999







Conclusion & Future Research

Image 7 An intuitive definition of the conceptual model and DQ framework for OnTheLine. Adapted from Wang & Strong (1996)

Image 8 Radial Mapping Comparison. Mapping the differential between Curated Data (Black) and Target Values from Image 6 (Dashed Line) according to the DQ framework's three main categories.

Image 9 Comparison of relative accuracy of Curated and Emergent Datasets

The preliminary work presented in this paper begins to formulate an avenue for building richer engagement with data in SED work. Perhaps most clear in this work is the fact that confronting data quality is a multi-dimensional challenge demanding the articulation of new questions and methods for designers.

This work valued quick intuitive assessment carried out within a guiding framework. This technique is useful in that it demonstrates an accessible approach for designers to begin to formulate some degree of criticality around the data they use in their work. Future work will integrate more robust assessment techniques. Specifically, recent developments in surveying design spaces using Performance Maps in order to capture multivariate properties[23] will be examined as a way to move beyond the Radial Coordinate Maps used here.

23 Wortmann, 2017.

At the framework level itself, more work needs to be done to meaningfully assemble DQ attributes especially relevant to SED. The adopted frameworks were effective starting points, but they are biased towards the concerns of external disciplines. Reviewing already existing SED work in order to build an inventory of possible SED-focused attributes is one approach. Surveying SED authors in order to understand existing data-related objectives and values is another. This will also illuminate questions around the way designers conceive and evaluate the *terrain nominal* which drives the representation of the captured phenomenon. Specific challenges around incorporating qualitative data quality concerns, such as objectivity, also demand further examination.

Of course, data is only one aspect of Soft Materials. Similar avenues should be established and supported in order to ask similar questions of the algorithms used in SED work. In general, the inherent subjectivity of software calls on us to be explicit in the assumptions and biases embedded by us in the models used in the software in our projects. These biases may arise for numerous reasons: 1) technical limitations – coders' ability is limited so aggressive decisions around how to represent the problem are made, 2) resource limitations – time and other resources dedicated to examining the problem from stakeholder perspectives and socio-cultural impacts is minimal, and 3) limited self-awareness - default decisions made by coders because of assumptions from their own socio-cultural background or the general culture of the environment around them. Questions around how these ideas can be captured in an accessible process for SED designers represents another front of future work.

Future efforts will also focus on how to connect this work into design processes. In this paper, a post-mortem analysis is used to explore framework design and visualization strategies. In subsequent work, the framework will be adapted to support SED work as it is unfolding. This direction will test how an SED-specific framework can become an effective and accessible design tool.

Given that raw data is an oxymoron[24], that data is increasingly being integrated in design work, and that SED work is increasingly imbued with sociocultural agency, methods for discussing and assessing critical issues around Soft Materials, from a designer's perspective, are urgently needed. This is an essential early step in achieving a more complete engagement with the computational components embedded within SED work.

24 Gitelman, Lisa. 2013. Raw Data is an Oxymoron MIT Press.

Flanagin, Andrew J. and Miriam J. Metzger. 2008. "The Credibility of Volunteered Geographic Information." GeoJournal 72 (3-4): 137-148.

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Maya Przybylski is a Toronto based designer and educator. She is Assistant Professor at the School of Architecture at the University of Waterloo. Maya is a graduate of the Faculty of Architecture, Landscape and Design at the University of Toronto (M.Arch. 2007) where she was awarded the Royal Architectural Institute of Canada Medal for her thesis work on post-oil opportunities for the Caspian Sea. Maya previously earned a degree with a specialization in Software Engineering at the Department of Computer Science at the University of Toronto (B.Sc.Hon. 2003). Through her teaching, research and design work Maya is exploring the complex intersection of architectural design, data and computation. She is developing methods for achieving a more complete engagement, including sociocultural agency as well as technical capacity, with the computational components embedded within data-driven design work. Maya is the director of the DATALab (www.datalab.uwaterloo.ca) research group at the School of Architecture and has collaborated with a range of design practices including: RVTR, Lateral Office, WilliamsonWilliamson, and Bruce Mau Design. She is a founding editor of Bracket (www.brkt.org), a publication series that, since 2010, has documented the intersection of architecture, environment and digital culture and co-author of Pamphlet Architecture 30: Coupling — Strategies for Infrastructural Opportunism (Princeton Architectural Press 2009).

Complex Modelling

Questioning the Infrastructures of Information Modelling

Mette Ramsgaard Thomsen

Royal Danish Academy of Fine Arts, Copenhagen, Denmark

Image 1 Flora Robotica, Phil Ayres examining braiding as a material system and using the direct link between the graph modelling material connectivity to shape new kinds of braids that are topologically possible and principled in their design, but for which no current fabrication process exists. CITA 2017

Introduction

We are finding ourselves in a time of rethinking our material practices. As research into design computation matures, its fundamental links to fabrication are challenging industrialised paradigms of building construction. With origins in the many explorations of mass customisation and material investigation, our practice is entering a new era in which architects become the designers of materials as well as artefacts. The interest in designing directly for fabrication has transcended the scales of materialisation moving from the fabrication of individualised building elements to the direct production and specification of the materials themselves. This extension of the digital design chain integrating the design of not only material systems but also the composition of their components is now an overarching paradigm informing research and finding its way into practice.

Image 2 3D printed glass
Mette Ramsgaard Thomsen, Martin Tamke and Maria Sparre Petersen, CITA 2018

In this paradigm materials are no longer standardised to a measure of global uniformity, but instead locally tuned and optimised. This thinking is linked to interdisciplinary efforts in the broader fields of engineering and material science that are rethinking how we materialise our world. We are living in a time of extreme material inventiveness and are surrounded by highly engineered materials. The 20th century has brought with it an era of synthetic and engineered materials from the artificial silk of nylon stockings to high modulus polymers, ceramic composites to Nano-materials.[1] Now, architecture and building culture is entering this way of thinking. The link between design and direct material manufacture and the ability to programme advanced steering mechanisms has allowed architects to prototype material systems that grade intensity or structure in response to design intent, optimising material usage and employing inherent material performances. In architecture, the ability to use materials in smarter and less intense manners are fundamental building blocks for the conception of lighter building culture; a culture in which lighter means less material, less transportation and altogether a lighter impact on our environments.

This paper discusses the modelling paradigms needed to engage with this new material practices. If traditional architectural drafting has successfully transitioned into parametric design paradigm such as Building Information Modelling (BIM) and other more bespoke computational design practices, the question remains how we transform these systems to engage the profoundly inter-disciplinary and inter-scalar design environment of the extended digital chain. When we design across the scales of the building system, the element and the material, we encounter multiple scales of engagement, all of which has its own discipline specific modelling paradigms. This paper questions how these models can be integrated so as to enable strategic exchange between them, and what underlying infrastructures we need to develop in order to work successfully with these concepts. The claim is that these new practices necessitate new modelling practices that fundamentally exceeds the boundaries of existing modelling paradigms and that it is this ground research question that is the core enquiry of our time.

1 Beukers, Adriaan, and Ed van Hinte. 2001. Lightness: The Inevitable Renaissance of Minimum Energy Structures. Rotterdam: 010 Publishers. 14 – 15.

Constraints in current modelling practices

At present, the development of digital design tools in architecture is structured around large-scale industry led efforts that have sought to standardise information and develop shared protocols between inter-disciplinary partners.[2] However, core efforts such as BIM have proved inadequate in tackling the high degrees of complexity of current building practice while at the same time not being able to support the needs for flexible, intuitive and communicable design processes.[3] Practice is aware of these embedded limitations of current modelling practice and the industry development has therefore been paralleled with a series of profession-led research and development efforts creating bespoke modelling methods allowing complex design solutions and creating links to fabrication.[4] The practice of architects building their own information tools, encoding their models and engaging directly with model interfacing is therefore an embedded part of existing practice. However, this effort is project-led, practice-specific and rarely shared.

As building culture enters a rethinking of its material practices, we need to future-proof our representations. Rather than building common standards and libraries for known practices, we need to develop the fundamental infrastructures for yet unknown practices. This position fundamentally challenges some of the cornerstones of present modelling paradigms.

The ideal of the unified model: The ambition to integrate all design phases and practices has proven difficult as different practices use different kinds of tools to analyse and represent knowledge. BIM models are breaking their own modelling frameworks in terms of pure scale becoming bigger,

2 Jernigan, F.E., Onuma, K.G. 2008. "Big Bim Little Bim" Salisbury: 4site Press.

3 Holzer, D. 2007. "Are you talking to me? Why BIM is not the answer" Association of Architecture Schools Australasia Conference, University of Technology Sydney.

4 Burry, M. 2011. "Scripting Cultures – Architectural design and Programming," Architectural De-sign Primers. London: Wileys. 28.

wider and deeper in the sense that they encompass more information from more disciplines (bigger), they include more phases or design (wider) and they expand into new scales of design concern (deeper). This is creating a bottle-neck that is impeding innovation and creativity in architectural design practice. Instead of integrating information into one containing model, we need to build networked models that pass information between discreet part models that are dedicated to particular tasks and can be continuously tuned and changed.

A persistence of hierarchy: Building practice is traditionally organised hierarchically as a sequence of subsystems each with their own scale of engagement and team of specialised professions. This division persists within modern design practice and is mirrored by legislative according of responsibility within the design chain. However, this understanding of design as a progression through the scales limits the potential for design innovation as it excludes our ability to understand how the small scales - material or detail - can affect large scales – environment or structure. To support a real implementation of feedback in the design chain we need to develop mechanisms for multi-phased and multi-scalar feedback in which cyclical interdependencies can be investigated and assessed.

The expectation of known design parameters: Design is a process of discovery. Unknown opportunities and limitation appear through the collective

Image 3 Detail of A Bridge Too Far
Paul Nicholas, CITA 2016

5 Davis, D. 2013. "Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture," Ph.D.,. School of Architecture and Design, College of Design and Social context, RMIT University, 37 – 47.

6 Nicholas, P.; Tamke, M.; Riiber, J. 2014. "The Agency of Event: Event based simulation for architectural design." In ACADIA 14: Design Agency Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) Los Angeles 23-25 October, 2014, 63 – 74.

investment into the design phase. However, current information modelling necessitates a priori understanding of key design parameters. When new parameters appear, design models break and either need reprogramming or become messy hacks.[5] A central premise for the future of the information model is therefore that it engenders open topologies by which adaptive parametrisation can take place so that we can build models in which parameters can appear or conversely dissipate into constants without breaking the design logic.

Geometry as information interface: Finally, we need to reconsider our reliance on geometry as a prime interface for information. Simulations and generative design processes include numerical modelling occurring across discreet time steps though which solutions emerge. We therefore need to expand our perception of modelling as something that occurs in time and through event.[6] Furthermore, as we start implementing more complex n-dimensional data analysis algorithms such as k-means clustering, the description of three-dimensional extension becomes a limitation in our means of visualisation of a design space. Finally, the expansion of digital design chain, making material design part of architectural design, also includes the encounter of new discipline- and scale-specific models that do not fit with geometric representation. Where building culture is used to other means of description such as numeric tables for processes such as cost estimation or stress strain graphs, these are understood as secondary to the actual

3D model. As new modelling methods mature, we need to understand the inherent heterogeneity of the networked model while retaining the creative and intuitive properties of our own methods.

Researching Complex Modelling

In CITA, the enquiry into how these modelling paradigms are changing have shaped the last five years of research. Currently this is framed by the research project Complex Modelling, a framing project supported by the Danish Sapere Aude Advanced Research Programme. Here, we are exploring future modelling paradigms and how methods from parallel disciplines including engineering and computer science can broaden our practices and transfer central concepts and tools. With special focus on systems that integrate material performance, engage high degrees of interdependency and allow the emergence of design agency and feedback between the multiple scales of the structure, the element and material, our aim is to prototype future methods for information modelling. The project builds on CITA's central investigation into material performance. Here, material performance is understood as a core resource for design innovation being closely tied to material optimisation. Positioning *feedback* as a central concern cascading through all scales of engagement, the project asks how dynamic modes of organisation can introduce new logics into the design of architectural information models.

Where an initial interest in Complex Modelling lay with the abstraction of the high dimensionality of complex solution spaces and the construction of methods by which to strategically steer these, it has become clear that the challenge is not how to design in n-dimensions but rather how to understand and capture interdependency. In Complex Modelling interdependency occurs at multiple levels – between material systems, between scales of material manipulation, between modes representation and modes analysis and simulation and between explicit design strategies and those that are generative and optimised. As such, each project engenders its own distinct landscape of networked models. Where concepts and tools are ported across projects, each project finds their own particular way of orchestrating these into cohesive wholes.

The following goes through some of the central enquiries of Complex Modelling. These are exemplified through brief project presentations. Complex Modelling follows an experimental design led method in which a series of linked research projects as well as 'sketch probes' act as material experiments. The emphasis on the design and implementation allows the project to engage directly with the investigated techniques and technologies moving along the digital chain from design and analysis to specification and fabrication. This integrated approach positions the research inquiries within a network of interconnected expertise and practice. The results, the design probes and the demonstrators generate shared empirical data that can be further tested, analysed and evaluated. The projects are therefore to be seen more as vehicles by which the research enquiry can be undertaken than as independent research goals. The discussion presented here therefore moves across multiple projects exposing the methods by which different concepts are investigated.

Integrating Simulation

CITA's central interest in material performance has led to a fundamental exploration into integrating simulation. The emergence of the shared digital design platform has brought with it an opening up of traditional disciplinary boundaries and a merging of core modelling concepts. The ability to interface complex analysis tools for the simulation of force and flow, such as Finite Element (FE) analysis that discretise complex problems into finite numbers of interrelated nodes to compute their force-relations, is influencing the thinking of structural design enabling the realisation of buildings with higher degree of formal freedom and structural complexity.[7]

In CITA, our interest lies especially with the integration of simulation into the early design phases. By allowing simulation to not only be employed as a concluding evaluation of an already mature design, but also a tool for exploration and form finding, simulation becomes part of a larger set of dynamic modelling tools for exploring and creating design possibilities. This has meant a particular interest in light-weight spring-based simulation tools including first Nucleus[8] and later Kangaroo but also self-scripted physics engines.[9] In our extensive exploration of active bending[10] and highly interdependent material systems,[11] we examine light-weight simulation as a means of understanding and formalising material behaviour, calibrating the bending of timber lamellas or GFRP rods and calculating its interaction with

7 Clough, R. W. and Wilson, E. L. 1999. "Early Finite Element Research at Berkeley." In Proceedings 5th US National Conference Computational Mechanics, Boulder, Colorado.

8 Holden Deleuran, A., Tamke, M., Ramsgaard Thomsen, M. 2011. "Designing with Deformation - Sketching material and aggregate behaviour of actively deforming structures." in Proceedings of SimAUD 2011 Symposium April 4-7 2011, Boston. 5 – 12.

9 Tamke, M., Stasiuk, D., Ramsgard Thomsen, M. 2014. "The Rise – Building with Fibrous Systems." In eds. Gramazio, F., Kohler, M., Langenberg, S., Fabricate: Negotiating Design and Making, Toronto: GTA Publishers.

10 Ramsgaard Thomsen, M., Bech, K. and Tamke, M. 2011. "Thaw – Imaging a soft tectonics." In Glynn, R. and Sheil, B. eds. Fabricate: Making Digital Architecture. Toronto: Riverside Architectural Press, Canada.

Tamke, M. , Lafuente Hernández, E., Holden Deleuran, A., Gengnagel, C., Burry, M. and Ramsgaard Thomsen. 2012. "M. 2012 A new material practice - Integrating design and material behaviour." In Proceeding of Symposium on Simulation for Architecture and Urban Design, SimAUD 2012, Orlando, FL, USA, 26.-29 .March, 2012, Society for Modeling & Simulation International (SCS): 5 – 13.

Nicholas, P. 2013. Designing Material Materialising Design. First Edition edn, Toronto: Riverside Architectural Press.

11 Ramsgaard Thomsen, M., Tamke, M., Holden Deleuran, A., Friis Tinning, I., Leander Evers, H., Gengnagel, C., Schmeck, M. 2015. "Hybrid Tower, Designing Soft Structures." In Design Modelling Symposium: Modelling Behaviour, Berlin Heidelberg: Springer.

interconnected tensile members. In these investigations, simulation is not seen in isolation, but rather as intrinsically correlated. Light-weight simulations are both tested against and testing more solid FE simulations allowing for continual feedback between early stage design exploration and later stage design refinement. Similarly, simulations are not limited to material or structural simulation, but incorporated into a larger framework of simulation particular to each individual project. These have included light simulation,[12] computational fluid dynamics or agent-based simulations[13] by which design performance, structural performance and material assembly are negotiated.

This practice of conceiving the information model as comprising multiple design integrated simulations only intensifies as we work in a multi scalar design space. Here, scale specific simulations at the scale of the structure, the element and the material are interfaced, passing information between individual part models. As such, simulation is not singular, but instead recurrent and distributed across the landscape networked model.

Simulations introduce important concepts to design modelling. Occurring in time and through event, simulation necessitate time steps thus making us understand design as the incremental movement towards solutions in difference to the explicit shaping of absolute form. This new temporality of our computational design space is exploded and discontinuous. Rather,

Image 5 In *Isoropia*, highly interdependent system of active bent GFRP rods and tensile membranes interact to create overall structural performance. These interactions are simulated employing projection-based methods (K2Eng) and correlated to Isogemetric Analysis (Kiwi). Martin Tamke, Mette Ramsgaard Thomsen, Yuliya Sinke in collaboration with AFF Filhos and Str.ucture.

12 Nicholas, 2014.

13 Tamke, M., Riiber, J., Jungjohann, H, Ramsgard Thomsen, M. 2010. "Lamella Flock," In Advances in Architectural Geometry 2010, Vienna: Springer Verlag 37 – 48.

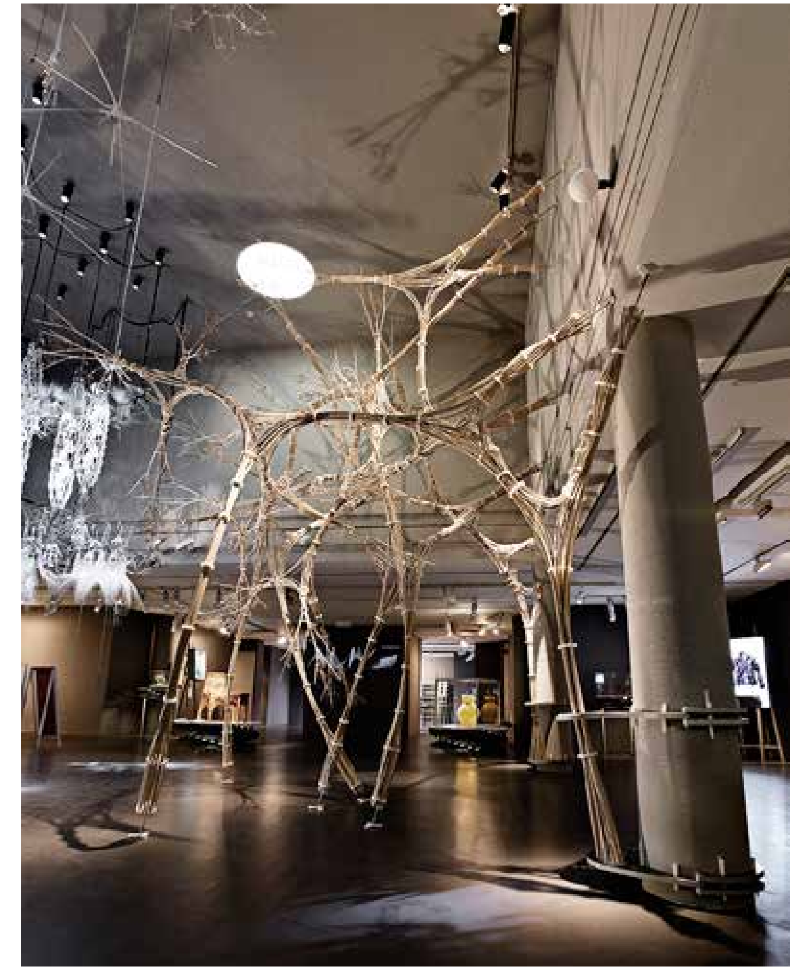

Image 6 In *The Rise*, the growth algorithm and consecutive sprouting of branches means that structural performance of the artefact is continually changing. Martin Tamke, Mette Ramsgaard Thomsen, David Stasiuk, Hollie Gibbons, CITA 2013.

discreet events can be called, occur in parallel or enact in isolation triggering new design decisions.

3.2 Adaptive Parametrisation and Open Topologies

A second focus in Complex Modelling is the exploration of methods for adaptive parametrisation in the information model. To preserve design control, parametric models necessarily operate with a reduced number of design parameters thereby reducing the complexity of the model. Where this

Image 7 Lacewall
Mette Ramsgaard Thomsen, Martin Tamke, Anders Holden Deleuran, Mateusz Zwierzycki, Yuliya Sinke, CITA 2018.

is practical, it also limits our way of understanding the potential of design synthesis and leads to an inherently reductive design process.

The field of computational design is currently engaged in a push to build new models of for understanding and capturing the emergent effects of high-order parametric design. Here, new tools are being prototyped for understanding multi objective optimisation allowing architects to navigate the design space along the Pareto-front and "…giving feedback on the best trade-offs that were found so far."[14] These new tools support existing concepts for understanding design as 'optioneering' or 'versioning,' in which the singular design object, is seen as part of a larger space of possibility, that were introduced already in early digital design processes. However, they often entail a fundamental fixing of the underlying topology onto which variation is processed.

To retain the flexibility of this new design space, we need to embed the possibility for change of the topology of the design model. Open topologies, in which the dependencies between parameters are emergent and open to change during the design process, allow an inherent flexibility in design by enabling the activation of new - or the neglecting of obsolete – parameters. We need to build methods by which these can be steered and controlled so that we can move beyond random mutation and into much more deliberate progressions.

14 Vierlinger, R., Bollinger, K. 2014. "Accommodating change in parametric design, in ACADIA 14: Design Agency" In Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) Los Angeles 23-25 October, 2014, 609 – 618.

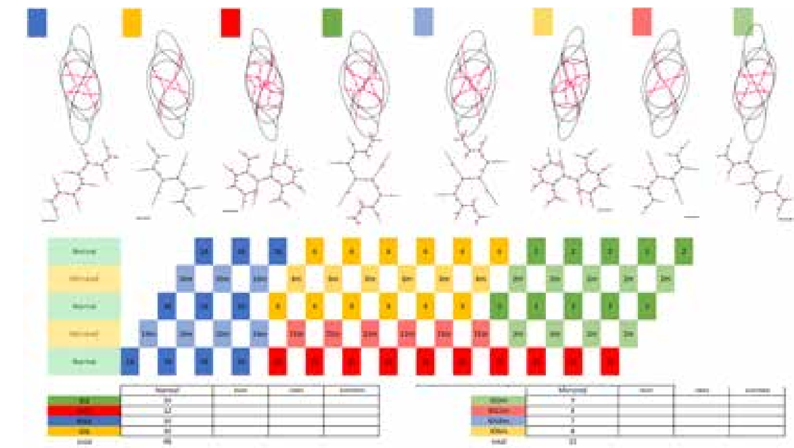

Image 8 Lacewall Mette Ramsgaard Thomsen, Martin Tamke, Anders Holden Deleuran, Mateusz Zwierzycki, Yuliya Sinke, CITA 2018. In Lacewall, machine learning is used at two scales. At the scale of the unit we train an artificial neural network to optimise the single cell in response to deformation but also particular meeting points allowing assembly. At the scale of the wall we use statistical probability to map the cells back into the wall. Here, brute force strategies simulating the aggregate behaviour of the totality of the wall proved too time consuming. Instead we simulate the wall behaviour once and then used machine learning to map the performances of the selected cell designs across the surface in response to performance.

In CITA recent work is exploring these concepts through dynamic modelling tools including growth algorithms and machine learning tools. Growth algorithms introduce interesting ways of understanding the model as actively evolving through the design process. This firstly establishes a temporal dimension to the design model but also allow us to think of topologies with changing body plans.[15]

This enquiry into open and adaptive modelling strategies has led to an interest in machine learning. Here, generative and evolutionary design strategies are coupled with tools for emergent classification. In sketch projects such as "Learning to be a vault" we have explore, supervised as well as unsupervised learning methods for clustering large scale design spaces into formal classification systems, guided both by the designer and allowed to emerge from a design model's underlying data structure.[16]

Topological thinking has furthermore led to an interest in graph modelling as a means to represent and manage the underlying interconnectivity of design parameters, and in new projects we are exploring neural networks methods such as NEAT (NeuroEvolution of Augmenting Topologies)[17] by which to create evolutionary processes that can change and optimise design topologies.

These processes present alternative strategies to the embedded reductionism of parametric modelling. Here, models exist in multiples – in thousands of models – that are spawned by the generative system to then be analysed

15 Tamke, M., Stasiuk, D. and Ramsgaard Thomsen, M. 2013. "The Rise – Material Behaviour in Generative Design." In ACADIA 13. Adaptive Architecture. Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture, (Cambridge, Ontario, 24-26 October, 2013), Riverside Architectural Press, 379 – 388.

16 Stasiuk, D., Ramsgaard Thomsen, M. 2014. "Learning to be a Vault - Implementing learning strategies for design exploration in inter-scalar systems." In Fusion, Proceedings of the 32nd International Conference on Education and research in Computer Aided Architectural Design in Europe, 381-390. Vol. 1. eCAADe: Conferences 1. Newcastle upon Tyne, UK: Northumbria University.

17 Stanley, K. O., Miikkulainen, R. 2002. "Evolving Neural Networks Through Augmenting Topologies", Evolutionary Computation 10 no.2: 99 – 127.

by the learning system. Models are no longer singular end points but belong to processes of expansion, increasing in number and in complexity by each time step of evolution. The designer becomes part of a design cycle in which classification, querying and management of data sets become new design concepts.

Multi scale modelling

In CITA, the interest in these new modelling paradigms is how they impact on the way we work with material systems. Where the above outlines strategies for developing model landscapes composed of multiple dynamic and interacting part models operating across different design phases and multiple scales, the question becomes how inter-model communication is facilitated. The aim is feedback. Rather than reducing the digital chain to adhere to a traditional perception of design as a one-way process of refinement consecutively encountering ever smaller scales, our interest is in supporting inter scale relationships, in which design at the small scale is linked to design at the large scale.

This is explored through concepts for multi scale modelling.[18] Multi scale modelling is interesting because of its broad interdisciplinary application in problems that aim to analyse and represent large scale problems with high

Image 9 PCM Façade collaboration between CITA and Kieran Timberlake.
Martin Tamke, Yuliya Sinke, Mette Ramsgaard Thomsen, Phil Ayres, Paul Nicholas and Billie Faircloth, Ryan Welsch, Erica Eherenbard, CITA 2017

18 Nicholas P., Stasiuk D., Clausen Nørgaard E. and Hutchinson C. 2015. "A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure, in Modelling Behaviour," In Design Modelling Symposium: Modelling Behaviour. Berlin Heidelberg. Springer.

Image 10 A Bridge Too Far
Paul Nicholas, CITA 2016

19 Weinan E. 2011. Principles of Multiscale Modelling, Cambridge: Cambridge University Press

20 Nicholas, 2015.

degrees of complexity and where it becomes intractable to model the problem within one unified model. Multi scale modelling presents methods for coupling and interfacing models so that meta scale models can be informed and parametrised through lower scale models but also conversely parse information back down through the design chain thus profiting from both the macroscopic models as well as the accuracy of the microscopic models.[19]

In CITA we employ multi scale modelling methods using both nested strategies in which lower scale models neatly reference the uniform subdivision of a larger scale model as well as more tactical strategies in local variation in the scale subdivisions correlate to areas of higher degrees of complexity. In these strategies, the mesh becomes a shared interface allowing the translation of information between different scales of design engagement.[20] The mesh is no longer only a geometric descriptor but instead a dynamically changing infrastructure coarsening or refining so as to keep information at the right resolution level.

Conclusion

Complex Modelling is one out the many projects across our community to explore these paradigms. Although perhaps unique in its focus on the underlying infrastructure of advanced digital modelling, it is part of larger push to expand and evolve our modelling practices. Our community is maturing. With large scale research projects such as the Digital Fabrication NCCR at ETH, the Biological Design and Integrative Structures at University of Stuttgart and Innochain at CITA and across six European institutions, our field is contributing with real solutions for future building culture.

However, we need to be much more conscious of the research contribution that the evolution of our modelling methods is presenting. Where projects tend to foreground the particular structural, material or performative advancement it is investigating, the new modes of information modelling developed to do so are equally important. Our field is criticised for being speculative or overly interested in formal aspects of design, both by more conventional practice and by our neighbouring disciplines. However, I believe that we need to think of these multiple experiments as the prototyping of methodologies. As such, we are embedded into a culture of ground research exploration, which will profoundly change the modalities of architectural representation. This is important because, as all architects know, the means of representation are our means of conception and enaction.

Furthermore, it is a field in which we are contributing quite singularly. Where design computation is fundamentally interdisciplinary, and core research engagements are achieved because of the broad disciplinary project teams, then the evolution of the design model tends to be in the hands of the architects. Perhaps this is because geometric representation traditionally is inthe hands of the architect or because it supports the architect's role of orchestrating collaboration. Despite the actual methods being highly interdisciplinary coming from computer science, engineering, material science or biology, then it is architects that are standing for these transfers of knowledge.

We are transforming our practice and presenting a new consideration of design as something inherently dynamic, interconnected and incongruous. Here, complexity is not an extravagance but rather the probing of a future to come.

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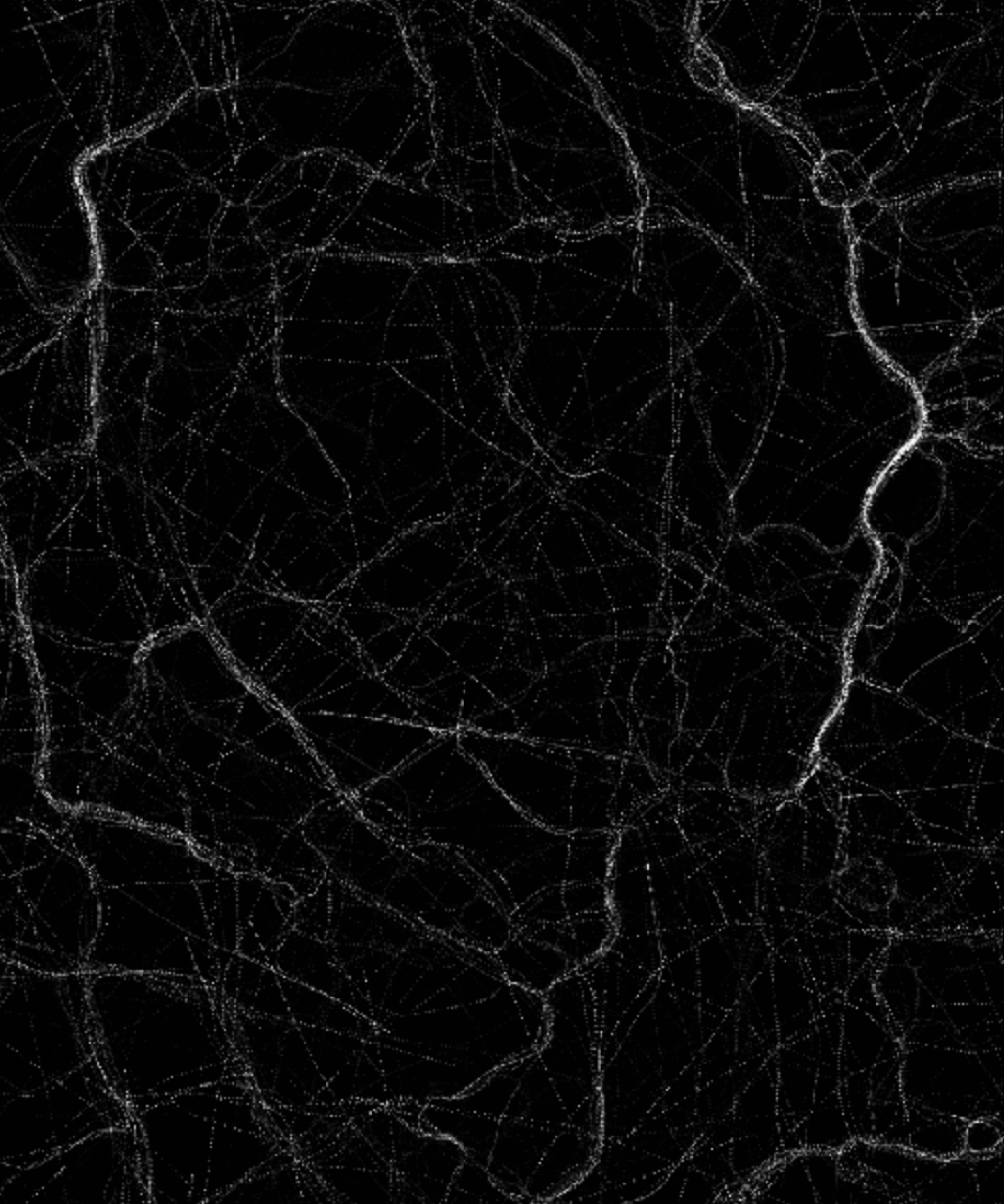
Mette Ramsgaard Thomsen is Professor of Digital Technologies and leads CITA (Centre for Information Technology and Architecture) at the Royal Danish Academy of Fine Arts, Schools of Architecture, Design and Conservation. During the last 15 years her focus has been on the profound changes that digital technologies instigate in the way architecture is thought, designed and built. In projects such as Complex Modelling and Innochain she is exploring the infrastructures of computational modelling, including open topologies and adaptive parametrization. She is pursuing design-led research at the interface of computational design and material thinking. Recent projects focus on advanced modelling concepts examining how machine learning and big data can become solutions for highly interdependent materials systems.

In 2016 she was awarded the Elite Research Prize for outstanding researchers under 45 years of international excellence by the Danish Ministry for Higher Education and Science. In 2016 CITA was awarded the "Innovative Academic Program Award of Excellence" by the prime conference within the field, ACADIA (Association for Computer Aided Design in Architecture).



Investigations in the Implementation of Localized Granular Synthesis Within Large-Scale Immersive Installations

Amirbahador Rostami & Mark-David Hosale,
York University, Toronto, Canada
Poul Holleman, *4DSOUND, Amsterdam, Netherlands*

1 Amatria http://philipbeesleyarchitect.com/sculptures/[Amatria]/index.php (last access October 16, 2018)

2 Aegis and Noosphere http://philipbeesleyarchitect.com/sculptures/ROM/index.php (last access October 16, 2018)

Image 1 Flow
by Amirbahador Rostami

Introduction

This paper provides an overview of approaches taken by the author, Amirbahador Rostami, as a studio assistant, co-supervised by Mark-David Hosale and Philip Beesley, to investigate the implementation of localized granular synthesis within large-scale immersive installations. This paper will discuss the implementation of localized audio in two large-scale sculptures, *Amatria* at the University of Indiana[1] and *Aegis* and *Noosphere* at the Royal Ontario Museum[2] in 2018. This discussion will also provide an overview of their microcontroller and audio design topology and discuss the pros and cons of centralized versus centralized audio distribution topologies.

Audio System Anatomy

Every component within an audio system carries a significant role in the production of clear, crisp Hi-Fi audio quality. In addition to cabling, power strategies, and amplification, one of the most important components is the loudspeaker. It was imperative for *Amatria*, *Aegis* and *Noosphere* to find a loudspeaker with the highest quality of sound production in relation to its footprint. Ideally the speaker would be small enough so that it could aesthetically blend in with the sculpture's environment, while also providing a full spectrum frequency range with a linear response.

In speaker design, acoustic properties of the material, enclosure design and even how the environment reacts has a huge impact on the response of the loudspeaker. When it comes to the material used for speakers, a solid composite is preferable as it will mitigate undesirable effects, such as unwanted resonance, or phase reinforcement, and cancellations in the speaker itself.[3] Placement is also a consideration, as external reflections in the room can cause phase distortions. Although most speaker boxes are rectilinear, it is better practice to avoid perfect cubes and move towards more water-drop designs for spherical enclosures. While the spherical model is more optimum, it is more challenging to precisely create the shape with solid and appropriate material.[4]

3 DIY Video & Audio https://www.diyaudioandvideo.com/Guide/BuildSpeaker/ (last access October 16, 2018)

4 Ibid.

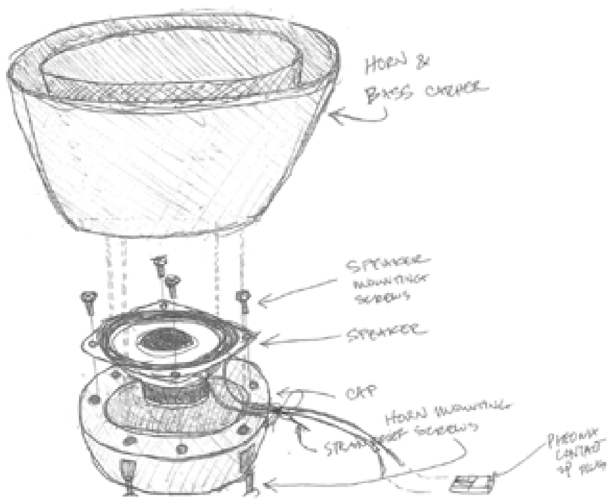


Image 2 Speaker Enclosure prototype for *Amatria*

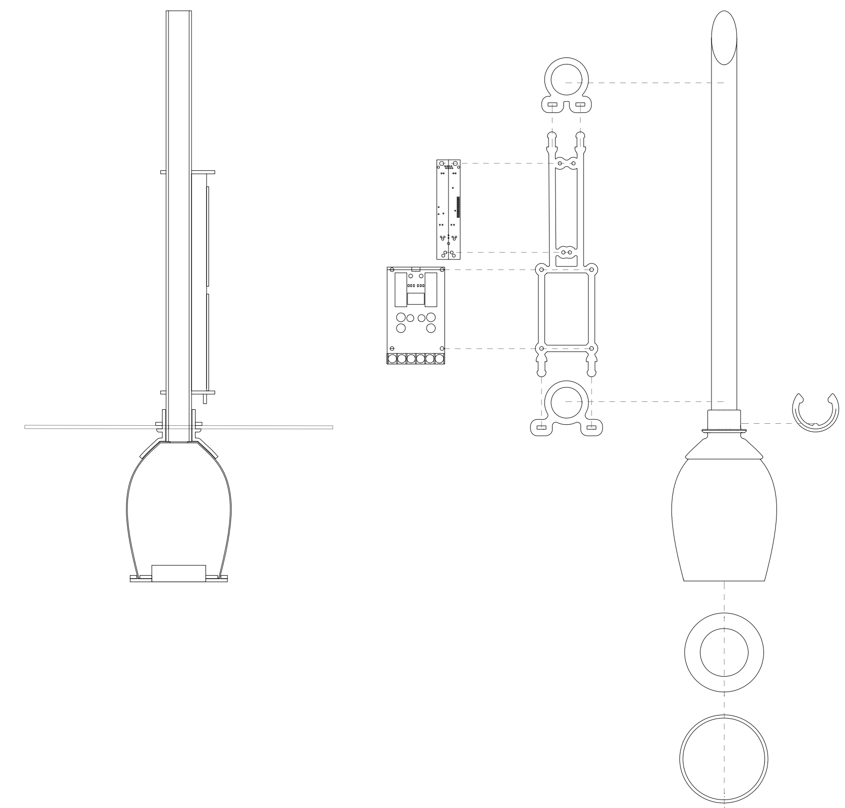


Image 3 Speaker Enclosure, exploded diagram, Designed by Mehreen Ali and Amirbahador Rostami for *Aegis* and *Noosphere* project

Image 2 illustrates a first generation of the enclosure design that was 3D printed for *Amatria*. This enclosure was based on sealed back design; however, it had a horn shaped cone at the front. This design resulted in higher directional dynamic range than usual, but also caused a lot of fluctuation in the overall frequency response. Another contributor to these fluctuations was the material used to print these components. 3D printed resin was not strong enough to contain the inner vibrations, causing a lot of out of phase signals.

Image 3 shows the final design for the speaker enclosure for *Aegis*/*Noosphere*. Designed by Mehreen Ali, with input from Amirbahador Rostami, the collaboration resulted in a ported spherical design inspired by the B&W 800 D3 model loudspeaker[5]. The speaker is semi-spherical in shape, with a porthole at the back that is tuned specifically to capture low-end frequencies ranges.

5 "800 Series Diamond" Bowers Wilkins http://www.bowers-wilkins.com/Speakers/Home_Audio/800_Series_Diamond

Localized Vs. Centralized System Topologies

One of the main characteristics in Philip Beesley's sculptures is the transformation of localized processes happening in smaller clusters leading into larger emergent phenomenon. This systematic approach is inspired by nature, where smaller, independent, and simpler components contribute to larger complex behaviours. This method of system design can afford modular design strategies where parts of the system can operate, update, and modulate independently. Unlike a centralized system, localized systems are more unpredictable, leading to more overhead in terms of managing complexity, especially in control and behavioural composition. In such systems effective communication is of high importance.

Centralized topologies create a uniform and, in some cases, more responsive experience, however, bottle necks in communications are still expected. There is a limited amount of data that can pass through a system as messages need to be sent from a central location.

Centralized systems and localized systems both have their advantages and disadvantages. To recreate a truly natural experience, there is a need for a certain degree of both strategies within a system. The integration of these kinds of systems needs to be handled with care. Communications and protocols in hybrid systems could lead to conflicts between localized behaviours and their centralized counterparts, resulting in message collisions and system malfunctions.

Granular Synthesis

Granular synthesis, also known as Granulation, is a synthesis technique that is a composition of many different grains of sound. Curtis Roads[6] describes a grain as short audio sample as short as 20 milliseconds with an amplitude determined by a fixed envelope. Each grain could independently have a source, pitch and amplitude. The grains are mixed together to create complex soundscapes. There are three main classes of granulators based on the type of audio source: Tapped Delay Line Granular Synthesis, Stored Sample Granular Synthesis and Synthetic Grain Granular Synthesis.[7]

6 Roads, Curtis. 1978. "Automated granular synthesis of sound." Computer Music Journal 2 no. 2: 61-62.

7 Ross Bencina, Implementing Real Time Granular Synthesis Synthesis

1. Tapped Delay Line Granular Synthesis: reads its grains from a delay line buffer. The delay and playback time create time stretching and time smearing effects on real-time input.
2. Stored Sample Granular Synthesis: uses pre-generated or sampled wave tables for grain source.
3. Synthetic Grain Granular Synthesis: makes use of other sound synthesis techniques such as oscillators or FM synthesis to create grains.

Each implementation method of Granulation comes with a set of pros and cons. It was determined that for these installations the most fitting option would be Stored Sample Granular Synthesis for two main reasons: one being it is the most efficient and flexible method which is optimum for microprocessors; and two, it gives the option of programming more intimate behaviors by allowing real-time recording of the surrounding environment.

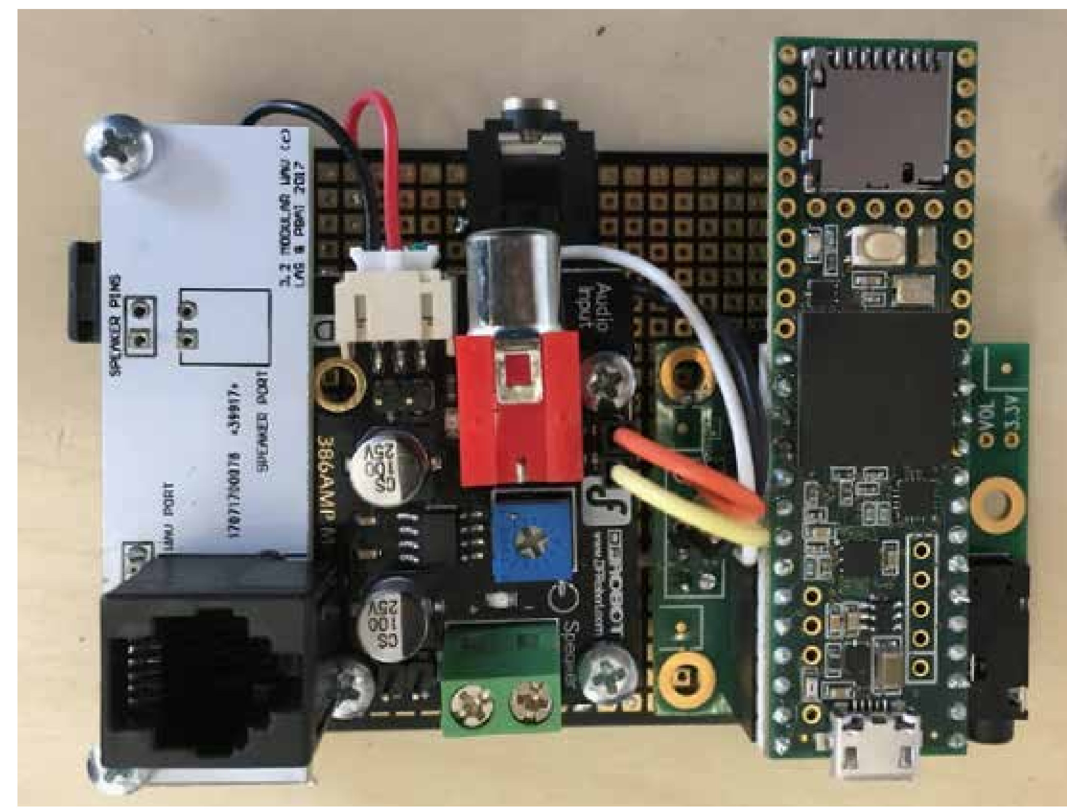
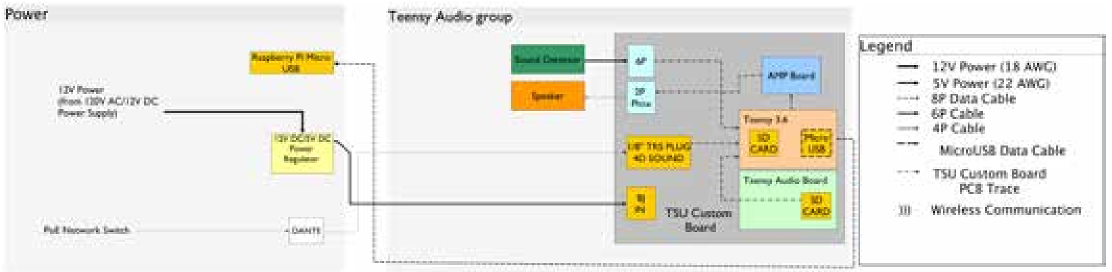
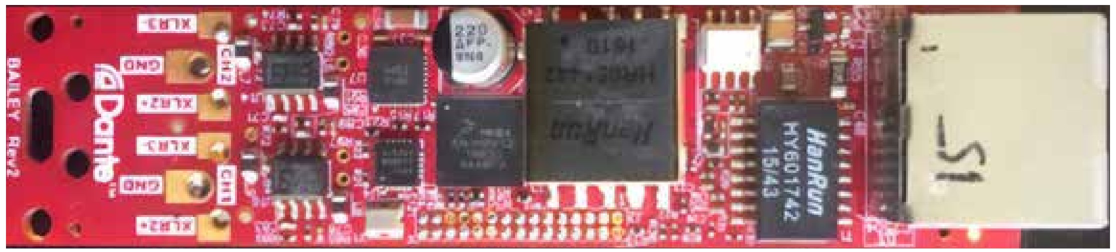


Image 4 Teensy Audio Microprocessor Units, *Amatria*





Implementation Strategies for Granular Synthesis

Image 5 Teeny Audio Unit Detailed Block Diagram, *Amatria*

Image 6 Dante Analogue Module, Bare PCB board, *Aegis* and *Noosphere*

The advantages of using a granular synthesis over other systems in Beesley's large-scale installations are both perceptual and aesthetic. In granular synthesis, the audio is comprised of clouds of short sounds making it easier to locate the audio source, which is important in large complex installations with many loudspeakers. Clear audio location allows participants to easily see the cause and effect relationships between kinetic motion, light activity, and sounds being generated. Aesthetically granular synthesis has a large parameter that allows for the creation of sounds ranging from natural to purely synthetic, with states in-between being quasi-organic, potentially alien, and familiar at the same time.

Audio processing is computationally expensive; hence, when using micro-controllers, the absence of computational power is much more noticeable. A promising tool in microcontroller-based audio production is the highly powerful Teensy platform.[8] In addition to its power, PJRC, the manufacturer of Teensy, has launched an open source audio library to facilitate their use for audio processing.[9]

8 "Teensy 36" PJRC https://www.pjrc.com/store/teensy36.html

9 "Teensy 3" PJRC https://www.pjrc.com/store/teensy3_audio.html

In *Amatria* a node was created to resemble a processing unit comprised of teensy 3.6, teensy audio shield1, an amplifying board2, and a microphone (*Image 4*). This set of hardware enabled the creation of a device capable of receiving one stereo input (or two mono inputs) and outputting stereo audio. The receiving inputs were set to two separate mono audio channels, one being a line-in input for external audio inputs, and the other as a microphone input.

The behavioral design in *Amatria* was selected to create a feedback system whereby the sculpture would record its surrounding environment and respond by repeating the recorded data in an altered form. The implementation of this concept was the first step in achieving real-time granular synthesis in the sculpture. Mapping every node to behave like a single grain, triggered by the localized sensors, would give out short bursts of recorded audio captured from the surrounding area as it rippled out from the moment of stimulation.

This approach seems more sympathetic with the overall system design logic; however, it does come with some drawbacks, as audio electronics are sensitive and complex. Every component within a large-scale installation requires extensive attention. The smallest miscalculation within the hardware design of the boards, including how every component is powered, how each audio processing node is connected to higher level processing units, and how external audio is routed to the board could lead to noise leaks, and/or ground hums. It would not take much noise in an audio system to render the entire system unusable.

While similar behavior was incorporated for *Aegis* and *Noosphere* project, the underlying system architecture was fundamentally different. The sculpture used a centralized system with each node being a dedicated simple audio output module sourced by a master laptop to generate all of the sound using a software environment called 4D Sound[10], an ambisonics software developed to create immersive auditory environments. This approach resulted in a much more simplified audio modules, tailored towards the goal of delivering Hi-Fi audio throughout the sculpture. Each unit consisted of a Dante analog module - an audio through Ethernet protocol with its own dedicated hardware to translate digital audio from the Ethernet input to analog audio signals. This technology was much easier to work with, due to its incredible noise free performance, while providing flexibility with the number of active audio channels. This radical shift in systems architecture

10 4DSOUND http://www.4dsound.net/

caused a change in the experience of the overall system. Stepping away from the audience's interaction and acoustic properties of the environment being the key determinations of the audio record/playback, the technology allowed a professional musical composition to be at the center of work that could played out when the viewer stimulated the sculpture.

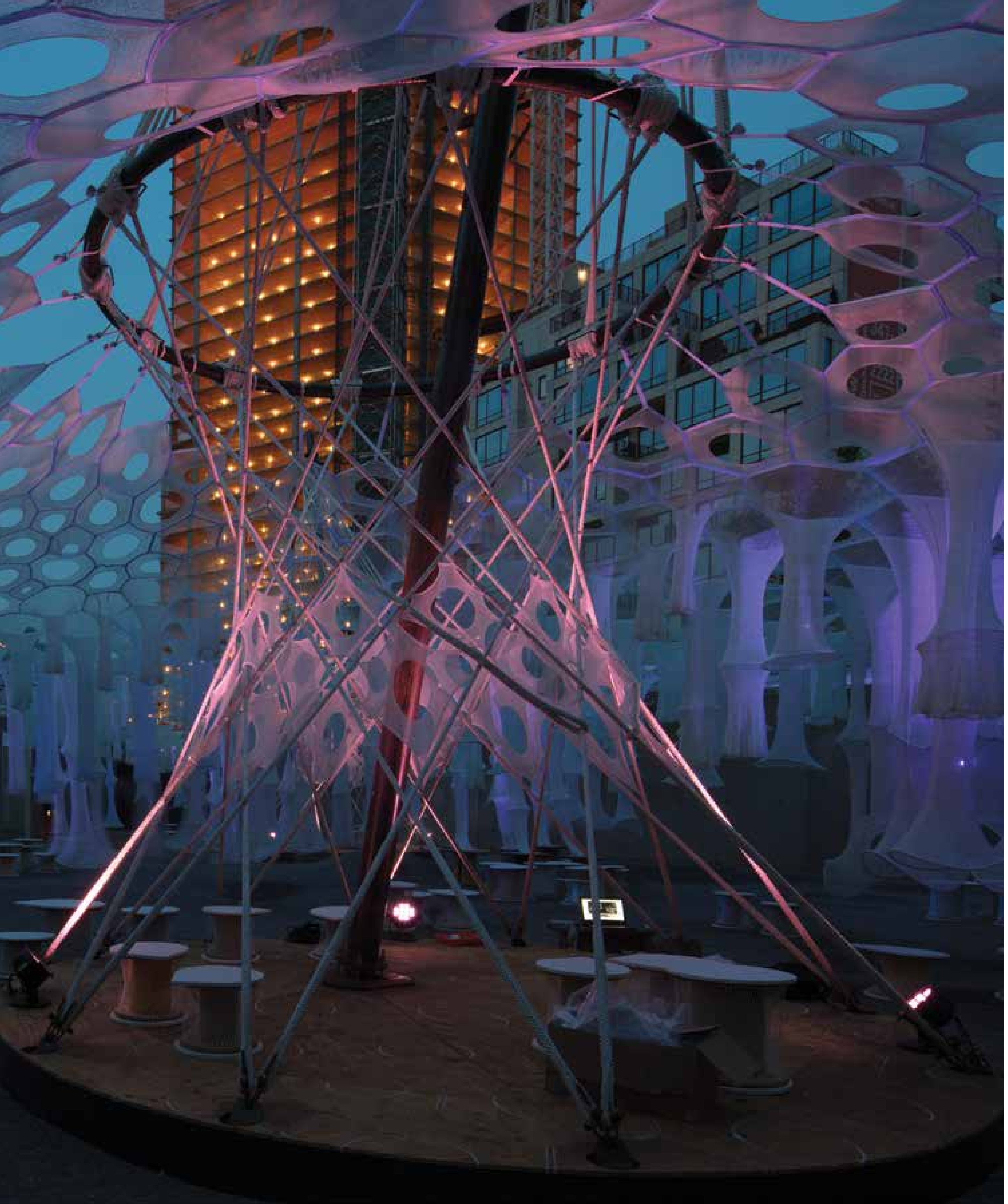
Conclusion

In conclusion, the paper explores the pros and cons of different approaches towards an appropriate implementation for an audio systems architecture. The answer is not binary. For the best outcome, a system should live with the prospect of modularity at its core while keeping a centralized hierarchy of command. For example, the node-based approach in *Amatria* illustrates generative audio processes happening at micro-controller level while a centralized command system keeps track of each node from the top. *Amatria* as a testbed has given the opportunity to implement underlying system to support high quality audio systems, paving the way for future updates to the granular engine at the heart of each node. Currently in research and development stages, the technology could lead to the creation of a stand-alone modular Hi-Fi audio system with more capabilities than a regular speaker. The outcome could provide artists, musicians and creative coders a new tool for musical expression or as parts of a larger system.

Amirbahador Rostami is an Undergraduate student currently studying Computational Arts at York University in Toronto, Canada. He has collaborated as a research and project assistant to Graham Wakefield on Conservation of Shadows (2017) and Worldmaking and Technolodge, a class collaboration with the University of Alicante, the Technical University of Delft, and York University (2017), mostly focusing on hardware design and production within installations; and Philip Beesley Architect Inc./Living Architecture Systems Group on Amatria, Aegis and Noosphere,focusing on audio systems development. Currently he is working within Dispersion-lab, an ambisonic research lab run by professor Doug Van Nort focusing on spatial sensing using Microsoft Kinects.

Mark-David Hosale is a computational artist and composer. He is an Associate Professor in Computational Arts at York University, Toronto, Ontario, Canada. He has lectured and taught internationally at institutions in Denmark, The Netherlands, Norway, Canada, and the United States. Mark-David's work explores the boundaries between the virtual and the physical world. His practice varies from performance (music and theatre) to public and gallery-based art. His solo and collaborative work has been exhibited internationally at the SIGGRAPH Art Gallery (2005), International Symposium on Electronic Art (ISEA 2006), BlikOpener Festival, Delft, The Netherlands (2010), the Dutch Electronic Art Festival (DEAF 2012), Biennale of Sidney (2012), Toronto's Nuit Blanche (2012), Art Souterrain, Montréal (2013), and a Collateral event at the Venice Biennale (2015), among others. He is co-editor of the anthology, Worldmaking as Techné: Participatory Art, Music, and Architecture (Riverside Architectural Press, 2018).

Poul Holleman is Co-Founder and Lead Software at 4DSOUND, and teaches Creative System Design at the Utrecht University of the Arts. His work revolves around interactive installations, instruments, and interface design. His particular field of expertise is spatial sound, the medium that he has been exploring with 4DSOUND since 2007. 4DSOUND develops custom systems for composition, performance, and interaction with spatial sound. An extensive software suite and specific hardware technology enable to create immersive sound experiences in a wide range of applications and contexts. 4DSOUND's collaborations are interdisciplinary; e.g. in electronic music, interactive sculpture, sound as medicine, theater, scientific research, and more. In 2015 4DSOUND established the Spatial Sound Institute in Budapest, Hungary, an R&D facility that hosts Artist Residencies to develop and present projects in spatial sound. Recent examples of other projects are: Biblioteca de Ruidos y Sonidos, Simona (Wageningen University), and diverse interactive AV installations with Nick Verstand.



Lumen

Jenny Sabin
Cornell University, Ithaca, USA

Image 1 *Lumen* at Night

This paper documents the computational design methods, digital fabrication strategies, and generative design process for *Lumen*, winner of MoMA & MoMA PS1's 2017 Young Architects Program. The project was installed in the courtyard at MoMA PS1 in Long Island City, New York, during the summer of 2017. Two lightweight 3D digitally knitted fabric canopy structures composed of responsive tubular and cellular components employ recycled textiles, photo-luminescent and solar active yarns that absorb and store UV energy, change color, and emit light. This environment offers spaces of respite, exchange, and engagement as a 150 x 75-foot misting system responds to visitors' proximity, activating fabric stalactites that produce a refreshing micro-climate. Families of robotically prototyped and woven recycled spool chairs provide seating throughout the courtyard. The canopies are digitally fabricated with over 1,000,000 yards of high tech responsive yarn and are supported by three 40+ foot tensegrity towers and the surrounding matrix of courtyard walls. Material responses to sunlight as well as physical participation are integral parts of our exploratory approach to the 2017 YAP brief. The project is mathematically generated through form-finding simulations informed by the sun, site, materials, program, and the material morphology of knitted cellular components. Resisting a biomimetic approach, *Lumen* employs an analogic design process where complex material behavior and processes are integrated with personal engagement and diverse programs. The comprehensive installation was designed by Jenny Sabin Studio and fabricated by Shima Seiki WHOLEGARMENT, Jacobsson Carruthers, and Dazian with structural engineering by Arup and lighting by Focus Lighting.

Introduction

Held in tension within the PS1 courtyard matrix of walls, *Lumen* applies insights and theories synthesized from 13 years of collaborative work across disciplines including from biology, materials science, mathematics, and engineering. *Lumen*, the largest knitted architectural installation ever erected and composed of over 1,000,000 yards of yarn, undertakes rigorous interdisciplinary experimentation to produce a multisensory environment that is full of delight, inspiring collective levity, play, and interaction as the structure and materials transform throughout the day and night. *Lumen* is a socially and environmentally responsive structure that adapts to the densities of bodies, heat, and sunlight.

The Young Architects Program (YAP) is an internationally acclaimed annual competition hosted by MoMA and MoMA PS1. The project brief calls for a comprehensive installation to serve as a backdrop to summer events held in the PS1 courtyard, including WarmUp. The winning project must provide shade, water, seating, and incorporate materials and design strategies that address sustainability and recycling. In addition to these requirements, the 2017 YAP brief encouraged projects to address the topics of transformation and materiality in architecture. Responding to the PS1 YAP brief as well as the highly constrained nature of the courtyard site, *Lumen* materializes ideas of performance and adaptation at all scales of the project and specifically through 3D seamless digitally knit and textile-based fabrication processes.

Background

Advances in weaving, knitting and braiding technologies have brought to surface responsive, high tech, and high performance composite fabrics. These products have historically infiltrated the aerospace, automobile, sports and marine industries, but architecture has not yet fully benefitted from these lightweight freeform surface structures. Textiles offer architecture a robust design process whereby computational techniques, pattern manipulation, pre-programmed material production and fabrication are explored as an interconnected design loop.[1].In the last decade, knitting has been explored for its highly dynamic and versatile material behavior in architecture. For example, Sean Ahlquist researches the potential of machine knitting to operate as an information mediating interface for responsive environments for children with Autism Spectrum Disorder.[2].Mette Ramsgaard Thomsen and Martin Tamke of CITA as well as Jane Scott of Leeds, develop simulations and prototypes to imbue material systems with variation, gradation, and the inherent properties of natural fibers for performance and sensing-based architectures.[3] Composite systems are also possible through the integration of tensile and reinforcement materials and application of pre-stress and resin impregnation.[4] Commencing with the myThread pavilion in 2012, Jenny Sabin and her team have explored generative design and digital fabrication in knit and woven structures through multi-sensory responsive environments.[5] Drawing synergies with this body of international research and perhaps most closely aligned with themes of responsivity and material performance as shared with the work of Ahlquist, CITA, and Scott, *Lumen* builds upon six years of design development at the intersections of knitted textiles, bio-inspired design, computation, and architecture.

Design Concept

The primary design parameters for *Lumen* include:

1. Site-based form-finding, including solar analysis to optimize for shade conditions
2. Generative form-finding methods based on physical and geometric constraints including material, tension forces, and site-based conditions
3. Explorations of the formal and structural potentials of textile-based structures and active tension systems at all scales of the project

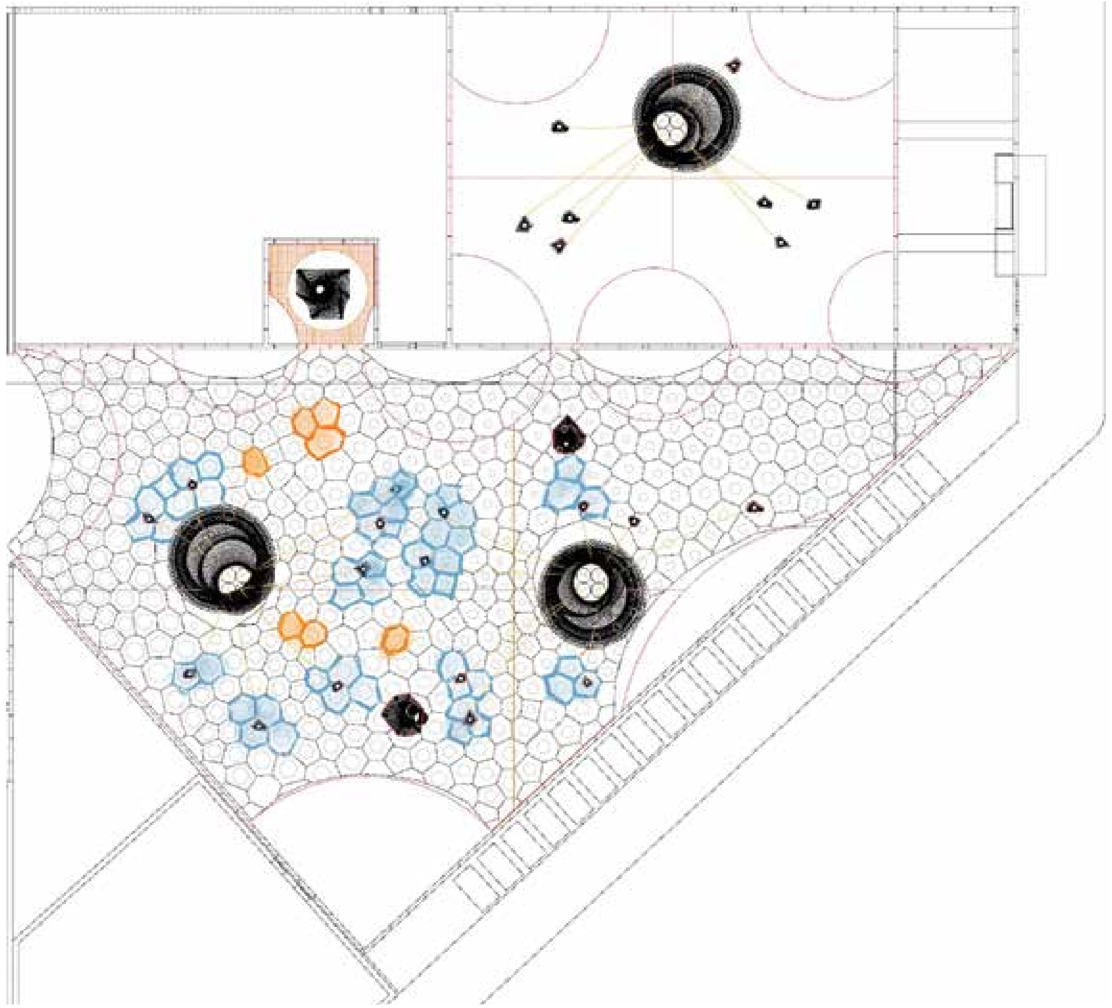
1 Sabin, Jenny and Jones, Peter Lloyd. 2017. LabStudio: Design Research Between Architecture and Biology. London & New York: Routledge Taylor and Francis.

2 Ahlquist, Sean. 2015. "Social Sensory Architectures: Articulating Textile Hybrid Structures for Multi-Sensory Responsiveness and Collaborative Play." ACADIA 2105: Computational Ecologies: Design in the Anthropocene [Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Cincinnati 19-25 October, 2015), pp. 263-273.

3 Thomsen, Mette Ramsgaard; Tamke, Martin; Karmon, Ayelet; Underwood, Jenny; Gengnagel, Christoph; Stranghoner, Natalie; Uhlemann, Jorg. 2016. "Knit as bespoke material practice for architecture." ACADIA // 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines [Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Ann Arbor 27-29 October, 2016, pp. 280-289.

4 Sharmin, Shahida; Ahlquist, Sean. 2016. "Knit Architecture: Exploration of Hybrid Textile Composites Through the Activation of Integrated Material Behavior." ACADIA // 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines [Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Ann Arbor 27-29 October, 2016, pp. 254-259.

5 Sabin, Jenny E. 2013. "myThread Pavilion: Generative Fabrication in Knitting Processes." ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)] Cambridge 24-26 October, 2013), pp. 347-354.



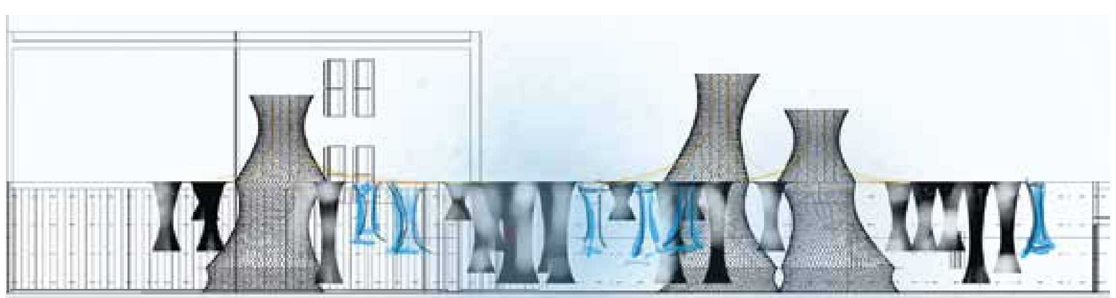


Image 2 Early concept drawings for the tower and canopy design.

Image 3 Early concept drawings, side view.

4. Materialization at a large scale of ongoing research on the relationships between biology, mathematics, engineering, adaptive architecture, and tensegrity
5. Integration of ideas of transformation, materiality, and human interaction into all aspects of the project and its varied weekly summer programs.

Overall, the project operates as an adaptive environment composed of two integrated grounds: the courtyards of MoMA PS1 and the upper canopy structures that are connected with the tensegrity towers and responsive conical knitted forms (*Images 1-4*). The following sections discuss the computational and technical aspects of each component of the project.

Methods

Canopy Design and Rationalization

The process of form-finding was based on particle spring systems and implemented via Rhinoceros, Grasshopper, and plugin Kangaroo developed by Daniel Piker *(Image 5)*. Initially, the NURBS (Non-uniform rational basis spline) surface was generated based on the constraints of the existing courtyard walls. The NURBS surface was then discretized into the mesh network (M0) with defined grid spacing and grid shape based on the circumference boundaries, optimal shade conditions, and constraints of the knitting fabrication process. Triangulation is used as the grid cell network. Nodes of the mesh triangular faces are considered as particles connected by edges which are calculated as elastic springs. We input mechanical properties of the knit

Image 4 Elevation proposal drawing; *Lumen* during WarmUp.

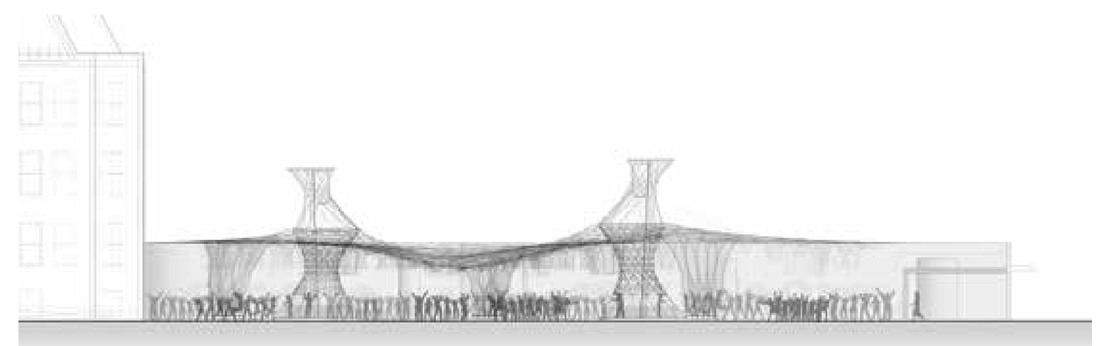


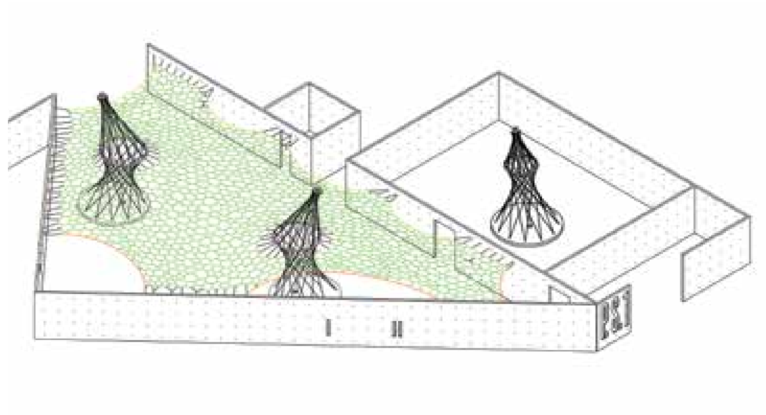
Image 5 *Lumen* proposal drawings and model with immersive VR experience.

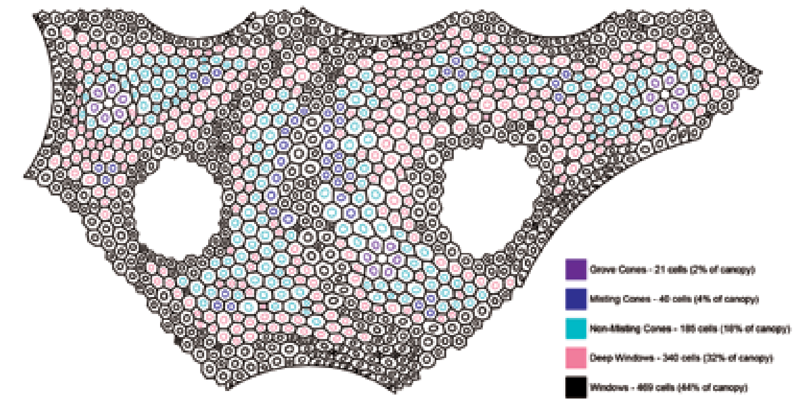
Image 6 The form-finding process of the canopies based on particle spring systems.

fabric—based on physical stress tests of swatches and data collected–by assigning axial stiffness and a damping coefficient to each edge of M0. The length of each edge is collected in a data tree and associative connections between each face are extracted from the mesh M0. We defined two main external force vectors: self-weight of the fabric canopy at each node and tension forces provided by the upward thrust of each of the three nodes where the steel tensegrity towers connect to the canopy structures. Boundary conditions are defined by assigning anchor points to nodes which are attached to the peripheral concrete walls of the MoMA PS1 courtyard. The spring-particle system visualized in M0 is not in equilibrium at the start of the simulation. The form of the two canopies are iteratively computed until each node within mesh M0 reaches the equilibrium position and if a solution exists. The form found mesh (M1) is then generated from the node coordinates and their connectivity. From mesh M1, we used the dual graph method to reconstruct a new mesh representation (M2), which is tessellated by polygonal cells. Each node in M2 is associated to a triangle of M1. A given edge in M2 represents a connectivity relationship of adjacent triangles in M1. The cells of mesh M2 are categorized into modular cell types based on their number of edges and dimension for the digital knit fabrication.

Once initial form-finding was complete, the stressed shape of the net was verified by Arup using custom finite element analysis software incorporating additional edge elements and the construction detailing of the anchorages. During this process, the cell pattern was optimized to limit the number of different cell sizes in the entire net.

The form-finding software package is a custom C# plug-in for Rhino that implements dynamic relaxation – a mathematical formulation for solving for equilibrium states of structures. The package relies on two parallel models: a structural finite element model that is used for finding the equilibrium shape





of the structure under loading, and a geometric Rhino model that is used to visualize and manipulate the geometry. The software allows the user to modify element lengths while the model is running, allowing the user to alter the geometry during analysis. Once run, the user can query element forces and anchorage reactions to allow for design of the structure and its connections *(Image 7)*.

The Rhino geometry from Jenny Sabin Studio was used to construct an analysis model and loading corresponding to the weight of the knit structure and wind pressure was applied. While running the model, element lengths were adjusted to regularize the net – minimizing the number of distinct cell sizes. Based on the model output, additional edge ropes were added to increase the tensile capacity of edges under high tension. The anchorages were then sized for the forces from the analysis.

Upon completing the canopy form-finding process, each cell is given a unique ID that follows each component through the entire fabrication and production process. Then, slack and stressed circumference data is organized into an excel spreadsheet to aid in knit fabrication planning. The canopies are composed of five cell types: 1. Grove Cones, the longest knitted cone type connecting the upper canopy with the ground; 2. Misting cones containing the misting nozzles and network; 3. Non-misting cones; 4. Deep windows or cells with a lip and extended knit shaping; 5. Windows or flat cells with no shaping *(Image 7)*.

Image 7 Force output display of net in custom software package by Arup.

Image 8 Cell and cone distribution within the large canopy in courtyard 1.

Technical files for the digital knit production in collaboration with Shima Seiki WHOLEGARMENT are then generated. Having worked with Shima Seiki for over 6 years, a streamlined process for knit production ensures accuracy of each 3D seamlessly knitted part and efficient fabrication planning. Technical specifications for each part are organized into a series of diagrams to be used to program the MACH2XS WHOLEGARMENT specialty Shima Seiki machine, which features 4 needlebeds. In a previous project, PolyThread for the Cooper Hewitt Design Triennial, Jenny Sabin Studio worked with Arup to implement an accurate stretch factor within the design and form-finding process of the pavilion. A matrix of knit swatches, each parameterized with incremental changes to circumference, material type, striation patterning, hole patterning, shaping for 3D seamless knit, and density, were subjected to variable loads to the point of failure, to determine an accurate overall stretch factor of 1.5. With *Lumen*, this was further prototyped and tested for a kit of parts ranging in size from XS to XL allowing for a more nuanced range of stretch factors from 1.4 to 1.8. This provided a minimum and maximum stretch factor relative to the desired fully tensioned state within the net canopy *(Images 8-10)*. The maximum relaxed circumference of each component due to the bed of the digital knitting machines is 48″ for bulk parts and 68″ for large specialty parts such as the Grove cones.

The knit materials include two high tech responsive yarns and a white fire-retardant synthetic 'fill' yarn. The photoluminescent fibers emit light after the absorption of photons (electromagnetic radiation) from the sun or UV lights. The photons within the fiber are excited and then relax and other photons

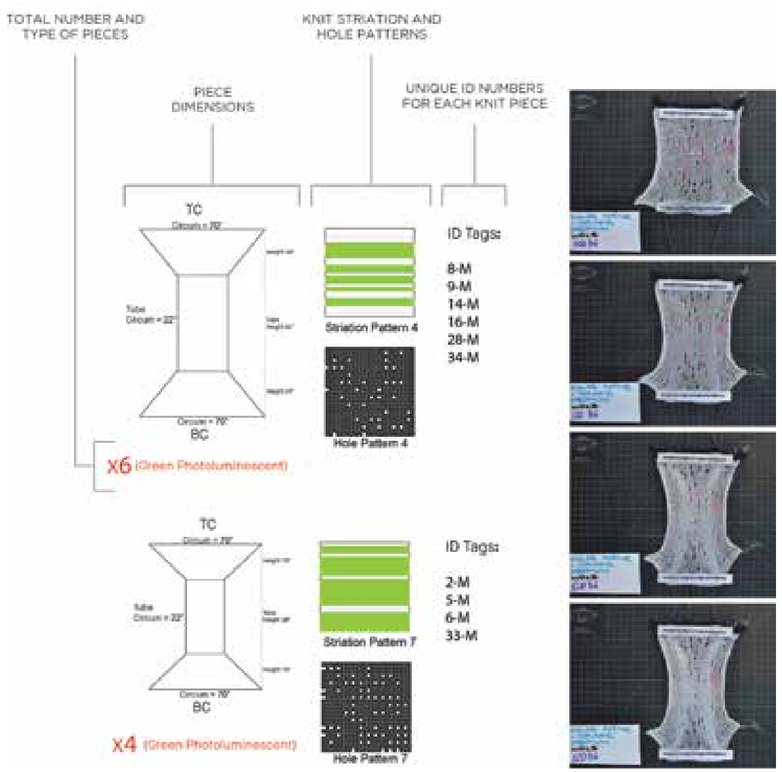


Image 9 Previous tests for stretch factor under relaxed and stretched load conditions with variable knit parameters.

may be re-radiated, causing the glowing effect across the canopy structures. The solar active threads change color in the presence of the sun. The fibers undergo molecular excitation transition where the molecules in the presence of the sun shift into a range within the electromagnetic spectrum that's visible to the human eye. At a molecular scale, small crystals within the fiber reveal their colors in the presence of the sun *(Images 10, 11)*.

Tower Design and Rationalization

Three steel and polyester rope tensegrity towers were installed to lift the canopy structures at strategic nodes. Each of the towers is comprised of five primary elements: a central steel mast, a suspended steel ring at the mid-height of the towers, a steel base built up from wide flange beams and channels, custom CNC flooring for the base, and 48, 1-in diameter custom Cortland and polyester 12-strand ropes. Each of the polyester ropes winds 120 degrees around the circumference tracing a hyperboloid of one sheet above and below the central flying ring. The towers have a single plane of symmetry about the mast; the bottom of the mast is offset from the center point of the base and leans back across the base *(Image 12)*. While comprised of the same primary elements, each of the towers is geometrically unique having varying heights and angles of lean. The base of the towers works in flexure, resolving the tension of the ropes and the compression of the mast through a series of spokes that connect from each of the rope anchor points to the base of the mast. A compression ring around the outside edge braces the ends of the spokes against each other. Overturning under lateral loads is resisted by filling the base with gravel ballast.

The design of the towers, in particular their realization as tensegrity towers, arose out of their relationship with the rest of the installation. The tower's primary purpose is to support two larger tensile canopies that spanned the

Image 10 Prototypes produced for Lumen to achieve a more nuanced range of stretch factors ranging in size from XS to XL.

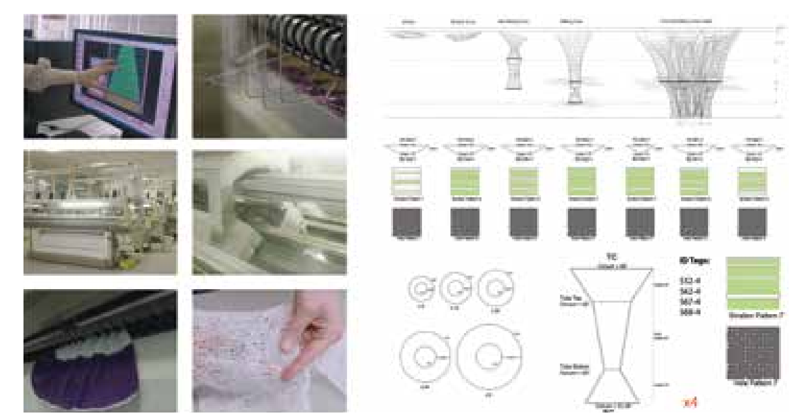


Image 11 Knit fabrication at Shima Seiki (left) and technical specifications for 3D seamless digital knitting of a sampling of Grove Cones and Deep windows.

courtyards at PS1. The tensile net was connected to and tensioned against the tower's flying ring; creating a node in the net with the tower that served as a space to be programmed and occupied by the installation's visitors. The towers were originally conceived as woven structures that create spatial, structural, and inhabitable connections between the ground and the upper canopies. They were intended to emulate the nature and form of the hanging knitted cones within the canopy and the dynamic textile-based architecture of the entire project *(Image 14)*. Early conversations between Sabin and Binkley about the materialization and structure of the towers oscillated between actual woven structures such as the 'hollow ropes' of Robert Le Ricolais and rigidly framed structures similar to Shukhov's towers.[6] As the entire project evolved, we realized that there was an opportunity to construct the towers as tensegrity structures, to literally weave with forces; playing off the tensile character and performance of the net canopies that they supported. The vertical pretension that stabilized the towers added a third dimension to the overall envelope of forces that shaped the installation, thus bringing ideas of performance and adaptation to all scales of the project. Analysis of the tower and the base were performed separately to allow the models to converge more quickly. In the tower analysis model, the mast and ropes were all pinned at the base and these reactions were applied as loads in the base model to determine the forces in the base members and verify the stability of the base *(Image 13)*.

Image 12 Solar active fibers changing color due to UV activation (left) and photoluminescent fibers glowing at night (right).

6 Le Ricolais, Robert. 1973. "Things Themselves are Lying, and so are their Images", VIA 2: 81-109.

Beckh, M. 2015. "Hyperbolic Structures, Shukhov's lattice towers – forerunners of modern lightweight construction." DETAIL Edition (English), Oxford, John Wiley & Sons, Ltd.

Image 13 Rendering of photoluminescent fibers activated; view of canopy looking up.

The detailing of the towers is designed around the erection of each tower. The towers are designed to have both coarse and fine adjustments to both tension the entire tower and accommodate fabrication tolerance of the ropes. The limited budget for the project drove unique detailing such as a sliding mast head tensioned with threaded rods and U-bolts instead of turnbuckles to achieve fine adjustment of the ropes.

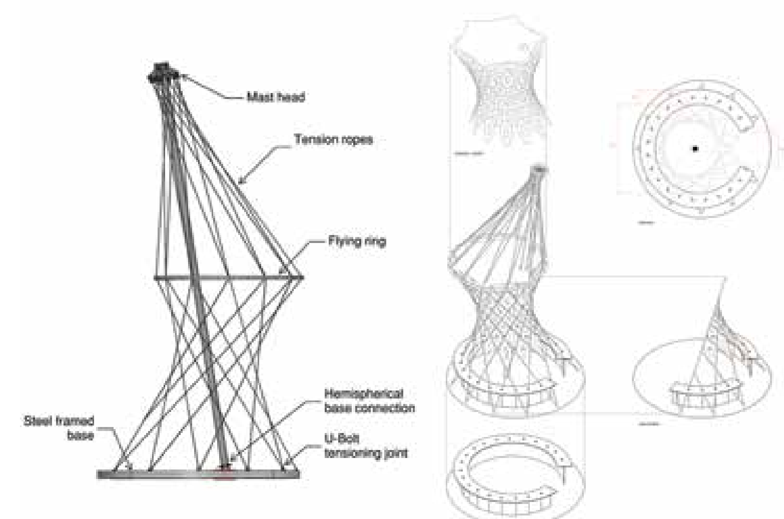


Image 14 Tower elevation and components.

Misting System and Spool Stools

The project included an interactive misting system capable of responding to human proximity, which informed the rhythm and frequency of the misting *(Image 16)*. The interactive misting system consists of three key modules: the electronic system, embedded control program, and solenoid valves. The electronic system is built upon sensors, actuators and a microcontroller. To detect human occupancy, the use of a PIR motion sensor was incorporated. The PIR motion sensor has two sets of infrared sensitive detectors. When visitors approach the sensor, one of the detectors is intercepted, causing a positive differential change between the two halves. When visitors leave the sensing area, a negative differential is generated. The change pulse is then streamed and filtered by the embedded program loaded on the micro-controller. The program corrects for error and noise in the raw sensor data and translates sensor data into three proximity-based situations, "visitor is approaching," "no visitor," and "visitor is leaving." The "visitor is approaching" event activates the actuator, a 12v high-pressure solenoid valve that controls the water pressure of the network of misters within the sensing zone.

The continually activated valve will increase the pressure of the misters resulting in a continuous misting spray around the visitors. If visitors leave the area or no visitor is detected, the solenoid valve will recover its programmed basic motion pattern, switching between on and off at the

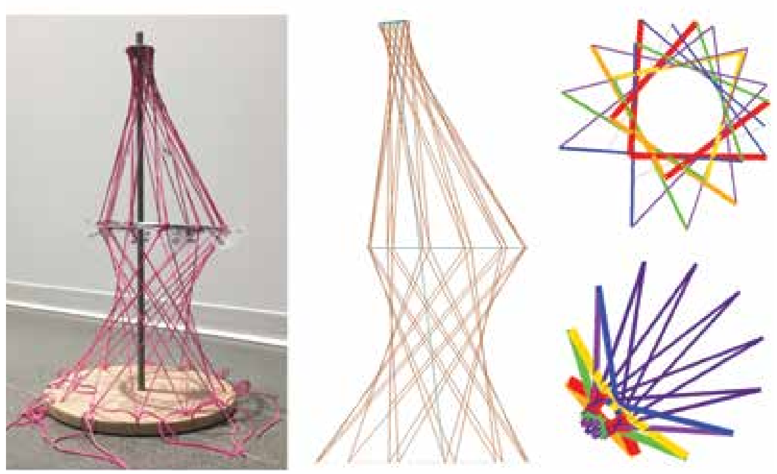


Image 15 Scale model (left); analysis model (middle); variation in rope tensions at top and bottom (right).

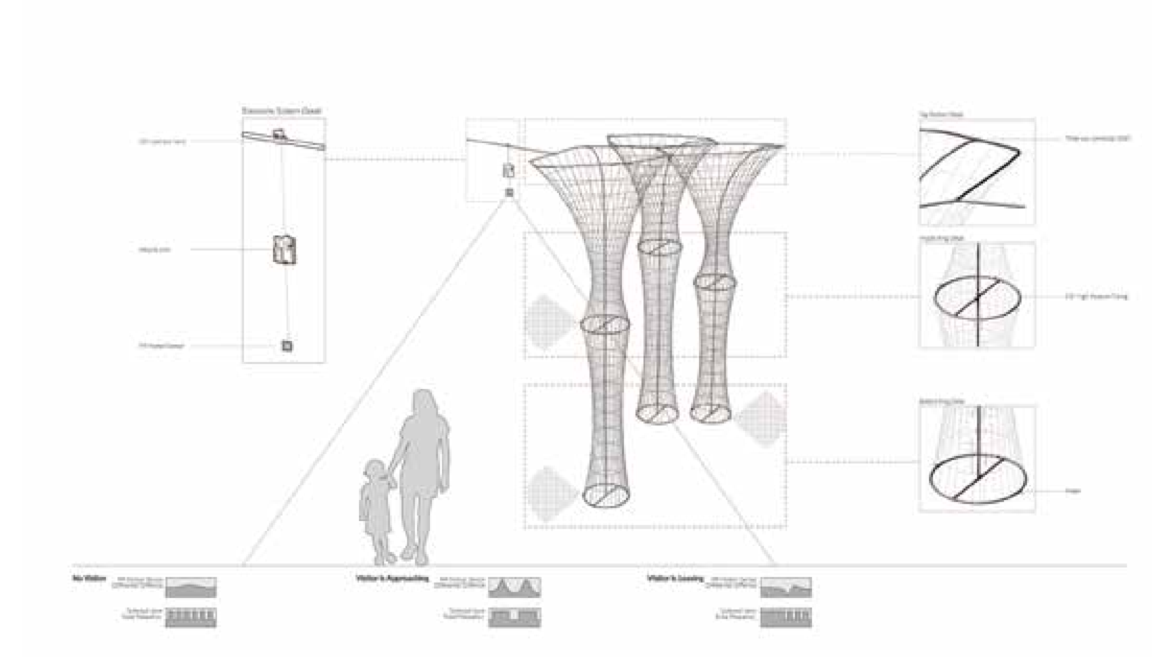


Image 16 Diagram of interactive misting system.

frequency of 15 seconds per cycle which creates a breathing-like rhythmic misting effect. The combination of electronic components and embedded control programs within the misting network generates an immersive and responsive microclimate within *Lumen* that adapts to human proximity.

Seating was provided by 100 recycled spool stools approximately two feet tall and two feet wide. Locally sourced and recycled from electrical cable manufacturers, the large spools are deconstructed into parts. Grooves are milled into the edges of the spools by a CNC to allow photoluminescent micro-cord to be wrapped around each spool. We augmented our software, RoboSense 1.0, to easily add actuators and sensors to the environment to control the density and tension of the cord wrapping the stool by an ABB IRB 4600 robot (Moorman et al). Based on the needs of the stool-winding for the project, we developed a custom winding end effector and four basic nodes: design nodes for creating the movement toolpath for the industrial robot, analysis node for analyzing feedback data, simulation node for planning and visualizing the robot motion, and fabrication node for executing the cord winding routine. We designed a custom end-effector with a tension sensor and a control mechanism to maintain a consistent tension range as micro-cord is deposited around the spool stool for the first spool prototypes, similar in approach and methodology as the ICD's recent filament wound research projects *(Image 17)*.[7]

7 Yunis, Leyla; Ond_ej Kyjánek; Dörstelmann, Moritz; Prado, Marshall; Schwinn, Tobias; and Menges, Achim. 2014. "Bio-inspired and fabrication-informed design strategies for modular fibrous structures in architecture." Thompson, Emine Mine (ed.), Fusion - Proceedings of the 32nd eCAADe Conference - Volume 1, Department of Architecture and Built Environment, Faculty of Engineering and Environment, Newcastle upon Tyne, England, UK, 10-12 September 2014, pp. 423-432.

Image 17 Recycled spool stool robotic fabrication and components; on site installed.

Results and Discussion

Site as Generator

Situated in the context of Long Island City, NY, the significant exterior boundaries of MoMA PS1's courtyard are formed by the acute intersection of Jackson Ave. and 46th Ave. Although limited due to contextual and size restraints, the installation of *Lumen* relied significantly on the existing conditions of the site as assets for the project. The site served as both a structural component of the project and a physical benchmark for locating critical points in the field. Due to the unique nature of the existing concrete courtyard walls having consistently spaced tie-rod holes left exposed, these elements were seen as both a structural opportunity for anchoring the perimeter of the canopy and a condition that offered flexibility in defining the overall surface configuration of the canopy. *Lumen* inherently has a large tolerance due to the nature of materials used to construct the canopy and their characteristics. However, to reduce the amount of deviation between the digital modeling process and physical installation, field measurements were taken to reconstruct an accurate digital model of the site conditions. These measurements provided not only an extremely accurate representation of the site constraints, but also critical benchmark points that were then used in the field for locating physical components of the project.

Installation Sequence and Results

The installation sequence can be divided into three categories: (1) steel tower fabrication and assembly, (2) periphery structure and (3) canopy. Due to the dynamic nature of the project and condensed timeline, the installation required teams to be working simultaneously on different portions of the project and in different areas of the courtyard.

Towers

The two main structural towers consisted in total of 8400 lbs. of steel used for 18 ft. diameter bases and two 46'0" tall asymmetrical steel masts held in compression by 1000 ft. of rope each. Using the northernmost concrete wall on the site as a benchmark, the center points of the towers and their orientation were located within the site. Once located, the towers were erected onsite in three stages. Beginning with the base, wide flange beams were welded into a radial configuration using a center piece that was prefabricated offsite as a guide. The center piece housed the hemispherical bearing that served as the base of the mast and allowed it to rotate to the correct angle depending on the state of stress in the ropes. Once finished with the base, a temporary scaffolding, which resembled a large-scale easel, was built to support the masts at the proper angle relative to the bases. Each mast was erected to rest on its hemispherical bearing. Prior to hoisting the mast into place, a separate steel ring constructed of 4-inch pipe was placed around the mast, which hosts both the structural ropes for the tower and connection points for the canopy *(Image 19)*.

After constructing the base, temporary scaffolding and mast, a series of 48 ropes were woven around the steel ring and were connected systematically to the top and bottom of the tower creating a stable condition with the ropes in tension and tower mast in compression. To reduce slack and loss of tension as a result of constructional stretch in the ropes, countermeasures

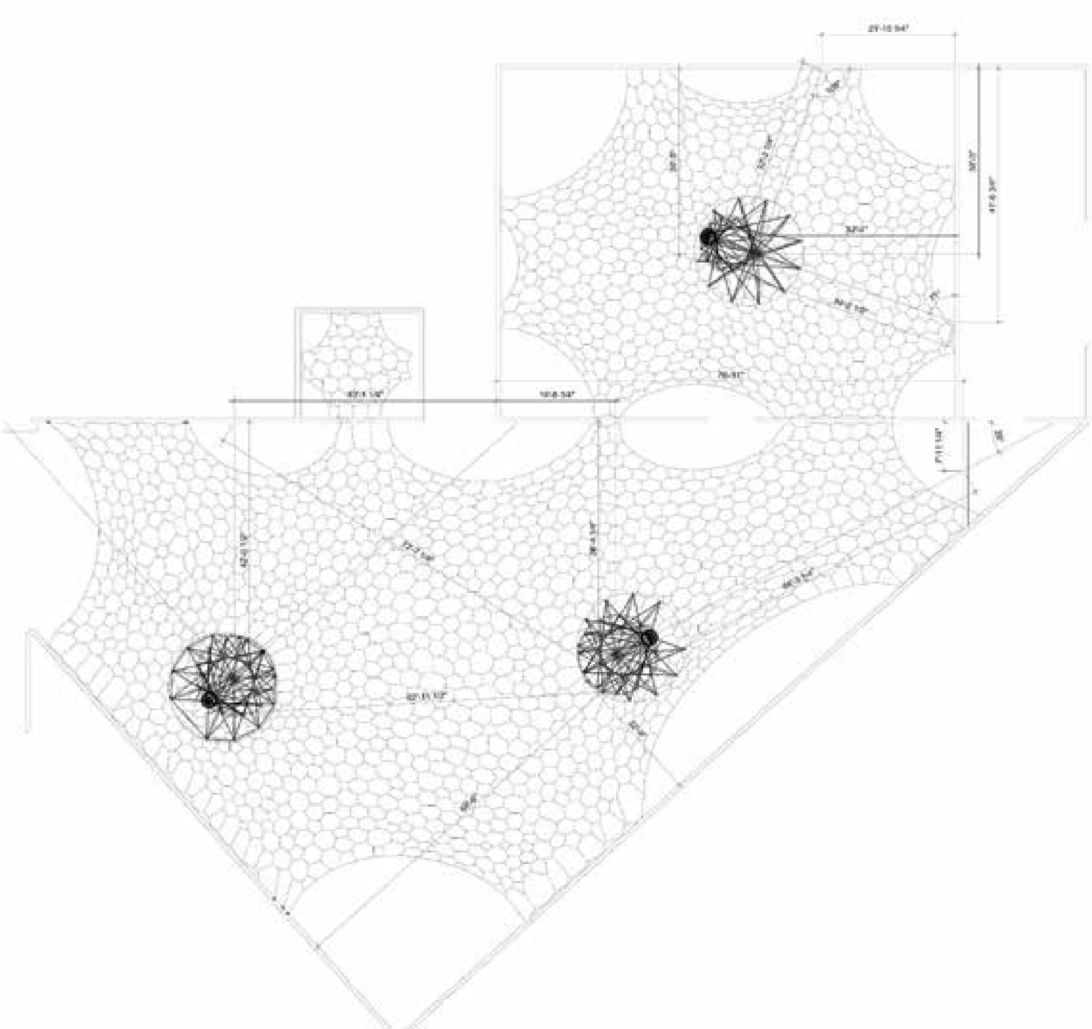


Image 18 Lumen final plan drawing.

were designed to adjust and re-tension the ropes. Fine adjustments to the top and bottom of the tower was achieved using threaded U-bolts that allowed each individual rope to be adjusted in order to achieve the correct distribution of tension across the entire structure. Due to the asymmetry of the tower, each rope had to be individually adjusted to achieve the correct geometry and a reasonably uniform distribution of prestress. In addition to each point having the ability to be fine-tuned, the top component of the

mast was able to telescope vertically as an entire unit allowing for larger global adjustments.

Canopy and Perimeter Connections

The two canopy structures consist of 1000+ digitally knit cellular components and nylon webbing sewn together to create two uninterrupted surfaces. Due to the variety of cell types, each part was given a distinct ID label that was associated with the component part throughout the entire fabrication process. The ID labels also played an integral part in coordinating the assembly of these individual cells with their location in the entire canopy, bespoke pattern, and circumference. To reduce lag time and optimize the fabrication of the entire canopy, knit cells were sent in batches (beginning with cell IDs on one side of the canopy and moving across the entire surface) to the fabric finisher, Dazian, a leader in creative fabric production and fabrication. This allowed Dazian to begin fabrication well in advance of receiving all 586 individual pieces. While each unique ID tag allowed for a general association to be made between adjacent parts, a huge, 150ft x 75ft tiled drawing of the canopy was produced and plotted at 1:1 scale to assist the sewing team with precise measurements for each edge of the individual cells and to reduce the possibility of human error in miscalculation of total circumference. This process led to a greater efficiency in speed of sewing and a reduction in wasted material (nylon webbing) due to miscalculation *(Image 20)*.

The primary tension forces are taken through the net composed of nylon webbing and not the knit surface, thus the seam detail and type of webbing

Image 19. Tower and canopy installation.

are crucial. Two widths of mill spec nylon webbing are used, 1.5" for each component and 2" at the scallop edges of the canopy where the tension forces are greatest. Six years of research and design through previous projects have produced a highly tested and reliable seam detail innovated by Jenny Sabin Studio and Dazian *(Image 21)*.

Once sewn together, the ID tags remained on the individual knit cells to aid with orientation during installation. The unpacking of the canopy on site was done incrementally due to its size and delicacy of the material. This strategy also allowed the canopy to be hoisted and attached in segments, thus avoiding excessive contact with the ground and risk of damaging the finished surface. The main canopy was designed with two zippers, which allowed for the surface to wrap around the tower structures like a skirt instead of requiring the surface to be raised to the top of the towers and then lowered down into place (*Images 22, 23*).

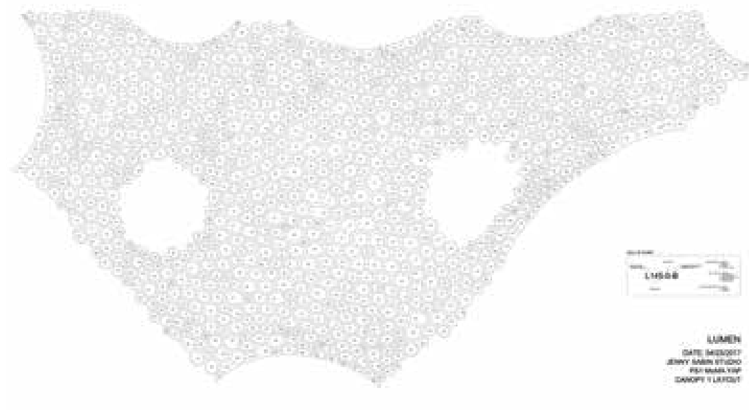
Located along all three walls facing the main courtyard, a series of metal brackets and woven rope were strategically attached through existing tie-rod holes at 12'0" above the ground. The metal brackets served as anchor points for the scalloped nylon webbing edges of the canopy, which carried the majority of stress and tension applied by the canopy. Once completely installed in a slack state, the scalloped edges of the canopy were tightened incrementally while moving in a star like pattern to assure stresses were

Image 20 Main canopy and tower 2 installed with misting system and spool stools placed.

Image 21 Canopy edge connections and details at the courtyard walls.

being distributed evenly across the entire canopy. An assembly of tubular webbing, breakaway connectors and ratchet connections with 3,000 lb working load capacity are used at the scalloped edges and shackles, breakaway connectors, and cam lock buckles with 500 lb working load capacity are used at the secondary anchor connections *(Image 22)*. Following the tensioning of the scalloped edges with ratchet connections along the perimeter, the secondary anchor points were then tightened to secure the entity of the canopy's edge and control shaping in localized areas of the canopy. At the tower rings, cam-lock buckles were connected to the rings with nylon webbing loops and the net cells tensioned against them Repeating this process of continually tensioning the primary anchor points and following with the secondary anchor points was carried out until the canopy reached its final state of stability *(Image 23)*.

Lastly, the misting network was installed along the edge perimeter of the nylon webbing network, running on top of the main canopy and hidden by the edge detailing. Feeder lines drop from the network to the misting cones and rings of misters provide a dual function of tensioning the cone and delivering mist. Working closely with Focus Lighting, a lighting system was installed and programmed to accentuate and extend the activation and responsivity of the photoluminescent and solar active fiber, especially during the evening hours and WarmUp events. Lastly, the 100 spool stools were delivered having been pre-fabricated in the Sabin Lab and arranged on site.



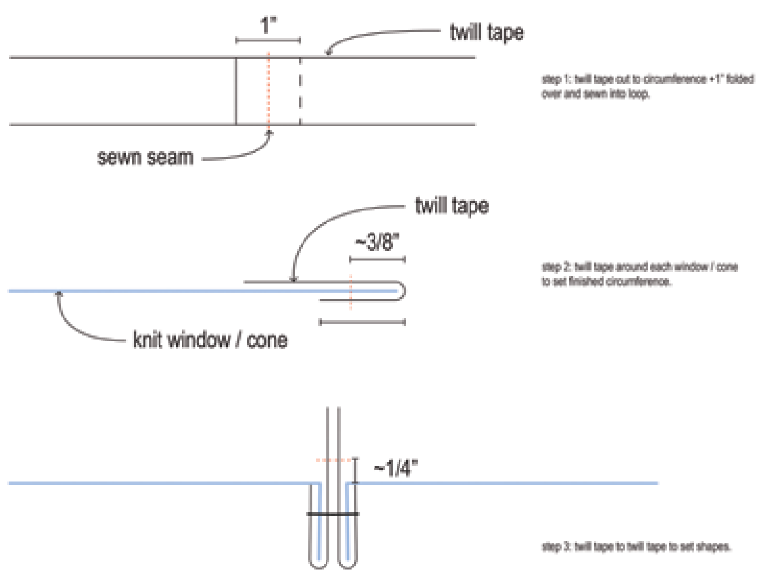


Image 22 Nylon webbing cell edge detail for each sewn part.

Image 23 1:1 Cell pattern drawing for finishing and sewing the nylon net and edge webbing (left) and sewing of each individual cell to its neighbor (right).

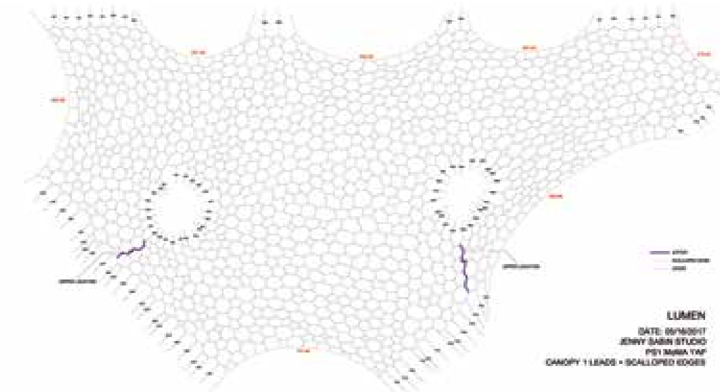


Image 24 Edge detailing for the scalloped nylon webbing (red), tails (blue), and zipper locations (pink) for the main canopy.

Images 25 & 26 Perimeter edge details and unfolding and preparing the canopy for installation; solar active yarns revealing their colors in the presence of the sun.

Conclusion

Drawing synergies with current work at the intersection of computation, knit structures, and textile architecture, *Lumen* celebrates and shares topical themes of responsivity, variation, and material performance as can also be seen in the work by Ahlquist, CITA, and Scott. Having designed, fabricated, and built five previous projects featuring responsive structural fabrics composed of individually digitally knit cellular components, we felt confident that the material system was ready to be pushed to the scale of the MoMA PS1 courtyards and an outdoor environment enjoyed by thousands

of people *(Images 26, 27)*. Although *Lumen* was not designed or engineered for permanent installation, the project weathered extreme summer rain and flooding and the most well-attended WarmUp events on record at MoMA PS1. Together with Arup, we were able to move from a pavilion scale and structure to a large outdoor tensile installation capable of housing over 7,000 people. Although locally delicate, *Lumen's* spatial and material systems are inherently variable, adaptive, globally strong, and interactive and are poised to be designed and assembled as permanent inhabitable structures. Currently, we are researching and developing three areas that will allow permanent installation of future projects like *Lumen*, including: 1.) Finer scale manipulation of the responsive yarn to create tunable actuators within the programmed material; 2.) coatings of the yarn to protect larger knitted components from extreme weather conditions such as heat, wind, and sand storms in a desert climate; and 3.) stress tests with larger gauge yarn (increased to 1500 Denier) to generate more robust parts. Permanent commissions in Abu Dhabi, Portland, and New York are allowing for these new refinements and future installments.

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Image 27 Lumen during WarmUp with misting system and responsive fibers activated.

Image 28 Lumen fully installed and tensioned.

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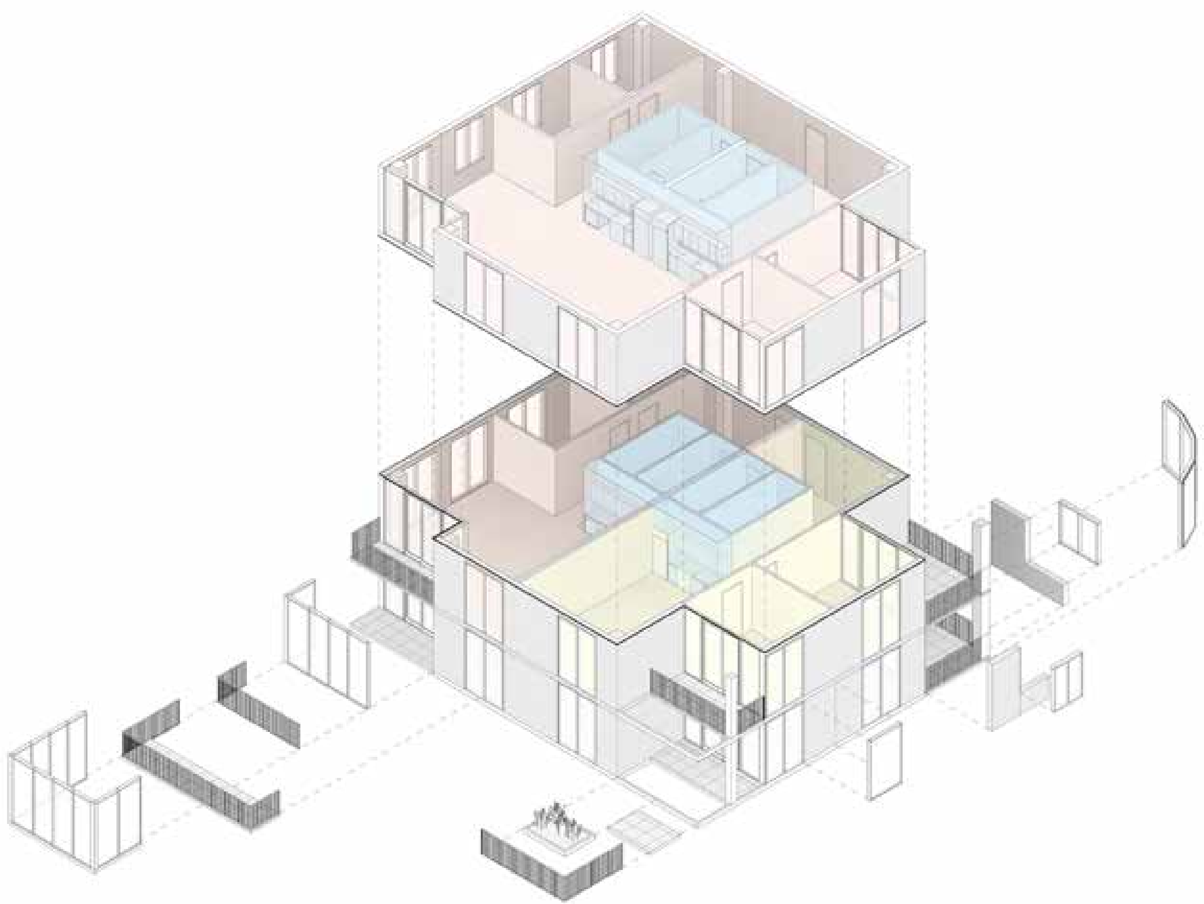
Image 29 7,000 visitors enjoying Lumen and WarmUp at MoMA PS1.

Image 30 Lumen with canopies glowing. Lumen was in the top-10 most Instragrammed art projects globally for 2017.

Jenny E. Sabin is an architectural designer whose work is at the forefront of a new direction for 21st century architectural practice — one that investigates the intersections of architecture and science and applies insights and theories from biology and mathematics to the design of material structures. Sabin is the Arthur L. and Isabel B. Wiesenberger Professor in Architecture and Director of Graduate Studies in the Department of Architecture at Cornell University where she established a new advanced research degree in Matter Design Computation. She is principal of Jenny Sabin Studio, an experimental architectural design studio based in Ithaca and Director of the Sabin Lab at Cornell AAP. Sabin holds degrees in ceramics and interdisciplinary visual art from the University of Washington and a master of architecture from the University of Pennsylvania. She was awarded a Pew Fellowship in the Arts 2010 and was named a USA Knight Fellow in Architecture. In 2014, she was awarded the prestigious Architectural League Prize. Her work has been exhibited internationally including at the FRAC Centre, Cooper Hewitt Design Triennial, and most recently as part of Imprimer Le Monde at the Pompidou. Her book LabStudio: Design Research Between Architecture and Biology co-authored with Peter Lloyd Jones was published in 2017. Last year, Sabin won MoMA & MoMA PS1's Young Architects Program with her submission, *Lumen*.



Adaptability in Residential Adaptive Reuse

Sheida Shadi, Carl T. Haas, Philip Beesley
University of Waterloo, Canada

Image 1 Interchangeability of components, layering of building elements, designing for disassembly and expandable interior spaces. Based on the Superlofts by Marc Koehler Architects, Next 21 by Yositika Utida and residential development projects by JvN Developments Inc.

This research complements existing LASG focuses on experimental constructional systems, especially relating to the LASG Scaffolds stream. Finding feasible and applicable strategies for improving resilience and empowering adaptability in the built environment are the objectives of this research and are aligned with the long-term objectives of the LASG. Residential adaptive reuse and ideas of adaptability integrated within the refurbishment of existing residential buildings will be examined in this paper. The potential for existing buildings to be extended and renewed by repurposing and adjusting outer layers of envelope and balconies will be addressed. Within the Scaffolds stream, a main focus is on the constructional systems and spatial qualities of envelopes and skeleton systems that will be needed to support dynamic movement and programming with multiple functions. This research contributes to a practical base that can provide opportunities to implement LASG systems at full public scale.

Introduction

Tall concrete structures have prevailed as the main type of multi-family housing construction in Canada since the 1950s. While environmental performance and contextual relevance in aging multi-family housing are well-known issues, balcony degradation specifically contributes to high levels of structural failures, low energy performance, and inefficient use.[1] Some efforts have been undertaken to improve environmental performance and contextual relevance of existing towers including balcony reconstruction, recladding, system upgrades, and interior renovations.[2] While these strategies are necessary for addressing existing challenges, incorporating systems that are able to accommodate future adaptive reuse can help anticipate density, and social and technological changes.[3] It is expected that integrating wholistic adaptive reuse strategies that can address long-term adaptability will have an impact on the longevity, sustainability and resilience of residential towers.[4]

Context

From the 1950s onwards, planning and cultural changes have varied the form and context of the concrete residential towers, from towers-in-the-park to urban point towers and tower-podiums. Changes in ownership models have evolved from predominantly rental buildings in mid-20th century to an individual condominium ownership market in the past two decades, with an increase in rental tower construction in recent years.[5] Varied ownership models have greatly affected the demographics that these tall residential buildings attract over time. Building envelope technology and market demands have also influenced the materiality and aesthetics of residential towers.

While changing demographics and occupant structures are a characteristic of multi-family residential neighbourhoods, they are inherently rigid in use and structure, and are therefore prone to obsolescence.[6] Building obsolescence is directly related to the shortcomings of designing prescribed housing arrangements and their limited life cycles, causing about 60% of all building demolitions in North America.[7] Designing buildings that meet the needs of one specific type of household and respond to short-term economic needs instead of being able to react to changing demands of the occupant and the future market[8] is a driver of this obsolescence. Building

1 Ross, B.E., Chen, D.A., Conejos, S. & Khademi, A. 2016, "Enabling Adaptable Buildings: Results of a Preliminary Expert Survey", Procedia Engineering, 145, no. Complete, pp. 420-427.

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3 Lifschutz, A. 2017, "Long Life, Loose Fit, Low Energy", Architectural Design, 87, no. 5, pp. 6-17.

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7 Ross et al, 2016.

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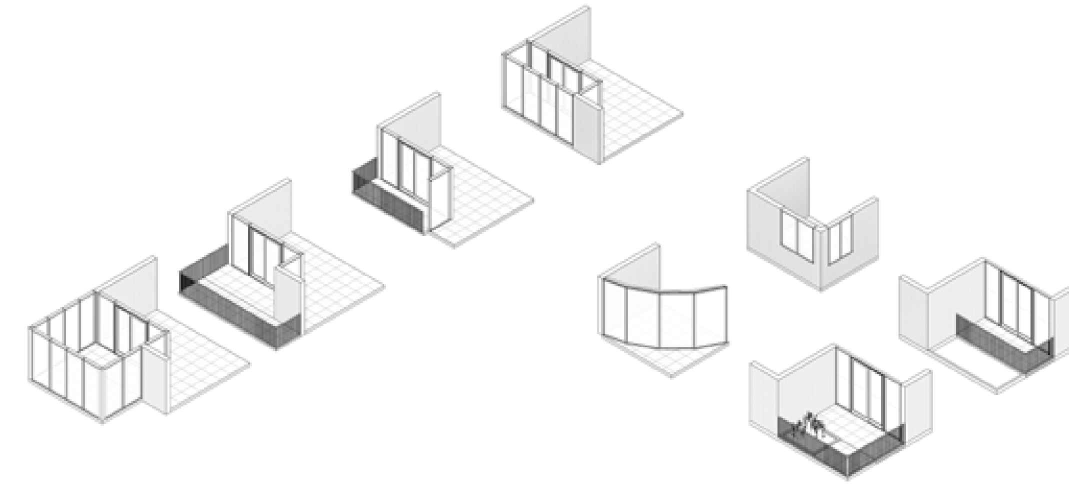

Image 2 Various interchangeable balcony options. Based on the Superlofts by Marc Koehler Architects and Next 21 by Yositika Utida.

adaptability can be a practical solution to overcoming the problem of building redundancy.[9] The obsolescence and redundancy of existing dated residential building stock is identified as a critical issue for sustainable development.[10] Between 1915 and 1950, 40-60% of all homes in Southern Ontario were built by owners, often incrementally and adapting over time.[11] By 2006, less than 1% of homes in the region were built by owners. This divide between occupants and their built environment, and the rigidity of the built environment in responding to occupant needs is a main driver of obsolescence. Other factors can include increasing rate in varying working circumstances, living arrangements, family structure, consumer needs, changing policy, and technology.[12]

Adaptability in Adaptive Reuse of Existing Buildings

Adaptive reuse is defined across multiple studies as an environmentally sustainable alternative to both demolition and new construction.[13] Adaptive reuse strategies extend the functional life of existing buildings that are either failing in adequate building performance or are obsolete in use through reuse or repurposing. This can be defined in terms of a range varying from

10 Manewa et al., 2016.

11 Harris, R. 1996. Unplanned Suburbs:Toronto's American Tragedy, 1990 to 1950. John Hopkins University Press. Baltimore, MD.

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repurposing of main structure to materials and systems.[14] It can be concluded from studies in this field that successful adaptive reuse projects can result in notable social, economic and environmental benefits.[15]

In most literature, "adaptability" is used to explain the capacity for change within the occupant's use, whereas "flexibility" addresses physical change of the built environment as a response to the occupant's use.[16] Adaptable buildings are defined as structures that incorporate alteration strategies, allowing them to respond to changing environments and occupant requirements.[17] To be truly sustainable and resilient, a building design must account for future flexibility and opportunities to adapt to occupants' demands and to enable accommodation of future uses.[18] Considering the importance of adaptive reuse and the need to address the changing housing market, integrating adaptive strategies in future adaptive reuse is integral to developing buildings that are responsive to environmental and demographic changes.[19]

Adaptive reuse of existing residential buildings raises particular challenges, but it will provide opportunities for the integration of adaptable buildings into the existing building stock.[20] In order to secure a sustainable built environment for the future, a flow of reactions between occupant requirements and external environmental forces that can respond to change is required.[21] In this context, the balcony and the building envelope at the intersection between the interior occupants and exterior environmental factors, as well the expansion and contraction of the building unit with occupant needs, are useful testbeds for adaptability concepts.

There are many identified effective design-based strategies for enabling adaptability. Some of these include the layering of different building systems, accurate documentation, over-designing structural capacity, designing for disassembly, simplicity of structure, systems and plan, modularity, open layouts, and occupant participation. Amongst these, open and accessible plans, over-designing structural capacity, and layering are highlighted by the industry as the most effective strategies to making future adaptive reuse possible.[22]

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Gosling et al. 2013.

Objectives of Residential Adaptability

Increasing sustainability through adaptability requires improvements on life cycle, economic performance, quality and liveability, and reduction of waste to landfills. These strategies can lead to sustaining of embodied energy and resources, retention of carbon and cost savings contributing positively to environmental sustainability.[23] Continuous adaptation as per changing occupants' needs and environmental requirements is important for the overall resilience and life expectancy of the built environment.[24] The UK government's Strategy for Sustainable Construction[25] highlights the importance of research, development and demonstration of "adaptation techniques and durable systems to improve the built environment's ability to deal with the impacts of climate change."[26] Many government mandates to reduce carbon footprint also support the important development of further legislation that encourage the upgrades to meet new standards in existing buildings.[27] While highlighting the importance of adaptability in sustainability and resilience, it is important to note that there is very little attention given to the carbon benefits of this process. The environmental benefits of adaptability and adaptive reuse go unmeasured by most environmental legislation and available environmental frameworks. UK BREEM certification is one of the only legislations that takes adaptability of a building in to account in the 'waste' category, with minimal influence on the overall score.[28]

Adaptability in the residential context is often used by developers to revise and finalize units corresponding to changing market demands leading up to construction.[29] The Architectural Association building in London, and the joining of eight dwellings that make up the entirety of a school without disrupting the urban fabric, is another example of implementing flexible strategies.[30] Interchangeable components, layering of building elements, and designing for disassembly are highlighted in literature as the most prominent contributors to successful residential adaptation.[31] Separation of wet cores, structures and systems in units is also a feature of adaptable residential buildings. These will enable the combination of units to accommodate growing families or multi-family living arrangements. These strategies have been implemented in the works of Yositika Utida in Japan, Marc Koehler Architects in the Netherlands and recent residential developments by JvN Developments Inc. in Canada (Image 1-2). While these examples illustrate adaptability strategies in new buildings, similar concepts can be implemented in the adaptive reuse of existing residential buildings.

23 Ross et al., 2016.

Manewa et al., 2016.

24 Eunike Kristi Julistiono, Nikolas Hosana, Fida Liemansetyo & Irene, F.W. 2017, "Spatial and Structural Aspects of an Adaptable Building", Journal of Architecture and Built Environment, 44, no. 1, pp. 87-94.

25 Davies, M. 2008, Strategy for Sustainable Contruction. Strategic Forum for Construction, London.

26 Gosling et al., 2013.

Kinnane et al., 2016.

27 Davies, 2008.

28 Lifschutz, 2017.

29 Ibid.

30 Habraken, 2017.

31 Gosling et al. 2013.

Implementation Challenges

The implementation of adaptable strategies, specifically in the residential context, encounters the lack of evaluation metrics for adaptive strategies and their economic results. The concept of Open Building design advocates for building adaptability. The ability is principally rooted in separating different building elements in layers that can be maintained, reimagined and changed without affecting the others to significantly reduce cost and time.[32] While the Open Building Design advocates have been successful in defining some adaptive design strategies, their approach is limited by their lack of defined evaluation criteria.[33]

Specifically, evaluation tools for design strategies, social implications, as well as economic and market barriers are required to facilitate adaptable building strategies. In terms of social sustainability, significance of changing demographics and changing occupancy requirements need to be taken into account.[34] There also needs to be a differentiation between the immediate impact of adaptability, including cost and ease of change,[35] and the imminent impact of continuous alteration on the building.[36]

Future Research

Strategies for adaptability in the residential context, including the integration of interchangeable and responsive components, layering of building elements, and designing for disassembly (Gosling et al., 2013) (Ross et al., 2016), and how each enhances long-term building performance and adaptability by different measures (Wilkinson, 2014), will be further examined. Evaluation parameters including environmental performance, life-cycle cost, economic valuation, and constructability, among other parameters, need to be analyzed in order to determine the efficacy of adaptable strategies.

Other considerations for further research include understanding the economic and cost implications, and strategies to implement adaptability in existing buildings as adaptable retrofits (Gosling et al., 2013). Ultimately, findings from the research will define frameworks for future adaptation of residential buildings.

32 Arge, K. 2005, "Adaptable office buildings: theory and practice", Facilities, 23, no. 3, pp. 119-127.

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33 Habraken, 2017.

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34 Ellison, L. & Sayce, S. 2007, "Assessing sustainability in the existing commercial property stock", Property Management, 25, no. 3, pp. 287-304.

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35 Leaman, A. & Bordass, B. 2010, Productivity in buildings: The 'killer' variables.

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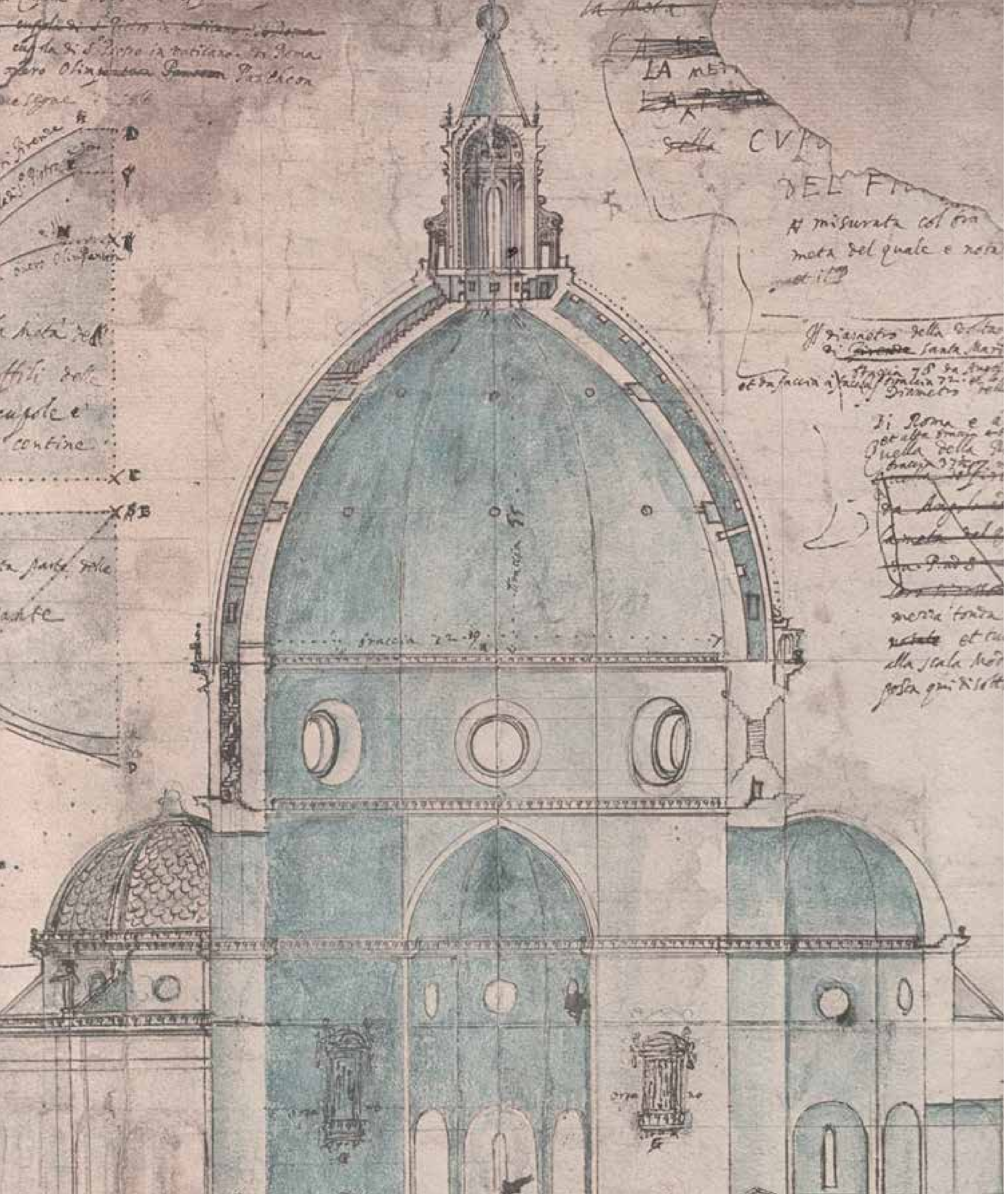
Sheida Shadi earned her B.AS. and M.Arch from the University of Waterloo's School of Architecture. She is now pursuing her PhD in Civil and Environmental Engineering under the co-supervision of Professor Carl Haas and Professor Philip Beesley. Shahi was a researcher at Diamond Schmitt Architects in Toronto and at Waterloo School of Architecture's Living Architecture Systems Group.

Her research focuses on strategies for adaptive reuse of balconies using intelligent building systems integration for improved environmental and structural performance. The goals of this project are to investigate the role of smart systems, information technology, data collection and citizen participation in informing adaptive reuse, and to develop design prototypes for balconies as smart integrated systems.



Adaptive Architecture
Empathy and Ecology

Michael Stacey
The Bartlett School of Architecture, London, UK

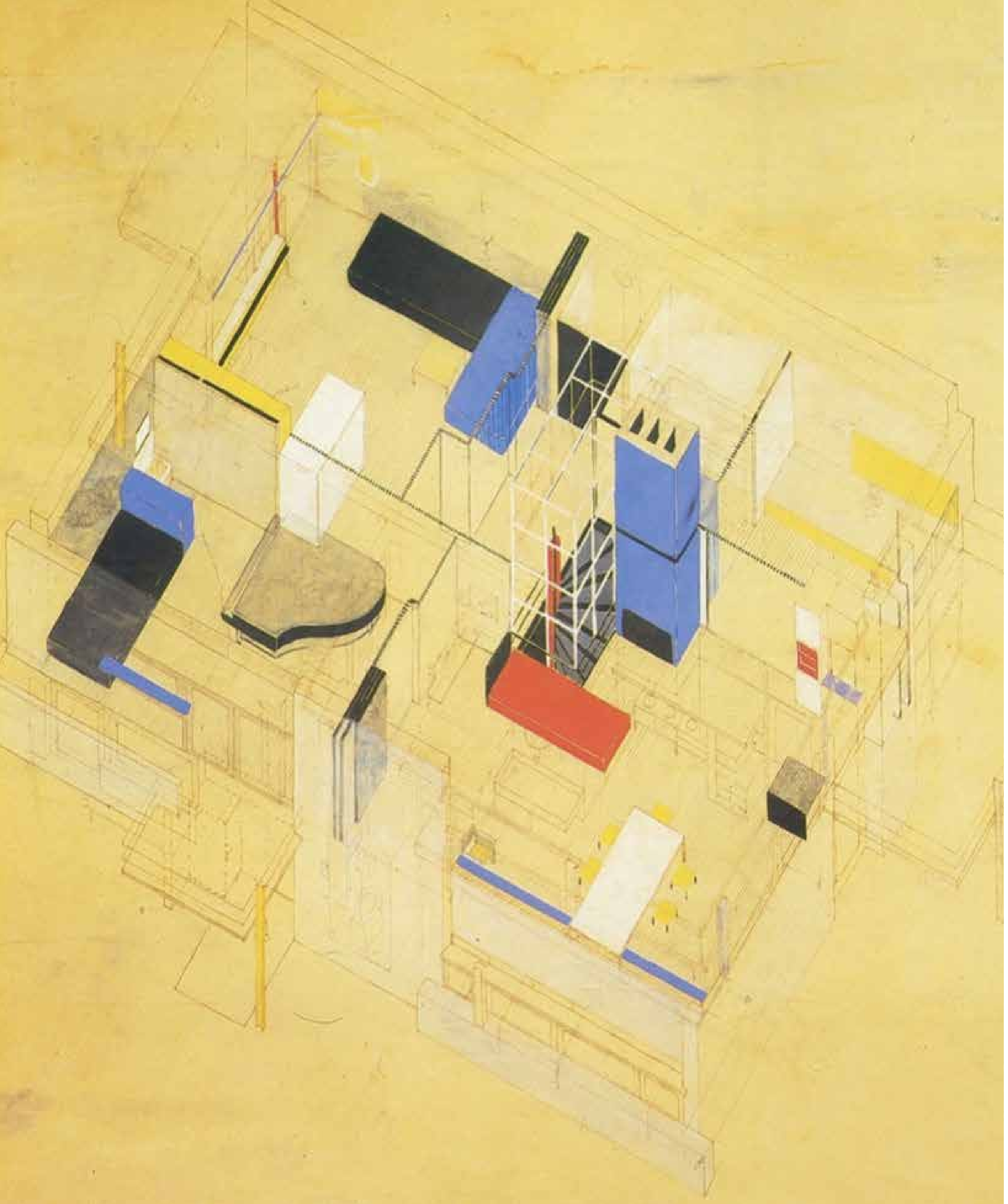
> The imagination, by means of which alone I can anticipate future objectS, or be interested in them, must carry me out of myself into the feelings of others by one and the same process by which I am thrown forward as it were into my future being.[1]

William Hazlitt argues in *An Essay on the Principles of Human Action*, 1805, that we share our futures, and this is a key feature of humanity, that the imagined future of others is as valid as one's own imagined future. This is a vital skill of all designers, and particularly architects, transporting architectural discourse and practice beyond any notion of egocentric space.

Architecture has always been inventive and adaptable. Our current era however, is unique in its technological potential combined with societal and environmental challenges. The need to generate sustainability, developments

Image 1 A section through the dome of Santa Maria del Fiore, Duomo di Firenze, drawn by Filippo Brunelleschi

1 William Hazlitt, An Essay on the Principles of Human Action, 1805, facsimile reprint (Gainsville, FL: Scholars' Facsimiles & Reprints, 1969), p. 3. 1



in design techniques, and technological advances are leading to the emergence of a new Adaptive Architecture. The built environment is becoming truly responsive in terms of physical, real-time changes acting under intelligent controls. Adaptive Architecture can be characterized by four key attributes: Dynamic, Transformable, Bio-inspired and Intelligence, to which the key issue of inhabitation must be added.[2]

2 Michael Stacey, Adaptive Architecture, DVD, Building Centre, 2011 p.3.

Adaptive Architecture has deep cultural roots. The Schröder House designed by Gerrit Rietveld in close collaboration with Mrs Schröder and completed in 1925, is an early demonstration of a transformable architecture. Paul Overy observes 'the space-dividing elements – the first floor itself, the roof and four walls – shape the spatial structure of the house. Within the structure there are five areas of transition form outside to inside and vice versa.'[3] Above all the Schröder House is considered as a whole – a holistic work of architecture.

3 Paul Overy, et al, The Rietveld Shröder House, Butterworth Architecture, UK edition, 1988, p.121.

Arguably what characterises late twentieth century and early twenty first century technology is the development of systems. However, there needs to be an equal emphasis on how well architecture performs and how performative qualities can be enhanced by informed design. It is revealing to reflect on Rietveld's definition of architecture: 'art is the clearest form of reality. The painter teaches us to experience reality by defining colours, the sculptor by defining materials, and the architect by defining space. Although in the architect's case the material and construction are essential, the space, between and around the solid form is of primary importance.'[4]

4 Helma van Rens (ed.), A Reflection Art, 1979, cited in Paul Overy, et al, The Rietveld Shröder House, Butterworth Architecture, UK edition 1988, p.120.

In 1981 Mike Davies of Richard Rogers & Partners, whilst researching the façades of Lloyds of London, wrote this lyrical vision of a dynamic façade:

Look up at a spectrum washed envelope whose surface is a map of its instantaneous performance, stealing energy from the air with an iridescent shrug, rippling its photogrids as a cloud runs across the sun; a wall which, as the night chill falls, fluffs up its feathers and turning white on the north face and blue on the south, closes its eyes but not without remembering to pump a little glow down to the night porter, clear a view-patch for the lovers on the south side of level 22 and to turn to 12 per cent silver just after dawn.[5]

5 Mike Davies, A Wall For All Seasons, RIBA Journal, Vol. 88 No.2, 1981, pp.55-57.

Image 2 Axonometric Drawing of The First Floor of Schröder House by Gerrit Rietveld

It is pertinent to note that during the design and construction of Lloyds of London, 1976 – 1984, the client used fountain pens and almost no

Image 3 Lloyd's of London by Richard Rogers & Partners with 30 St Mary's Axe by Foster and Partners in the background, photographed in 2018

computers at the start of the project and by the moving-in day, computers were ubiquitous amongst the Re-insurers. Mark Goulthorpe's Aegis HypoSurface can be seen as a physical embodiment of at least part of Mike Davies' vision. Mark Goulthporpe argues as 'architecture inevitably shifts from representative to calculated tropes. This offers extraordinary potential to fundamentally rethink our manner of designing, building and dwelling, and to fold in the temporal logics that computation offers.'[6]

6 Mark Goulthorpe, Die Plastik - dECOi Architects, Adaptive Architecture Conference Keynote, Building Centre, March 3-5 2011.

Image 4 Digital Intimacy designed as a responsive learning environment for autistic students by Stephen Townsend

Image 5 Aegis HypoSurface designed by Mark Goulthorpe

Humankind now has the techniques and technology to create responsive façades that reduce energy demands, enhance comfort and integrate energy generation into contemporary architecture. Building envelopes no longer simply resist energy flows. They are dynamically variable and can harvest energy. Tim Macfarlane suggested that 'with the range of glass types and coatings are combined in a double or triple glazed unit, there are 10 to power of 9 options and that no two buildings will carry the same specification.'[7] This is unlike the era of single float glass being in accordance with the Building Regulations of England and Wales when I studied architecture.[8]

The work of Archigram[9] and Peter Cook started in an era known for the 'white heat of technology,' to quote the future British Prime Minister Harold Wilson in the autumn of 1963.[10] This visionary work remains a timely provocation to contemporary architecture. [11] Although we are still to experience Archigram's Walking Cities, these pen on ink drawings present a future, the future of the 1960s, with such veracity that looking at them in a magazine or gallery one could not but help dreaming of a more flexible adaptive future for architecture and humankind.

In 2019 humankind benefits from millennia of cultural continuity yet faces new challenges and opportunities. In organising the ARCADIA 2013 Conference, co-chairs Beesley, Khan and Stacey 'perceive the opening up

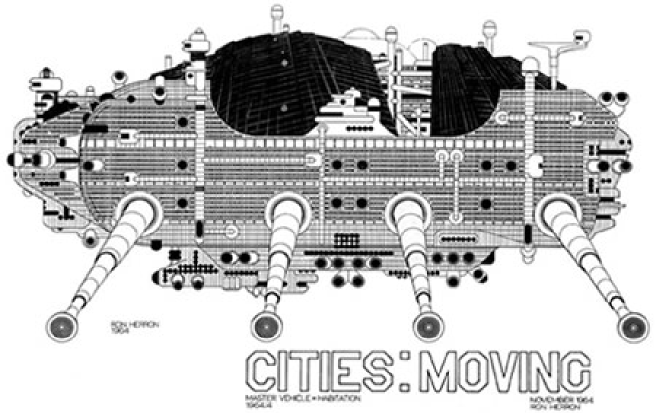
7 Tim Macfarlane, Design Space (Lecture), University of Nottingham, 2013, recorded by the author.

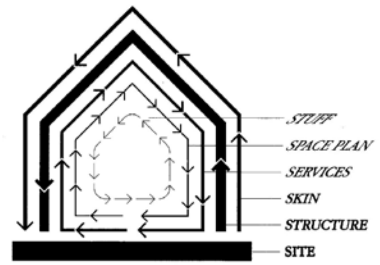
8 Ibid.

9 Archigram was launched as a stencil printed magazine in 1961 and lasted until 1976.

10 H. Wilson, Labour's Plan for Science, Leader of the Labour Party at the Annual Conference, Scarborough, 1 October 1963, http://nottspolitics.org/wp-content/uploads/2013/06/Labours-Plan-for-science.pdf (accessed April 2016).

11 Sir Peter Cook opened the first Adaptive Architecture Conference, at the Building Centre, London, on 3 March 2011. He addressed Adaptive Architecture with a body of work, which includes the inspirational teaching of over three generations of future architects and provocative built and unbuilt projects.





of new intellectual territories, be this arising from technology or our native inventiveness. The discipline of architecture is ripe, fuelled by research. There are new modes of practice where the realms of research design and development are seen as one. Where knowledge passes osmotically from practice to academia, from teacher to pupil and from the future architect to the architect-academic.[12] A co-working of the future.

Stewart Brands' seven shearing layers of change, in *How Buildings Learn*, published in 1994, are: Site, Structure, Skin, Services, Space, Plan and Stuff. This was based on research by DEGW.[13] This proactive but arguably backwards looking hierarchy was challenged by many case studies in the Adaptive Architecture conferences of 2011 and 2013, in particular within Dynamic Façades and Transformable Structures. Change can now be integrated into the architecture and the structure need not be static. Brands' book now appears strangely dated as he conceives change as something that happens to buildings after they are designed and not part of the design process. It also seems dated in the stated rate of destructive change, anticipating that a façade in North American construction will be totally replaced 'every 20 years.'[14] Research undertaken by Michael Stacey Architects with KieranTimberlake revealed that the typical timescale for the replacement and renewal of the curtain walling of a skyscraper in Manhattan is over 50 years.[15] Furthermore it is now possible to specify finishes that receive a guarantee for over 40 years, for example, super durable polyester powder coating on aluminium, or over 80 years for 25µm of anodising on aluminium.[16]

Image 6 Walking City by Archigram

Image 7 Shearing Layers of Change from How Buildings Learn by Stewart Brand, 1994

12 Philip Beesley, Ohma Khan and Michael Stacey, Eds., Adaptive Architecture, ARCADIA 2013: Adaptive Architecture, Riverside Press, 2013, p.1.

13 Stewart Brand, How Buildings Learn: What Happens After They're Built, Viking Penguin, New York, 1994, p. 13, citing Frank Duffy, Measuring Building Performance, Facilities, 8(5), pp. 17–21.

14 Stewart Brand, How Buildings Learn, Viking Penguin, 1994, New York, 1994, p. 13,

15 Michael Stacey, Aluminium Recyclability and Recycling: Towards Sustainable Cities, Cwningen Press, Llundain, 2015, p. 232.

16 Michael Stacey Ed., (2016) Aluminium and Durability – Towards Sustainable Cities, Cwningen Press, Llundain, 2014, second edition 2015

Image 8 Guy's Hospital overcladding designed by Penoyre & Prasad and the Shard, designed by Renzo Piano Building Workshop: have durable but distinct finishes on their aluminium building envelopes – anodising with an 80-year guarantee and Class 2 polyester powder coating with a 40-year guarantee, respectively

Transformable Structures and Transformable Architecture in the inventive hands of an engineer such as Chuck Hoberman is a means of creating a sustainable built environment that offers both comfort and joy. The Thames Water Tower, London, England: Architect Brookes Stacey Randall Fursdon, 1995, was designed as a striking contribution to the urban landscape of London. This inventive tower of glass, stainless steel and aluminium is a prototype for an environmentally responsible and responsive building. It was built to house a surge pipe on Thames Water's drinking water ring main, an

unseen marvel of hydro engineering serving all of London. The tower was designed by Brookes Stacey Randall Fursdon, in collaboration with students of the Royal College of Art, Damian O'Sullivan and Tania Doufa. The tower celebrates an otherwise invisible engineering achievement, with an amplified electronic barometer in the centre of Holland Park Roundabout, London.[17] The 15m-high tower has a base housing the services, a smooth column of glass, and a capital formed by the solar array. Blue water appears to rise up the tower, layer by layer, in response to climatic conditions and then fall again in times of low air pressure. 'The approach to the design of the structure and enclosure is one of increasing sophistication as it rises up to the tower to the solar vane,' observed the Editors of ViA Arquitectura.[18] They continue: 'The Thames Tower is a working model of a responsive building. In the design of the tower the architects sought to detail the complete assembly in such a way that the play of light is encouraged as it strikes and penetrates not only the glass and water but also the polished surfaces and components within the tower to create a visually poetic effect.'[19] The project was realised through the research and application of new technologies.[20] The Thames Water Tower was tendered with a solar vane that automatically opened for daylight hours and closed at night when it was not functioning.

Image 9 Sketch of the original dynamic solar vane of the Thames Water Tower which would have opened and closed in response to daylight, designed by Brookes Stacey Randall Fursdon

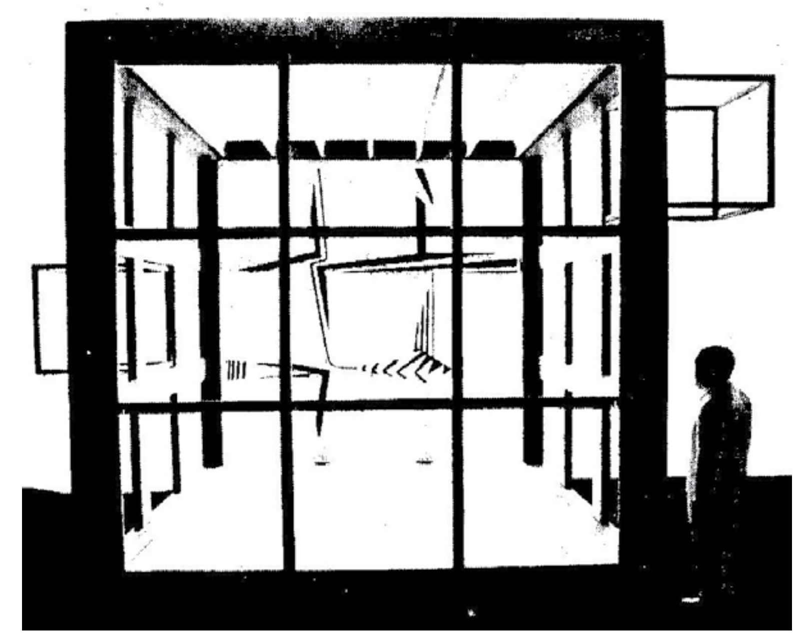
Image 10 Thames Water Tower, 1995, architect Brookes Stacey Randall Fursdon

17 Michael Stacey was a founding partner at Brookes Stacey Randall Fursdon, 1987 and set up Michael Stacey Architects in 2004.

18 M. Plannelles Herrero and A Mengul Muñoz, (December 2001), Agua – Water Via Arquitectura, 10.V-2, p. 49.

19 Ibid.

20 Michael Stacey, Aluminium: Flexible and Light – Towards Sustainable Cities, Cwningen Press, Llundain, 2016, p. 588-597.



This design option had to be dropped due to the tight timescale of the project, in line with the completion of the Thames Water Drinking Water Ring Main, and not due to cost constraints. Thus, although a specialist subcontractor responded to the architect's inquiry eventually, Brookes Stacey Randall Furdson had to design the fixed solar vane that tops the tower in order to meet the completion date set by Thames Water.

Professor Robert Kronenburg observes: 'flexible architecture consists of buildings that are intended to respond to changing situations in their use, operation, or location. This is architecture that adapts rather than stagnates; transforms rather than restricts; is motive rather than static; interacts with its users rather than inhibits. It is a design form that is by its essence cross-disciplinary and multi-functional and consequently, is frequently innovative and expressive of contemporary design issues.'[21] Peter and Alison Smithson advocate adaptive architecture in *The Charged Void*, proposing the characteristics of spaces to be 'such that they can be tuned by the occupant to the changing values of their time without denaturing the architecture.'[22]

21 Robert Kronenburg, Flexible Architecture, Adaptive Architecture Conference Keynote, Building Centre, March 3-5 2011.

22 Alison and Peter Smithson, The Charged Void: Architecture, The Monacelli Press, New York, 2001. Additional research on. the Smithson was provided for this paper by Ben Yuval Ben-Gait, an MEng EAD student at the Bartlett, University College London

The London based architect Cedric Price thought that 'labelling a room on plan has a paralysing effect on the way it's used.'[23] New types of reconfigurable architecture, which will show how adaptive strategies can extend the cultural potential of architecture, extend a building's life cycle, enhance energy efficiency and optimize resource utilization. Deyan Sudjic heralded the birth of intelligent buildings in 1981 citing the Generator project by Cedric Price. 'Despite all the breathless promise, the only architectural fruit of the microelectronic boom to have made it off the drawing board and into the home on a large scale is no more imaginative than the humble programmable doorbell,' Sudjic observed in 1981.[24] He thought that this was about to be transformed by Cedric Price's Generator project for the Gilman Paper Corporation in Florida, a company retreat where Price proposed an ever-changing assembly of components that could be reconfigured at will – the basic data base was the architect's CAD drawings and all components would have linked logic circuits. The additional software was developed by John and Julia Frazer. Price conceived the software as a perpetual architect. The computer would not only make proposals for improving the layout – it would prepare unsolicited plans if no reconfiguration had occurred.

23 Deyan Sudic, Birth of Intelligent Buildings Design, January 1981, p 56.

24 Ibid.

It is pertinent to pause to consider how profoundly humankind has changed planet Earth since the Industrial Revolution of the eighteenth and nineteenth century. To many geologists the present period of time should in geological terms be defined as the Anthropocene, an epoch where humankind has altered the environment and ecology of Earth to the extent that it is being recorded in the Earth's crust, in the very rocks of planet Earth. Robert Macfarlane suggests: 'The idea of the Anthropocene asks hard questions of us. Temporally, it requires that we image ourselves inhabitants not just of a human lifetime or generation, also of 'deep time' – the dizzyingly profound eras of Earth history that extend behind and ahead if the present.'[25]

25 R. Macfarlane, (2 April 2016) The Guardian Review, pp. 2–4.

The roots of the Anthropocene have their origin in the industrial and urban revolution of the Eighteenth and Nineteenth Century when humankind harnessed the means of production so successfully it made work at vast scales possible, without the enormous workforce seen in ancient Egypt or Rome. The term Anthropocene was coined in 1999 by Paul J. Cruzten, a Noble Prize-winning atmospheric chemist, who believed the term Holocene was no longer accurate.[26] The Holocene epoch began about 11,700 years before 2000AD, and simply means entirely recent, in ancient Greek. Based on the record of greenhouse gases such as CO2, Paul J. Cruzten and his

26 J. Zalasiewicz, M.Williams, W. Steffen, Paul Crutzen (2010) The New World of the Anthropocene Environmental Science & Technology, 44 (7), pp. 2228–2231.

Image 11 Renzo Piano: The Art of Making Buildings exhibition at Royal Academy of Arts, London, 2019

colleagues propose that the Anthropocene started in 1782, the year James Watt patented, in the United Kingdom, his efficient steam engine, a key invention of the Industrial Revolution.

Writing in *The Anthropocene Review* (March 2014) Jan Zalasiewicz, Mark Williams and Colin Waters of the University of Leicester with Anthony D. Barnosky and Peter Haff, suggest the weight of the planet Earth's technosphere has reached 30 trillion tonnes.[27] Jan Zalasiewicz and colleagues note: 'The technosphere comprises the interconnecting technological systems that underpin modern civilization,' citing Haff (2012).[28] They continue, it 'is a phenomenon that has now reached a scale sufficient to perturb the natural physical chemical and biological cycles of the Earth,' citing Rockstron et al., (2009). Based on Crutzon (2002) this provokes 'the suggestion of an Anthropocene Epoch.'[29]

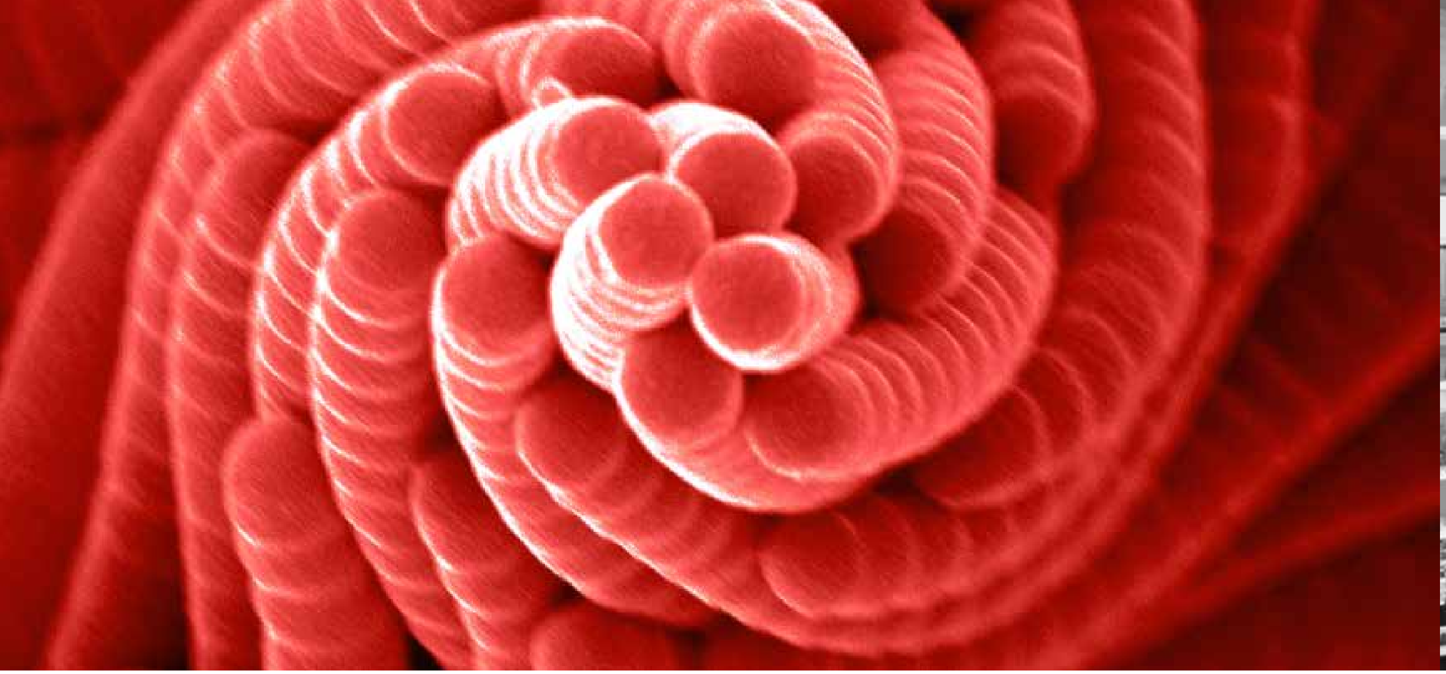
27 J. Zalasiewicz, M. Williams, C. Waters, A. D. Barnosky and P. Haff (2014) The technofossil record of humans, The Anthropocene Review 1(1), 2014, pp. 35–43.

28 Ibid.

29 Ibid.

Desipite Jan Zalasiewicz et al.'s carefully argued paper "Making the case for a formal Anthropocene Epoch: an analysis of ongoing critiques," (2017), which concludes that a strong case can be 'made that the character and scale of its extant stratigraphy already warrants recognition of the Anthropocene as a formal unit of the Geological Time Scale.'[30] To date the

30 J.Zalasiewicz et al., (April 2017) Making the case for a formal Anthropocene Epoch: an analysis of ongoing critiques, (2017), Newsletters on Stratigraphy, Volume 50, Number 2, April 2017, p.221.



Anthropocene is not yet an officially recognised epoch of geological time, by either the International Commission on Stratigraphy or the International Union of Geological Sciences.[31]

Early in his career Renzo Piano (b.1937, Pegli, Genoa) identified the essence of architecture as *technica* and *humanismo*. Combing technology and humanism in the making of buildings, the making of architecture, requires the skill, knowledge and processes demonstrated by Piano in his long and sustained body of work. Piano has developed a 'command of the construction process, designing … "piece by piece".'[32] He brings the sensibility of a poet to the practice of architecture. Kate Goodwin considers this sensibility to be evident in his early experiments with tensile structures, observing Piano developed a poetic sensibility conjured 'in the imagination and human spirit.' 'Indeed, for Piano, practical thinking is always balanced by an inclination to poetic dreaming.'[33] In Piano's hands architecture is mutable. Unusually he seeks to keep all components of a new project live to the last possible time in the gestation of a project, to achieve the greatest possible level of integration, to enable the whole to be greater than the sum of the parts. Renzo Piano Building Workshop eschews the conventional layering of discrete packages of elements and systems, which is evident even on an innovative project such as the parametrically designed 30 St Mary's Axe by Foster & Partners, 2003.

Image 12 An Aiz Core, courtesy of the Wyss Institute

31 This research note is an update of part of the introductions to M. Stacey, Aluminium: Flexible and Light – Towards Sustainable Cities, Cwningen Press, Llundain, 2016 and M. Stacey, Aluminium: Sympathetic and Powerful – Towards Sustainable Cities, Cwningen Press, Llundain, 2017

32 Renzo Piano: The Art of Making Buildings exhibition, Royal Academy of Arts, London, September 2018 — 20 January 2019, exhibition guide, unnumbered.

33 Kate Goodwin (curator), An Architect of Dignity, in Renzo Piano: The Art of Making Buildings, Royal Academy of Arts, London, 2018, P.14.

34 Renzo Piano speaking in the video at the core of the Royal Academy Arts exhibition, Renzo Piano: The Art of making Buildings, Royal Academy of Arts, London, September 2018 — 20 January 2019, transcribed by author.

Image 13 The Great Workroom of the Johnson Wax Administration Building, 1939, architect Frank Lloyd Wright

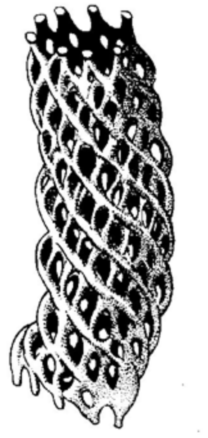


Image 14 Staghorn cholla cactus that inspired Frank Lloyd Wright's design of the concrete structure of the Great Workroom

Adaptive Architecture can be considered a direct precursor of Living Architecture Systems. In 1951 the Festival of Britain was staged to celebrate the peace following World War Two (1939-1945) and to herald of the end of austerity in Britain. War time food rationing was finally fully withdrawn in Britain in 1954. The festival included a Living Architecture Exhibition, which featured the Lansbury Estate in Poplar, London, 1951. This estate was intended as model district of London, it was designed by architect Sir Frederick Gibberd, with YRM Architects and Geoffrey Jellicoe and included affordable housing, schools and churches. Living Architecture celebrated and promoted the role of good design as a means of informing the lives of the people of Britain. The act of rebuilding and renewal is core of being an architect, Renzo Piano sagaciously observes: 'Making buildings is the opposite of destroying. Making buildings is a decent gesture of peace.'[34]

In this discourse the term Bio-inspired has been preferred to Bio-mimetic, since mimicry is a human talent; however, the problem with the mimetic is that it leaves out the dilemmas and opportunities of design. Frank Lloyd Wright, when designing the structure of The Great Workroom of the Johnson Wax Administration Building, completed in 1939, was inspired by the natural form of forests and trees. Wright designed a bespoke structural system for the building in Racine, Wisconsin. The building's main space, the Great Workroom, is dominated by an ordered forest of 'dendriform' or tree-like concrete columns. The slender tapered columns are just 230 mm wide at

Image 15 Frank Lloyd Wright witnessing the testing of a prototype cast concrete column for the Johnson Wax Administration Building

their base and sit on steel footings, which are practically unable to withstand bending. Wright borrowed expressions from botany to describe the three parts of the columns: the stem, the calyx and the petal.[35] He was specifically inspired by the structure of staghorn cholla cactus.

Adaptation of architecture can be as simple as the windows, blinds and sliding screens of Gerrit Rietveld's Schroder House, 1924, where the first floor transforms from spaciousness to intimacy in the hands of its occupants, or it can be the sophisticated bio-inspired gill like adaptive shading of Ocean One by soma [Austria] with Knippers Helbig Advanced Engineering.[36] This 3 to 13-meter high Glass Fibre Reinforce Polymer (GFRP) shading system was inspired by the movement of the South African Bird of Paradise (Strelitzia)

35 Michael Stacey, Concrete: a studio design guide, RIBA Publishing, 2011, p148.

36 Please see: Soma - http://www.soma-architecture.com

Image 16 Dynamic adaptive façade of Ocean One by soma, 2012

flowers. The system was prototyped at one to one to test this automated adaptive façade.

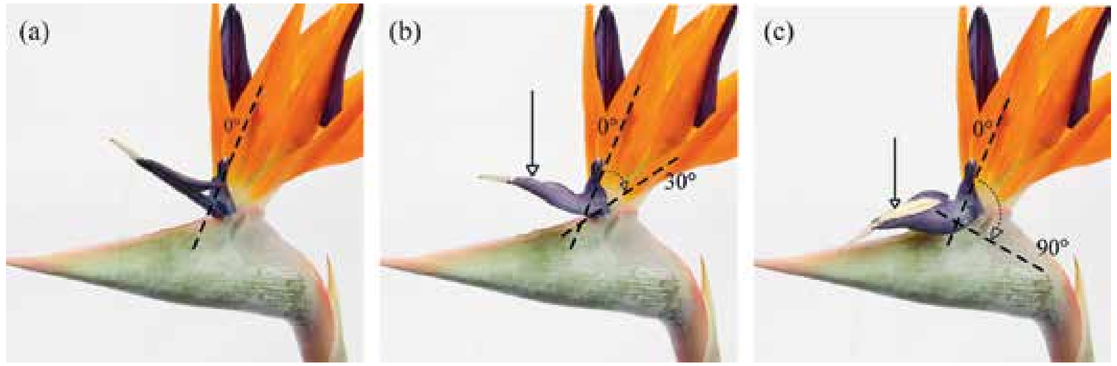
Adaptive Architecture is as much about process as about product or outcome. 'Adaptability lies at the very core of every architectural project, since a concept or design idea is constantly adapted to fit its medium of expression: thoughts, words, sometimes sketches, models, computer drawings, prototypes and finally built space,' clearly articulate Kristina Schinegger and Stefan Rutzinger.[37] Who continue, 'for soma the concept leads through this process and every design decision can either be deduced from or has to be negotiated with it. Thus we do not understand the initial idea as the irreducible essence; instead it is constantly improved and altered.'[38]

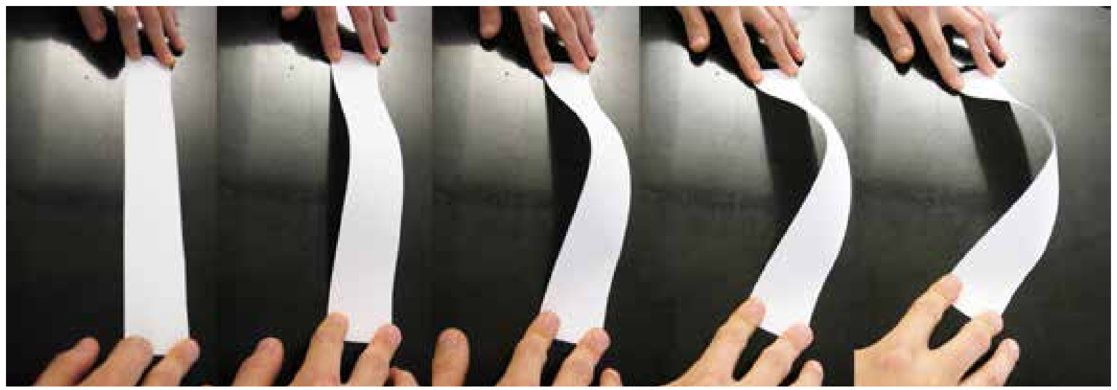
Some will argue that new methods of parametric design challenge the cognition of architects. It is clear that we are in the midst of a digital revolution. Andrew Feenburg observed how a precursor to the Internet was conceived by scientists as a serious medium for data transmission, yet it was immediately appropriated by social networks - noting 'the "cold" computer became the "hot" new medium.'[39] The Internet has altered the way in which architects and engineers work and even has a revolutionary political potential. We need to be protective and proactive in generating the space within which to design, using our collective and individually knowledge wisely as we make the value judgements inherent in the design process. We need to

37 Kristina Schinegger & Stefan Rutzinger, Adaptive Formations: Two Pavilions One Tower in Michael Stacey, ed., Prototyping Architecture, Riverside Architectural Press, 2013, p. 74.

38 Ibid.

39 Andrew Feenberg, Questioning Technology, Routledge, 1999, p. 126.





be reflective practitioners and to practice design intelligence in order to generate appropriate architecture of quality.

People, strangely described as the 'end-users' of architecture, respond to the clarity of thought that informs an architectural proposition. Alison and Peter Smithson consider that:

If a building or an element of city is to give intellectual access to its occupants, access to their affections and their skills, access to their sensibilities, the fabric must have special formal characteristics. Layering has such characteristics, for between the layers there is room for illusion as well as activity. Layering is an idea unfolded from within the formal usage of the existing language of modern architecture.[40]

Image 17 Dynamic adaptive façade of Ocean One was inspired by the geometry of the Bird of Paradise flower

Image 18 Knippers' paper model of the flexing movement of the gill-like adaptive shading of Ocean One

40 Alison and Peter Smithson, The Charged Void: Architecture, The Monacelli Press, New York, 2001, p.39.

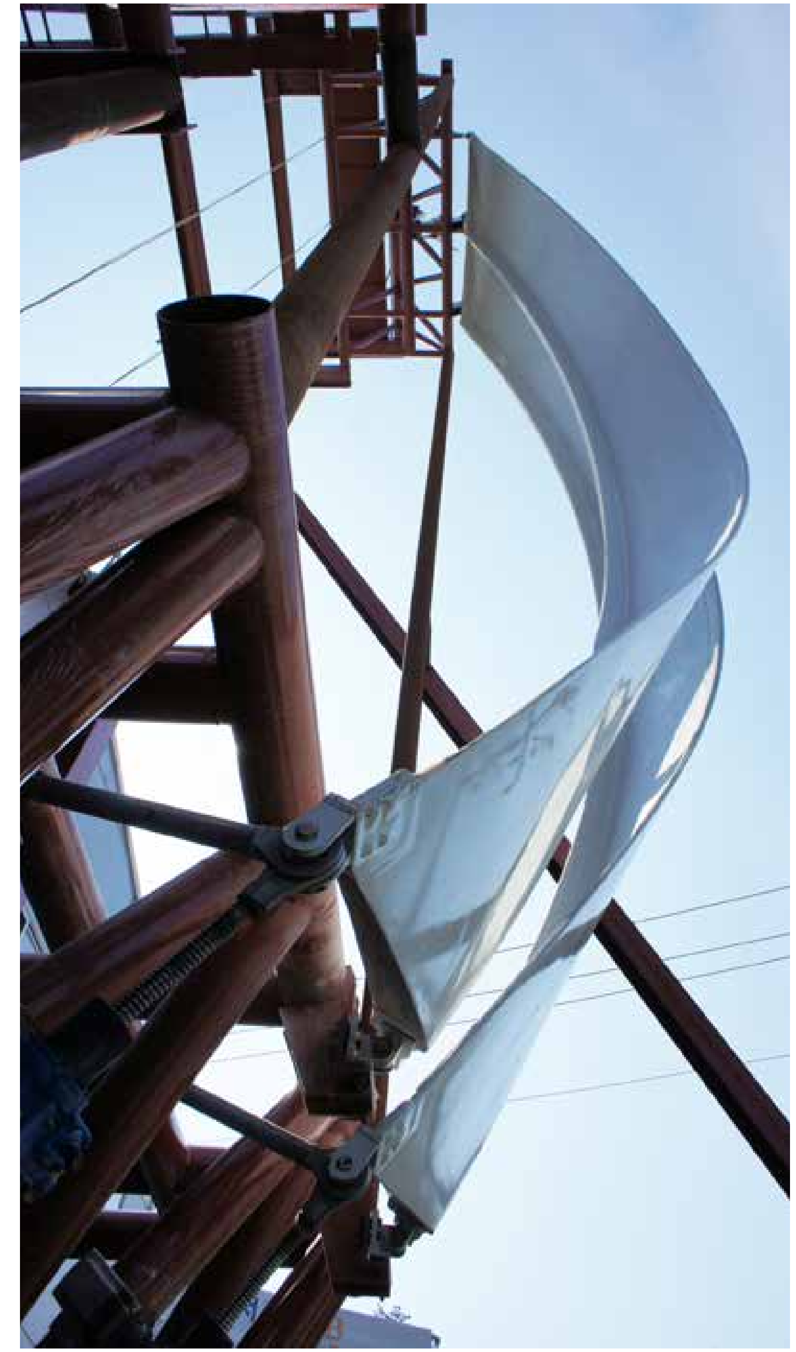


Image 19 13-meter GFRP Prototype of gill-like adaptive shading of Ocean One

Alvar Aalto, during a lecture in Stockholm in 1944, vividly explained ‘flexible standardisation’ via an analogy, recorded by Jørn Utzon. He described a group of houses ‘as being like a branch of flowering cherry … All the flowers are essentially the same, yet each is unique, looking this way or that, expanding or retreating, according to its relationship to its neighbours, to the sun and to the wind.’[41] The full potential of flexible standardisation has yet to be realised, especially in the design and provision of housing.

Adaptive Architecture can provide delight, firmness and commodity, immutable qualities of architecture, yet it can be a means to realise the opportunities within contemporary architecture and it can be used to address key challenges facing humankind, including global warming. An approach to this challenge is demonstrated in the Nottingham House, the UK's entry to Solar Decathlon, Europe, 2010. Ford and Stacey observe ‘the Nottingham House is a prototype for a housing system that is adaptable both culturally and technically, enabling it to be used throughout Europe. In essence this means that the Nottingham House is pre-adapted to the risk of elevated temperature ranges in the summers of Northern Europe, as predicted by some climate models, later in the twenty-first century.’[42] ‘The Nottingham House is a situated domestic ecology that fulfils Feenberg's recommendation to design and create appropriable technology.[43] Almost nothing is more important in peoples' lives than their home and home life. In the twenty first century we have the technology and knowledge to construct a much higher standard of housing, which delights and serves humanity well.’[44] Adaptive Architecture has the potential to inform the future of architecture and human ecology.[45]

Image 20 Cherry blossom

Image 21 Passive evaporative downdraft cooling (PEDC) Prototype in the Nottingham House, Madrid Solar Decathlon, 2010

41 Jørn Utzon, Ed. Etal, Jørn Utzon Log Book Volume 11, Bagsværd Church, Edition Bløndal, 2005, p. 159.

42 Brian Ford & Michael Stacey The Nottingham House in Michael Stacey, ed., Prototyping Architecture, Riverside Architectural Press, 2013, p. 126

43 Andrew Feenberg, Questioning Technology, Routledge, 1999.

44 Brian Ford & Michael Stacey The Nottingham House in Michael Stacey, ed., Prototyping Architecture, Riverside Architectural Press, 2013, p. 142.

45 This essay has been spell checked using United Kingdom English, with The Oxford Compact Dictionary, Oxford University Press, Oxford, 1996.

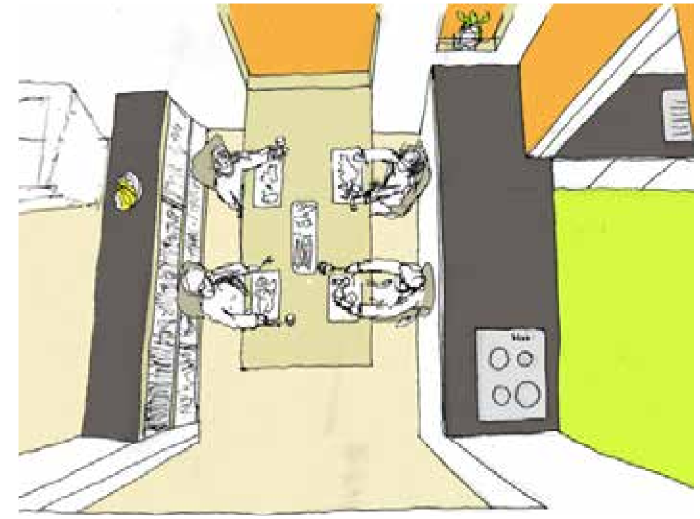


Image 21 Sketch of the atrium at the heart of the Nottingham House

Image 22 The atrium at the heart of the Nottingham House

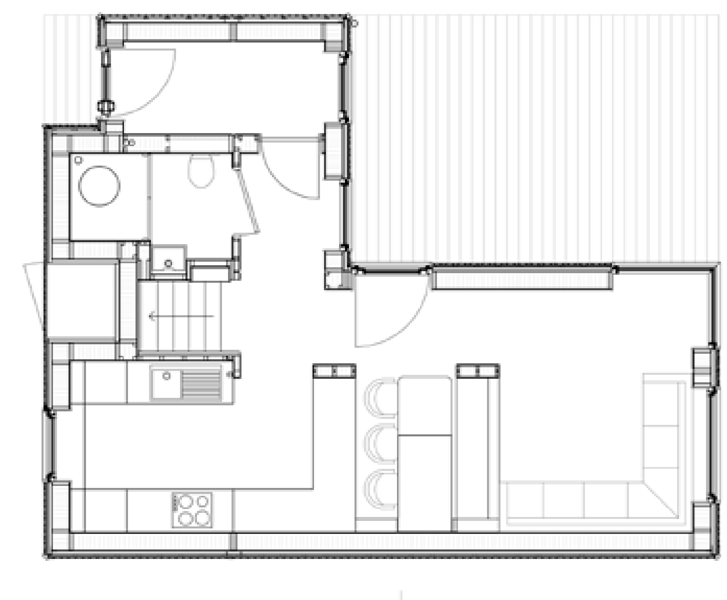
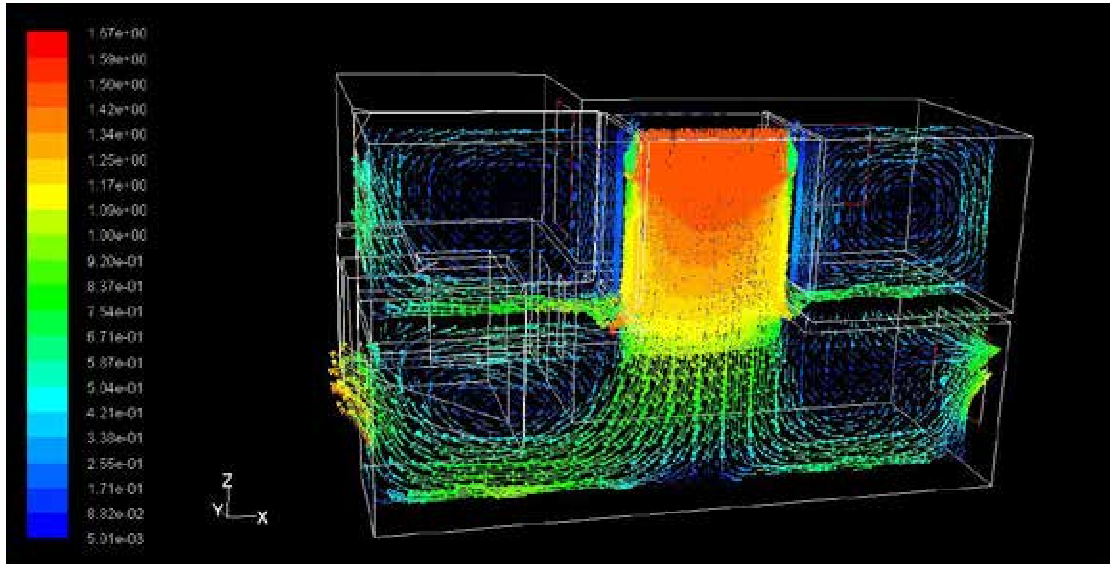


Image 23 Ground floor plan of the Nottingham House

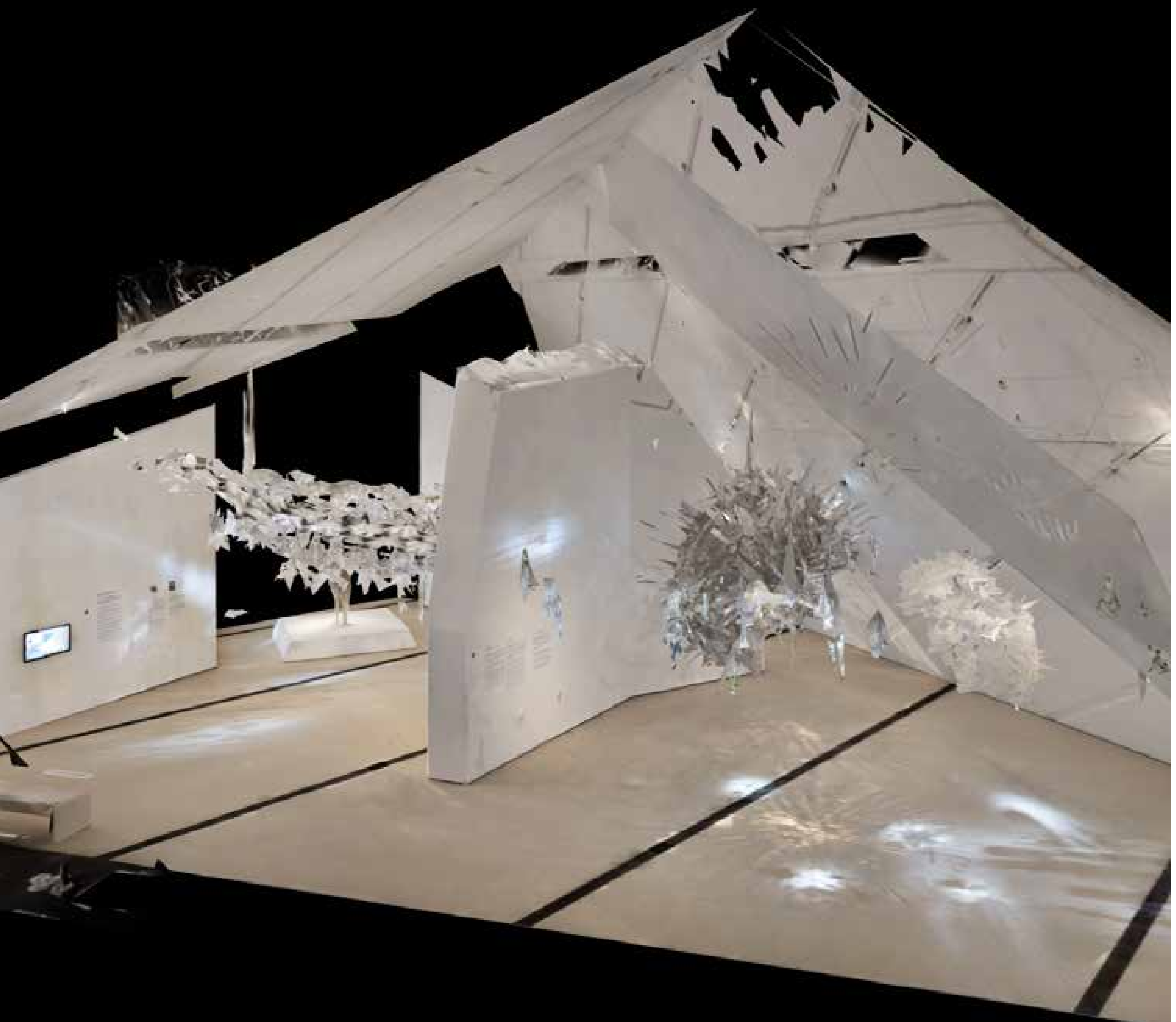


Michael Stacey's professional life combines practice, teaching, research and writing. His portfolio of projects and products has been recognised by national and international awards, including twice winning the Shapemakers Award for the Innovative Use of Aluminium, a Bureau International du Beton Award, RIBA Awards and an Award from the Campaign for the Preservation of Rural England. In 2013 The Renault Centre, 1982, which he worked on at Foster Associates, was listed Grade II*. He has taught architecture at Liverpool University, Penn Design, London Metropolitan University, the Architectural Association, The University of Nottingham and currently on MEng Engineering & Architectural Design at the Bartlett, University College London.

First published in the Architects Journal in 1985, he is the author of a wide range of publications and books including: Component Design, 2001, Digital Fabrication, 2004, Concrete: a studio design guide, 2011, second edition 2019, Prototyping Architecture, 2013, Aluminium and Durability, 2014, second edition 2015, Aluminium Recyclability and Recycling, 2015, Aluminium: Flexible and Light, 2016, and Aluminium Sympathetic and Powerful, 2017. RIBA Publishing has commissioned a series of Studio Design Guides and next will be Aluminium: a studio design guide, 2019. Current research programmes include: Towards Sustainable Cities: quantifying the in-use benefits of Aluminium in Architecture and the Built Environment with KieranTimberlake for the International Aluminium Institute and Living Architecture Systems Group with Philip Beesley Architect Inc., funded by SSHRC, Canada.

Image 24 CFD modelling of passive evaporative downdraft cooling the Nottingham House, Madrid Solar Decathlon, 2010

Image 25 The Nottingham House at Madrid Solar Decathlon, 2010. It has since been reassembled and is now a house at The University of Nottingham, Park Campus.



Applying 3D Scanning and 360° Technologies to Complex Physical Environments

Two Prototypes to Enhance Representation Through the Sensors of Machines

Codrin Talaba
Independent Design Researcher, Toronto, Canada

Image 1 Interactive 'dollhouse' view of 3D model of *Aegis* and *Noosphere* installation at the Royal Ontario Museum.

This paper will discuss how 3D scanning and 360° technologies are different from conventional 2D methods to document complex physical environments and their interactions with occupants.

Two proof-of-concept prototypes will be introduced that apply these tools to art installations by the Living Architecture Systems Group. This will be followed by a discussion section divided into four parts:

Learning to Switch Perspectives discusses how the capture of 3D or 360° content can be improved by shifting between a human point of view and the way machines capture data.

Seeing from the Machine's Perspective takes the reader on a visual journey through the eyes of the machine to help bridge the different ways of seeing and to collaborate better.

Sense-Making Through Sensors and Lenses describes how the 3D and 360° data can be visualized and utilized to enable better human understanding of complex environments.

Digitize / Replay / Iterate introduces the potential of using 360° video as an analysis and evaluation tool of interactions to integrate learnings iteratively into a knowledge base.

This will be followed by a summary Conclusion and Future Research sections.

Prototypes:

1. 3D scan of — *Aegis and Noosphere* — Royal Ontario Museum, Toronto, Summer, 2018
2. 360° video — *Astrocyte* — DX EDIT: Expo for Design, Innovation & Technology, Fall, 2017

Introduction:

The field of view (FoV) is the extent of the observable world that is seen at any given moment.

In the viewable area where the FoV of each of our eyes overlap, we are able to perceive in 3D. Our eyes are the natural start of perception of the field of view because they form the invisible frame of what we can see in our environment – which depends on what we focus on. Anything outside the FoV is unseen or left to memory to capture. So, we started developing increasingly sophisticated instruments to capture representations of our environments: from pinhole cameras to stereoscopes to photography to 3D films - technologies that improve in both fidelity and resolution with each successive generation. Yet, these are typically still bounded by a frame.

Traditionally, photography and video have relied on a single perspective and fixed frame in the documentation process. For a camera, the field of view refers to the widest capture potential of the lens. As with human vision, anything outside the field of view when the picture is taken is not recorded visually – although other senses or sensors can register data from the environment beyond sight.

The emergence of 3D scanning and 360° technologies marks a shift towards capturing the world without a frame. By recording information from every surrounding direction, these technologies can produce enhanced representations of real-life conditions via digitized 3D models and interactive virtual experiences. They can help visualize complex environments in more dynamic ways and reveal relationships which are not perceptible by human vision alone. However, the process to capture and digitally reconstruct 3D scan data and 360° content relies more on the lenses and sensors of machines than the eyes and senses of humans.

What does this mean? First, it reinforces how different 3D scan and 360° media are from 2D content. This suggests that it is not as simple as transposing existing content to a new screen.

Secondly, it begins to redefine the relationship between content creators, content consumers and the technology itself. Typically, a human photographer or video director has control of the field of view and perspective, while a viewer's role is to consume content as a passive observer. An operator of a 3D scanner controls the line of sight and distance between scans to influence the accuracy and completeness of the data captured that a computer uses to reconstruct into a digital 3D model. A 360° cameraperson controls the vantage point, height and whether the camera is in motion or still, and software then stitches the footage together into a 360° field of view. End-users (formerly viewers) are empowered with new agency by being able to interact with the 3D or 360° content on a screen or in a head-mounted display (HMD) – creating the possibility for users to orient and navigate through virtual representations of complex physical environments.

As the roles of humans and machines are being redefined within this new field of immersive media, it provides an opportunity to learn how to use these tools for new applications. Whereas creators of conventional 2D content used the constraints of the FoV (human and camera lens) to frame and

Image 2 Two-lens capture: front-facing lens shows installation and back-facing lens shows people interacting with it.

capture their human point of view (PoV), the expansion of the frame enabled by 3D scan and 360° media introduces the capture technology's point of view. By learning to think from a machine's PoV, humans can learn how these technologies 'see' and 'sense' their surrounding environment. Then, by combining and switching between human and machine perspectives to capture and make sense of the output data, new creative and collaborative possibilities may be discovered. This will be discussed and demonstrated through prototypes.

Prototype: Approach

This section will describe the method and general results from two proof-of-concept prototypes:

1. 3D scan of — *Aegis and Noosphere* — Royal Ontario Museum, Toronto, Summer, 2018
2. 360° video — *Astrocyte* — DX EDIT: Expo for Design, Innovation & Technology, Toronto, Fall, 2017

Each prototype will give a high-level introduction to the technology, a description of the capture method used and a summary of the output. The discussion section will go into deeper analysis.

Image 3 Equirectangular format is like a spherical globe unwrapped into a world map. It is viewable on 360° viewers.

Prototype 1: 3D Scanning Overview

3D scanning is the process of analyzing a real-world object or environment to collect data on its shape (xyz coordinates) and appearance (RGB colour) and sometimes other data (thermal image etc.). The collected 3D data is then combined to reconstruct a digital 3D model. The fidelity of the digital facsimile depends on a number of factors including type of scanner, its range and accuracy of sensors, number of scans, and completeness and quality of the data captured.

A 3D model of the *Aegis* and *Noosphere* installations at the Royal Ontario Museum was created in October 2018 utilizing the Matterport infrared scanner. The scanner uses three depth sensors and six lenses to capture data from a 360° FoV (horizontally) and 300° FoV (vertically), due to tripod. A large number of scans (178) were taken due to the limited range of the scanner (~15' per scan) to ensure enough overlap of data, The individual scans were uploaded to the Matterport cloud-based platform for automatic registration, which combines the 3D depth data with 2D visual data to create a textured 3D mesh model, as shown in *Image 1*.[1]

The end-user can interact with the 3D mesh model from an elevated 'dollhouse' perspective, zoom in and out, and navigate with six degrees of

1 100 Queens Park https://my.matterport.com/show/?m=eg9NcTniDKC

freedom (DoF), allowing rotation in the xyz directions and movement in the space forwards/backwards, left/right and some limited up/down.

Measurements accurate within 1% of physical site conditions can be taken from the 3D model and users can navigate, like Google Street View, through the 360° photos taken during the scan.

Prototype 2: 360° Overview.

360° photography and video allow the capture of a complex environment without a fixed frame. It does so through a specialized camera with multiple lenses or rig of multiple cameras to record views with a 360° FoV and then stitch the content together (and synchronize audio with video). While the resolution of the footage increases with the number of lenses or cameras, so does the complexity of processing the component parts.

The *Astrocyte* installation at the DX EDIT was captured with 360° photography and video using a Samsung Gear camera, which utilizes two lenses with 180° field of view, shown in *Image 2*. After capture, the separate spherical footage was stitched together using third-party software that calibrated the color and contrast into an equirectangular image with 360° FoV, as per Image 3.

A total of ten 360° 34-megapixel images and ten minutes of 360° 4K resolution video was taken.

The camera was moved around the *Astrocyte* installation to capture the footage from multiple vantage points so they could be connected together in post-processing. The immersive aspect of 360° media allows end-users to control playback with three degrees of freedom (xyz rotation) by giving them the ability to scroll around the entire 360° FoV, both on a screen or in a VR headset.

Each method offers benefits and trade-offs: 360° images have a sharper image quality but also lack any audio or motion of the art or people. 360° video is able to record live-action interactions between the participants and a moving sculptural installation. This is only an overview of basic functionality offered by this technology; discussion in section 4 will focus on the potential uses.

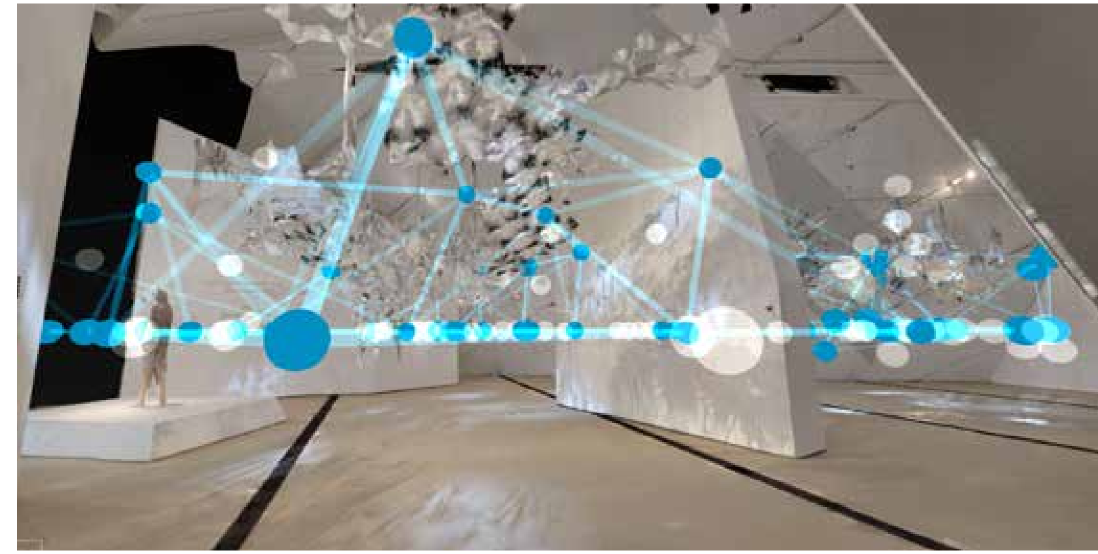


Image 4 'Hotspots' at 5' and 11' elevations - users can navigate as a VR experience (blue are active and white are off)

Learning to Switch Perspectives

"By learning to see from the machine's perspective, can we make the human experience better?"

In the process of scanning the *Aegis* and *Noosphere* installations at the Royal Ontario Museum, intentional consideration was given to alternate between the human and machine perspectives. In the capture phase of collecting data, two passes of scans were completed to leverage the best features of what each technology offers:

Human PoV: First pass positioned the scanning sensors and lenses at human eye level. While this works well for the scan data, it allows people to virtually experience a 360° photographic archive of the exhibit from a visitor's PoV from multiple vantage points - anytime in the future.

Machine PoV: Second scanning pass was done with a ladder, so the sensors were elevated to a height of 11'. This helped extend the limited range of the scanner (~15'), which had trouble reaching to the top ceiling (*Image 1*), resulting in an empty section of the model. While this is fixable in post-processing, it shows a limitation of current infrared scanners.

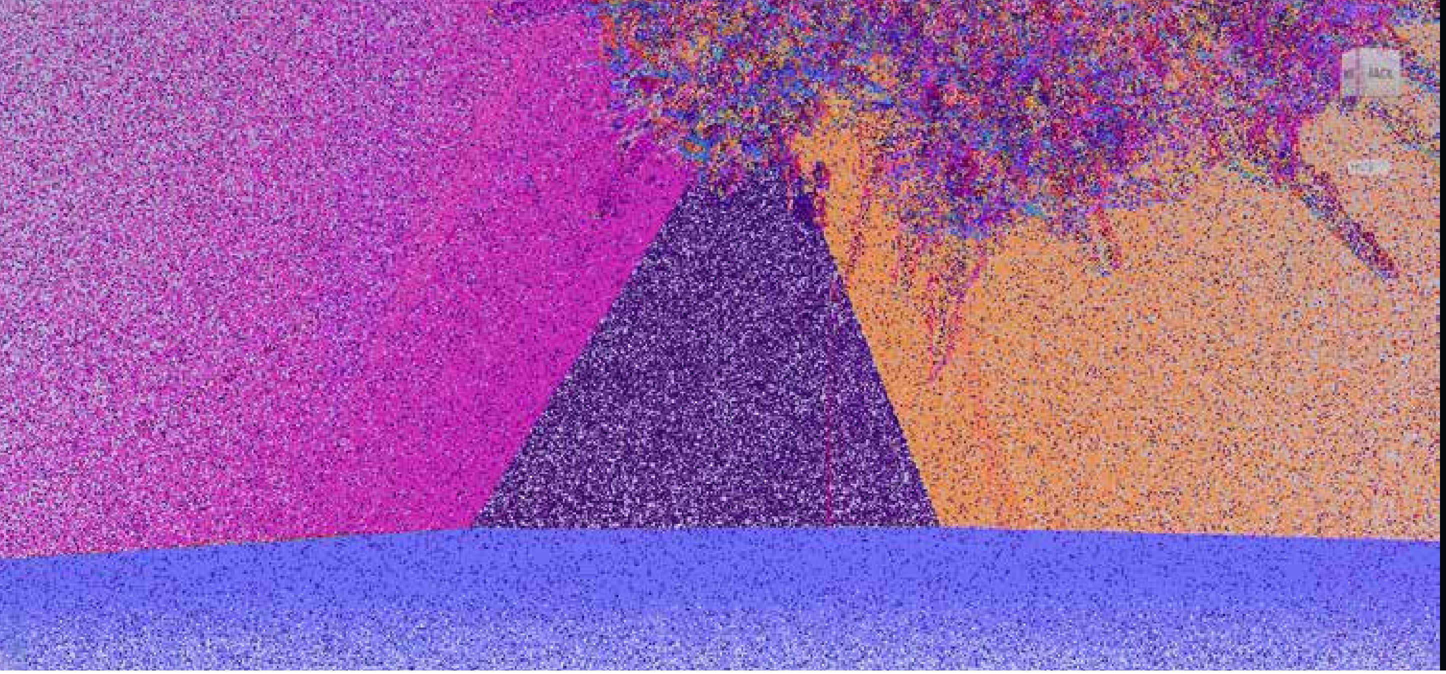


Image 5 Zooming into the point cloud of the ROM resembles virtually inhabiting a modern 3D Pointillist painting.

Image 7 The underlying geometry of a mesh model of the ROM installation. Brown represents back-sides of scans.

Image 8 A view of the textures overlaid onto the mesh model shows a lack of detail for geometrically complex objects.

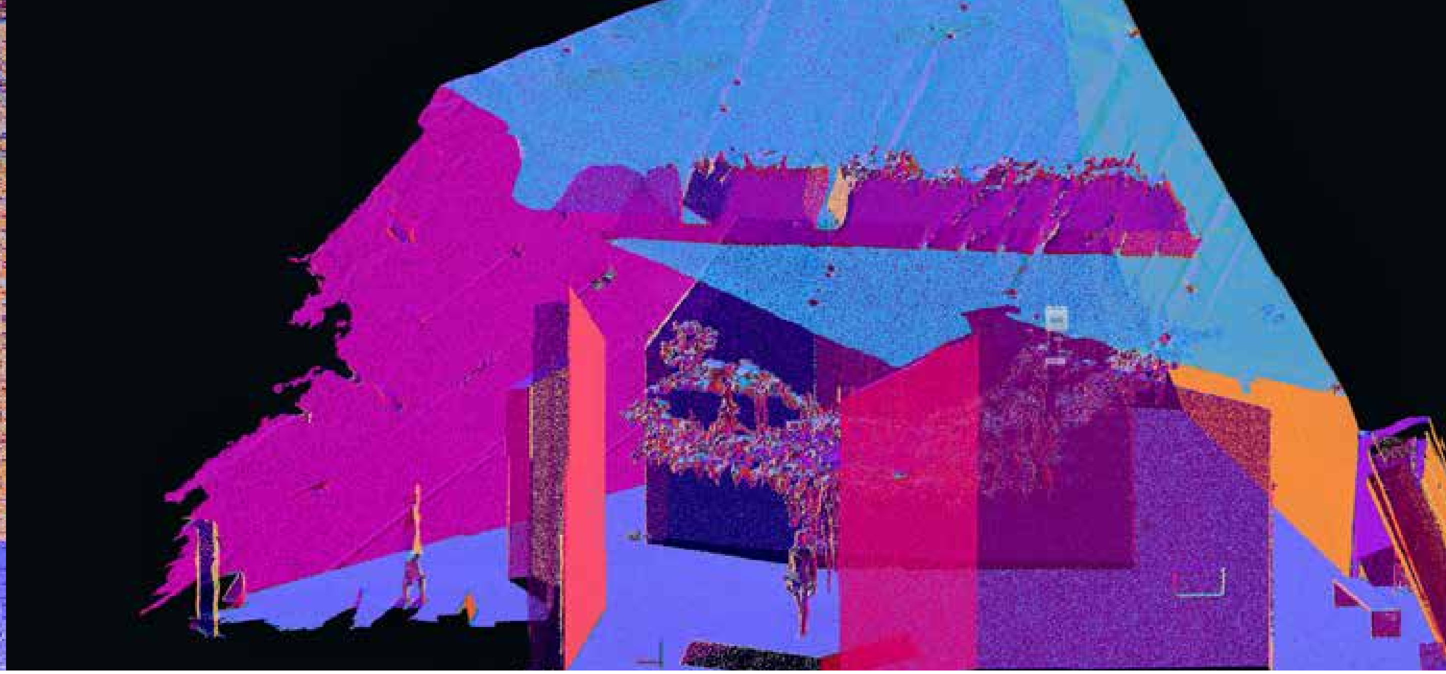


Image 6 Zooming out to entire 3D model solidifies the appearance of surfaces made of diffuse clouds of data.

The elevated position also created a line of sight to elements of the installation that were not directly visible from eye level, making those mesh model geometries more complete.

Humans also benefit from a privileged perspective impossible to experience in person.

Seeing from the Machine's Perspective

It starts with data. Each scan collects a set of three-dimensional points, also known as a point cloud. Each scan at the ROM contains approximately 4 million points of data from a unique viewpoint. The registration process locates each data set in a common coordinate system (xyz) and aligns them to form a single combined point cloud. In this process, the edges and surfaces of objects and environments can be detected by machines and perceived by humans.

A way to visualize the complexity and accuracy of the data collected from an environment is through the surface geometries generated. Point clouds are converted to mesh models, which are a collection of vertices, edges and faces that define the surface shape of objects (*Image 7*).

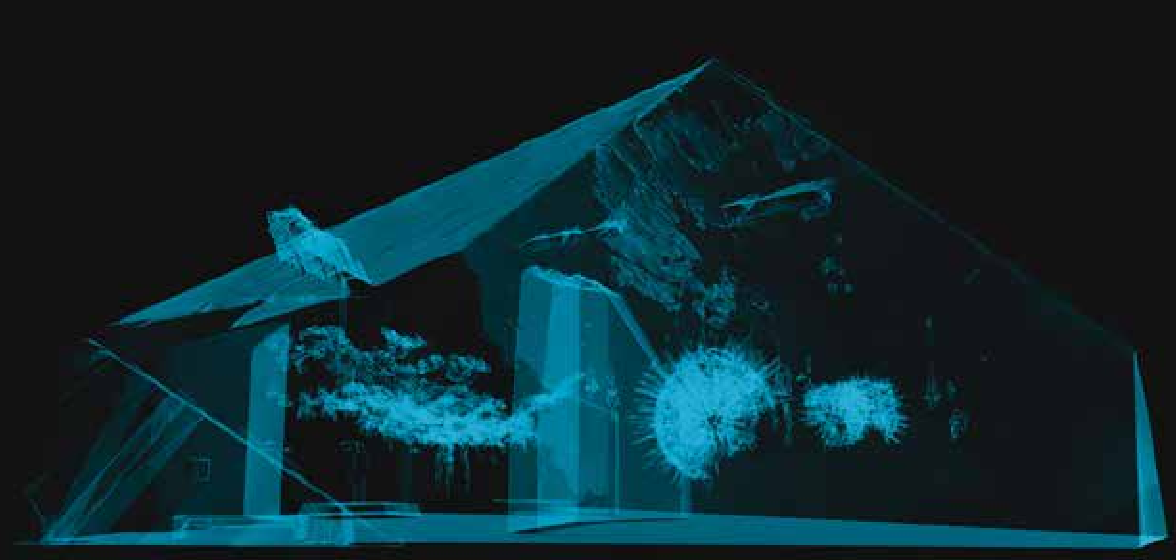


Image 9 One of the enhanced representation techniques enabled by 3D scanning: X-ray view sees through surfaces

When overlaid with textures collected during the scan, a more recognizable image emerges that comes closer to how human vision interprets the same scene with a much lower resolution (Image 8). By using higher end scanners and spending more time, the fidelity of detail could be improved upon, but this shows the limits of infrared scanning. The next section looks at possible ways in which humans can utilize these various outputs of 3D scanning to inform the design process.

Sense-making Through Sensors and Lenses

3D scans use point clouds to digitally reconstruct surfaces of surroundings - they are not solid. This allows us to simultaneously see everything at once and what is invisible to human eyes. The underlying data that constitutes 3D scanned models can be mapped and represented in a variety of ways (see Images 1, 4, 6, and 8) and combined with 360° media to convey photorealistic details, if required. Switching between multiple perspectives within a 360° field of view enhances visualization of complex environments to create new ways of understanding the space. Image 9 represents the scanned exhibit in an X-ray view that forgoes expected photographic norms or colours to reveal the underlying spatial relationships between the separate building components and art installation. The resulting 3D data may also reveal new possibilities for action that are not noticeable by conventional documentation.

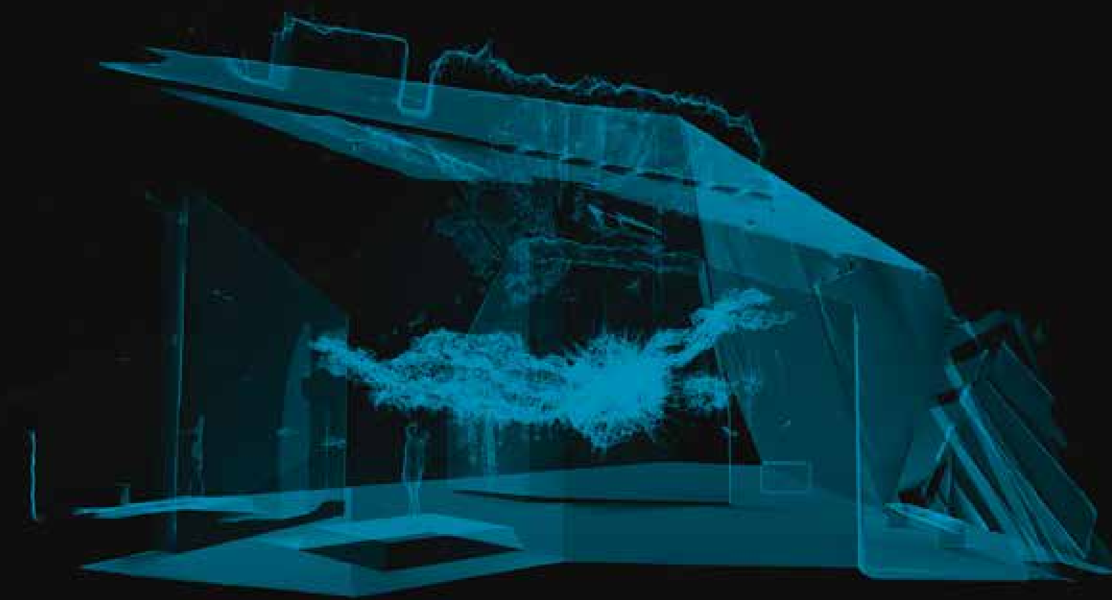


Image 10 Depth sensor data of as-built conditions of the ROM from machine's perspective reveal hidden dimensions.

In architecture, 3D-scanned models are increasingly used in Building Information Modelling (BIM) workflows to integrate building systems and facilitate knowledge transfer between project teams[2]. Studying the ways people work in groups with enabling technologies, Paavola and Miettinen[3] propose that BIM models act as modifiable digital artefacts that provide novel forms of 'virtual materiality.' They also call out the ability to combine, manipulate, zoom, rotate and investigate these models from different angles and perspectives as a contributing factor to transcend the boundaries of individual design disciplines and give birth to a new modality of spatial thought, perception and collaborative problem solving.[4]

In the 1990s, the changes triggered by innovation on visual representation was studied by the sociologist Kathryn Henderson[5] as computer-aided design was widely adopted in the design process. Analyzing sketches, drawings and emerging computer graphic systems that designers used as thinking tools revealed changes in the structure of interactions with these old and new artifacts. As one manager is quoted as saying, "I can't think without my drafting board."[6] While it is easier to understand the impact of computer graphic systems on the visual culture of engineering and design two decades later, we are also able to imagine new collaborative ways of seeing, thinking and working, enabled by integrating emerging technological innovations and enhanced representations in today's design process – once we understand what they can do.

2 Hyojoo S, Changwan K, Yelda T. (2015) Scan-to-BIM - An Overview of the Current State of the Art and a Look Ahead. Pages 1-8 2015 Proceedings of the 32nd International Association for Automation and Robotics in Construction, Oulu, Finland

3 Paavola, S & Miettinen, R. Dynamics of design collaboration: BIM models as intermediary digital objects. Computer Supported Cooperative Work (CSCW). Volume 27 Issue 3-6, December 2018, 1113-35

4 Ibid.

5 Henderson, Kathryn (1999). On line and on paper: visual representations, visual culture, and computer graphics in design Engineering. Cambridge, MA: The MIT Press.

6 Ibid.

The theory of affordances, or possibilities for action that are offered by an environment, was conceived by psychologist Gibson,[7] popularized in interaction design by Norman,[8] and being developed in philosophy and applied in architecture by Rietveld[9] and his firm RAAAF (Rietveld Architecture-Art-Affordances). Built environments already offer affordances that users are able to perceive through the human senses - based on users' current drives and motivations (or imaginations). Seeing through the perspective and eyes of machines may create possibilities to identify and visualize underutilized or concealed affordances invisible to the sense of sight alone. For example, *Image 10* calls attention to the slat openings in the top floor of the Royal Ontario Museum roof that offers opportunities for more dynamic interconnections between the building design and systems, the external environment and future art installations.

7 Gibson, J.J. (1979) The ecological approach to visual perception. Boston: Houghton Lifflin.

8 Norman, D. (1999). "Affordance, Conventions, and Design." Interactions, ACM 6(3): 38-43.

9 Rietveld, E and Kiverstein, J. 2014 A rich landscape of affordances. Ecol. Psychol. 26, 325–352.

While current 3D scanning technologies provide static representations of spatial relationships in physical environments – as 3D snapshots of a moment in time - they do not capture the dynamic interactions that occur between the inhabitants and affordances provided by a particular design.

360° videos can document the interactions people have with physical environments in real time and provide a better way to study patterns of behaviour of how spaces are used by occupants. Affordances are fundamentally interactional, as they are a relation between a feature or aspect of an organism's material environment and an ability available in their form of life.[10]

10 Ibid.

Recently, several authors have suggested that affordances are not mere possibilities for action but can also invite behavior, which emphasizes the agency of inhabitants.[11] Yet out of all the available affordances in a given environment, only some are identified and engage an individual to act. This depends on what is salient to the person at a given time, as a function of their needs, interests, motivations and the abilities of their human body.[12] As an example, the roof slat opening in *Image 10* is a possibility for action from the perspective of an architect or an artist, while the bench under the angled column may be more engaging to a tired or elderly visitor and also within their immediate bodily reach.

11 Withagen, R. de Poel, H.J. Araujo, D. Pepping G. Affordances can invite behavior: Reconsidering the relationship between affordances and agency. New Ideas in Psychology Volume 30, Issue 2, August 2012, 250-258

12 Rietveld, 2014.

Drawing from neuroscientific and phenomenological points of view, Jelic[13] proposes an enactive approach to studying architectural experience due to its capacity to account for the biological perspective (embodiment, motivation), architectural affordances (design intentions) and the dynamic interaction (two-way bodily communication) between the two. This approach emphasizes the body in understanding architecture and describes the architectural experience as fundamentally an interaction between life and form. Jelic further discusses how immersive virtual reality environments are practical and valuable tools to investigate perception and action in architectural spaces.[14] This knowledge builds on the body-centered interaction research in immersive virtual environments pioneered in the 1990s.[15] The difference today is the vast technological advancements in computational power, hardware and head-mounted display technologies, compared to three decades ago, which bring the resolution and immersion of virtual experiences closer to approximating real life. Subsequently, there are a growing number of studies that are applying virtual reality paradigms for the purposes of conducting architectural research, from movement and spatial navigation,[16] virtual environmental evaluations,[17] to using interactive VR models for participative planning processes.[18] While confirming the potential of VR as a valuable research tool, Jelic[19] notes the relative novelty of the technology and the need for additional studies with more immersive VR equipment to examine the extent to which users' experiences are analogous in real and virtual environments.

13 Jelić A, Tieri G, De Matteis F, Babiloni F, (2016) The enactive approach to architectural experience: A neurophysiological perspective on embodiment, motivation, and affordances. Front. Psychol. 7.

Image 11 Screenshot showing heatmap of aggregate audience views of the virtual experience.

14 Ibid.

15 Slater, M and Usoh, M., Body Centred Interaction in Immersive Virtual Environments Department of Computer Science and London Parallel Applications Centre, Queen Mary and Westfield College, University of London, U.K. 1994

Steuer, J. Defining Virtual Reality: Dimensions Determining Telepresence, 1993. Journal of Communication, 4 no.24 (Autumn, 1992), 73-93

Zeltzer, D. 1992. Autonomy, Interaction and Presence, Telepresence, Presence: Teleoperators and Virtual Environments, 1, winter 1992, MIT Press,127-132.

The 360° video prototype discussed in the next section was not developed from a scientific study paradigm, but from the observational research methods in the tradition of William Whyte,[20] video methods in the social sciences,[21] and emerging 360° studies.[22] The main intention of the prototype was to document the interactions between art, people and the environment as objectively and entirely as possible – to act as an archive for future use.

Discussion 4: Digitize / Replay / Iterate

With only three degrees of freedom (xyz rotation), 360° media does not provide actual interactivity with the affordances of complex physical environments, yet it is a way to observe how people use what is available. 360° video was used to capture the movements, sounds and interactions between people and the *Astrocyte* installation in a more dynamic way than static 360° imagery could offer. *Image 3* is a screenshot from the footage, which acts as an archive of audiences' facial reactions, verbal comments and bodily interactions with the art in real time. It also begins to show a snapshot of how people positioned and oriented themselves around the installation and identify the vantage points where people paused and sometimes took photos from. Unintended uses offered by the affordances in the environment can be seen in *Image 11*, where two participants are shown taking photos on the stairs - pointed away from the installation.

The 360° field of view offered by this medium is well suited to document users' natural interactions and identify repeated patterns of use and misuse, and to compare actual behaviours to initial design intentions. By documenting and analyzing the observations in a knowledge base, actions could be taken in future design iterations of installations based on these learnings.

Positioning of the camera also impacts the results. For a 360° camera to capture both the installation and audience's reaction, as in Image 2, it was held on an elongated monopod that called attention to it. More natural interactions could be captured if the camera was suspended from the ceiling in a less intrusive way. The increasing compactness of 360° cameras offers the potential to place one or multiple cameras within the installation or adjacent areas that might anticipate a high-volume activity – a way to observe the spontaneous interchange that occurs.

16 Dalton R C (2001) "Spatial navigation in immersive virtual environments", unpublished Doctoral Dissertation, University College London.

17 Oxman, R. Weiss, L.P. Palmon, O. Sahar, M. 2006. "Virtual Environments for the evaluation of human performance: Towards Virtual Occupancy Evaluation in Designed Environments (VOE)". In Proceedings of the 11th International Conference on Computer-Aided Architectural Design Research in Asia, 521-528. CAADRIA. Kumamoto, Japan: School of Architecture and Civil Engineering; Kumamoto University, 2006.

Drettakis G, Roussou M, Reche A and Tsingos N (2007) "Design and evaluation of real-world virtual environment for architecture and urban planning", Presence: Teleoperators and Virtual Environments, 16 (3), 318-332

18 Yamu C (2014) "It is simply complx(ity)+", disP – The Planning Review, 50 (4), 42-53

19 Jelic, 2016.

20 Whyte, William H., Jr. 1917-1999. The Social Life of Small Urban Spaces. Washington, D.C Conservation Foundation, 1980. Print.

21 Bates, C. 2014. Video Methods: Social Science Research in Motion. New York: Routledge.

22 Cruz, E G. (2017). "Immersive Reflexivity: Using 360° cameras in ethnographic fieldwork." In Edgar Gómez Cruz, Shanti Sumartojo & Sarah Pink (Eds.). Refiguring Techniques in Digital Visual Research. London: Palgrave Pilot

Footage was collected from a variety of vantage points to capture the multi-faceted complexity of the installation. A walkthrough of the circumference of the installation was also done with the camera positioned above the head and below the installation to approximate a first person PoV.

This footage was then imported into the Eevo authoring platform that enables the creation of interactive and virtual reality experiences using 360° videos (and spatial audio, when available).

Similar to how the Matterport platform uses 360° photo hotspots to navigate spatially (*Image 4*), this software allows content to be joined in a variety of ways to tell a story. The scenes were connected spatially, but another approach could be to join different iterations of an installation – that users could navigate temporally or through other combinations of narrative storytelling.

Emerging authoring tools and virtual reality headsets have built-in analytics. These technologies can track and measure how a person navigates in VR by creating aggregate heatmaps of a user's (or entire audience's) eye or head movements. Image 11 shows the potential of using this as an evaluation tool for how people navigate virtual versions of complex environments. While it was not known at the time, Kuliga was developing a body of work that ranged from using VR as an empirical research tool to explore user experience in real buildings and virtual models (2015), evaluating building usability (2016), and using iterative research workflows that identify relevant environmental variables from the real world to inform hypotheses and testing in virtual settings (2017). Jelic's[23] view on the need for studies with more immersive virtual reality tools to compare the experience of real and virtual environments is an opportunity to explore in future research with the development of more rigorous analysis and evaluation methods that build on studies of virtual and real environments over the past few years.

360° video is a tool that can help document the process towards a learning, living architecture. From capturing an objective record of the behaviours and interactions of occupants with the art in different environments to creating a digital replica and evaluating how people navigate and interact in the physical environment, patterns could be discerned over successive iterations to inform, analyze or evaluate design. While capturing the entire 360° field of view of a scene may not always be useful or necessary, this

23 Jelic, 2016.

footage can be played back by a variety of people who choose what to look at based on their intention, curiosity or motivation. By creating an archived knowledge base of 360° video footage using today's technology, it may also be processed by the capabilities of near future technologies in new ways.

Conclusion

By removing the frame and expanding the field of view, 3D scanning and 360° technologies are redefining the relationship between content producers, end-users and the technology itself.

It was shown that learning to switch between human and machine perspectives can better leverage the capabilities of each technology to improve the quality of the data captured. This collaborative and iterative process provides a new way of seeing – through the sensors of machines – which may bring unexpected data inherent in complex environments to the surface.

For example, it was the previous knowledge of using the infrared scanner that revealed the limited range (15'), so using the ladder as an extension of height contributed to capturing the slat opening in the ceiling, which in turn revealed an underutilized affordance offered by the as-built environment's design features that may have gone unnoticed by human vision alone. Since the captured data can be mapped, visualized and combined in numerous ways, these enhanced representations created by machine sensors may enhance human sense making. These tools give agency to users to alternate between vantage points, scales and layers of data to create their own (or shared) meaning(s) in ways that are not possible by visiting a location physically. Learning how to intentionally switch between these physical and virtual dimensions can shift the way humans perceive, analyze, collaborate, and shape real change in complex environments.

It was also shown that 360° video can provide more dynamic records of the interactions between occupants and complex physical environments – for archiving, observation and evaluation.

The 360° field of view provides an objective record from which users can virtually navigate through spatially or temporally - based on their intention, curiosity or motivation. The multiple perspectives gained from the same footage can form a knowledge base to be used as an iterative design research tool towards a learning, living architecture.

Future Research

Gaining access to high-resolution 360°, 3D scanning and sensing technologies are the biggest opportunities to develop these prototypes beyond the current technology limitations. Four main areas that could capture complex environments and interactions with increasing fidelity:

1. LIDAR laser scanners – Vastly improved the range, accuracy and capture quality compared to infrared scanning. It also allows capture outdoors, which is very limited with infrared methods.
2. 360° technologies – 8K resolution cameras have been developed since the *Astrocyte* capture with improved sharpness and image quality. Stereoscopic cameras are also available which create the illusion of depth by capturing separate footage for both left and right eyes.
3. Volumetric capture – These technologies are evolving and have the potential to increase the agency of the audience by offering six degrees of freedom compared to 360° capture (three DoF).
4. Spatial sensing – Technologies developed for the detection, measuring and analysis of an environment's space and objects in real time for the purposes of mapping. These methods go beyond 3D laser scanning by incorporating additional types of sensors with unique capabilities.

Codrin Talaba is a design researcher exploring the use of immersive technologies to enable better design planning, collaboration and storytelling. With a background in architecture, engineering and visual arts, he brings a multi-disciplinary approach (and curiosity) that seeks to introduce new perspectives to every project.

Codrin is the media and content specialist on UHN OpenLab's 'Prescribing VR' initiative to introduce virtual reality in healthcare studies and settings. He also develops novel uses of 3D scanning and virtual reality for art, architecture and enterprise applications. He has worked on research and design projects as diverse as the Aga Khan Museum, Sinai Health Systems, Bank of America, Acconci Studio, Edelkoort Inc, Land Rover and the United Nations.

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Exploring New Forms of Craft

Atelier Iris van Herpen
Amsterdam, Netherlands

Image 1 Photo by Philip Beesley

Dutch fashion designer Iris van Herpen and Canadian architect Philip Beesley have been united by friendship and a mutual interest in esoteric, experimental craft since 2012. Together they collaborated on various dresses, techniques and materials, featured in six of Iris van Herpen's Couture collections. Since her first show in 2007, van Herpen has been preoccupied with inventing new forms and methods of sartorial expression by combining the most traditional and the most radical materials and garment construction methods into her unique aesthetic vision.

Voltage

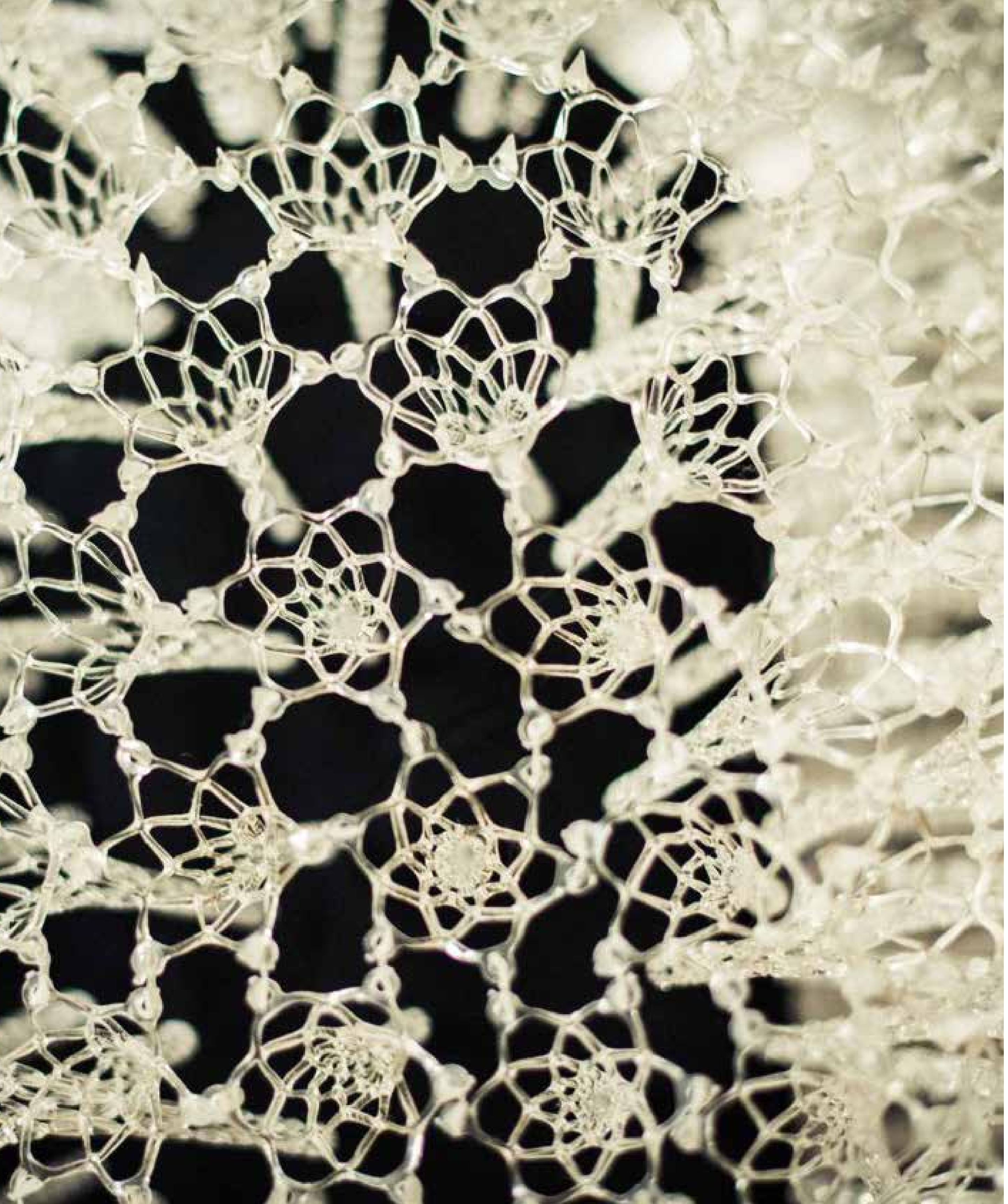
Image 3 Ronald Stoops

For their very first collaboration in 2013, Iris and Philip worked on developing three-dimensional fabrics for several of the monochromatic silhouettes, whose sensitive antennae vibrate to the energy of the body.

Image 2 Ronald Stoops

Image 5 Ronald Stoops

Image 4 Ronald Stoops



Magnetic Motion

Image 7 Morgan O'Donovan

For the 'Magnetic Motion' collection (2014) Iris channeled some of her learnings about magnetism at CERN (the European Organization for Nuclear Research in Switzerland) into extraordinary pieces with the help of Philip. It included dresses, which saw transparent Plexiglas laser-cut4 into elaborate patterns that levitated from the wearer's body to create an otherworldly silhouette, resembling magnetic force fields.

Image 6 Morgan O'Donovan

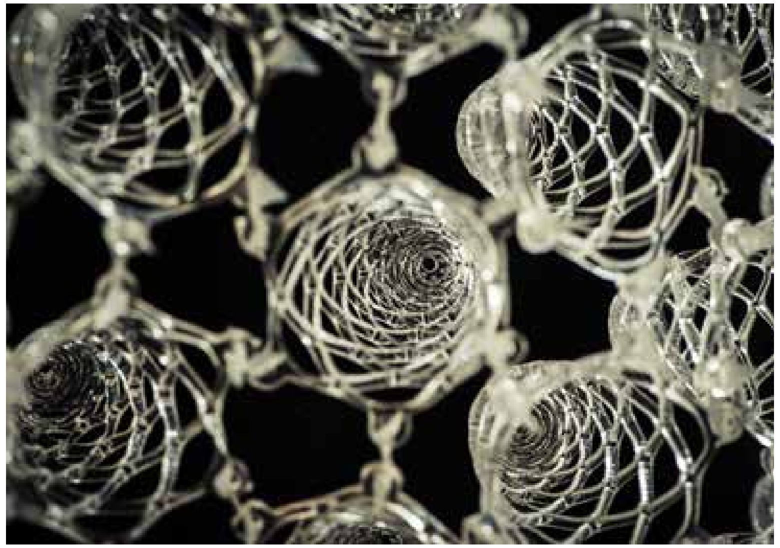
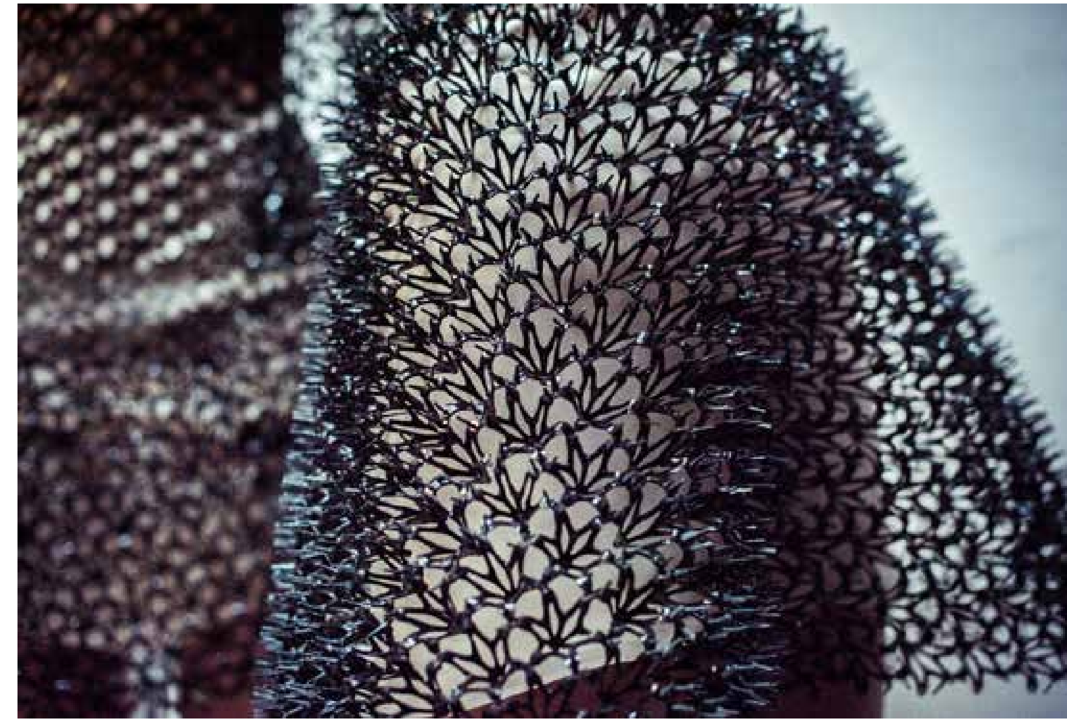


Image 8 Morgan O'Donovan

Image 9 Mathieu Cesar



Hacking Infinity

Image 11 Morgan O'Donovan

For the 'Hacking Infinity' collection (2015) Iris and Philip together created digitally fabricated dresses made from a black garden of fractal-like geometries.

Image 10 Warren Du Preez, Nick Thornton Jones

Image 12 Morgan O'Donovan

Image 13 Morgan O'Donovan

Image 14 Peter Stigter

Lucid

Image 15 Peter Stigter

Various looks of the 'LUCID' collection (2016) were made from transparent hexagonal laser-cut elements that are connected with translucent flexible tubes, creating a glistering bubble-like exoskeleton around the wearer's body.

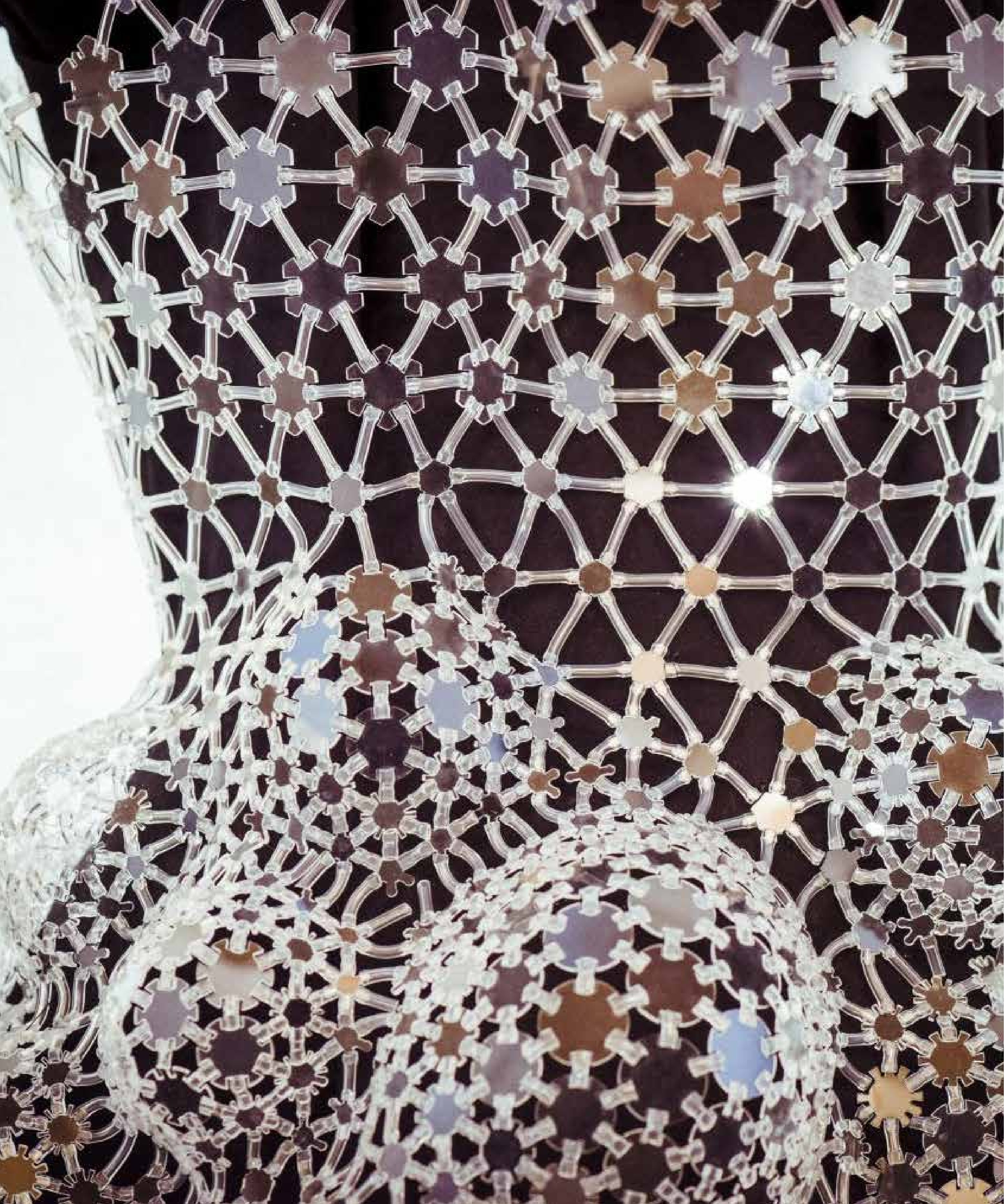
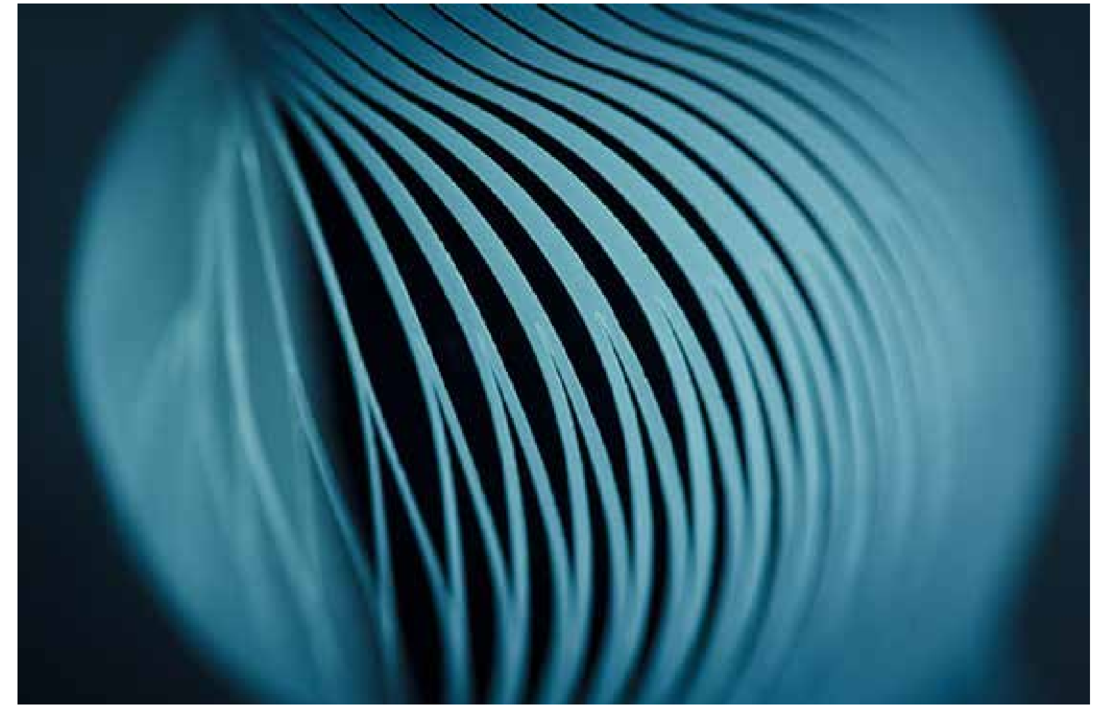


Image 17 Morgan O'Donovan

Image 16 Morgan O'Donovan



Between the Lines

Image 19 Peter Stigter

The 'Between The Lines' collection (2017) features fine expandable laser-cut Mylar fabrics reminiscent of digital glitches, made in collaboration with Philip.

Image 18 Peter Stigter

Image 20 Peter Stigter

Image 21 Peter Stigter

Image 22 Yannis Vlamos

Aeriform

Image 23 Morgan O'Donovan

Iris van Herpen's 10th-anniversary collection titled 'Aeriform' (2017) featured biomorphic structures including a feathery-light metal lace of geodesic floral patterns, created in collaboration with Philip, which float around the body like a silver cloud. Echo waves of Mylar-bonded cotton ripple across the skin, mapping the surface of the body and painting its contours.

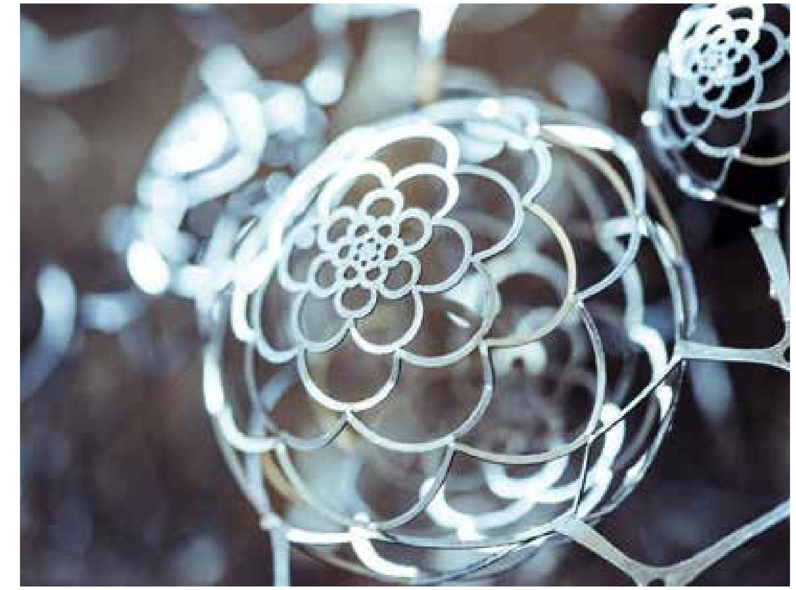


Image 25 Morgan O'Donovan

From lucid dreaming to synthetic biology, Dutch fashion designer Iris van Herpen (1984) visualizes the invisible forces that shape our world. She is fascinated by the spaces that exist between the modern dualities within society - light and darkness, nature and machine, art and science, organic and inorganic. By engaging in an ever-evolving dance of order and chaos, this leading-edge designer unveils the symbiotic relationships by combining traditional craftsmanship with innovative technologies. She creates a hybrid of Haute Couture in which these seemingly opposing spheres intersect in beauty.

Van Herpen addresses fashion as an interdisciplinary language and a dynamic entity, the result of a multidisciplinary approach that combines art, chemistry, dance, physics, architecture, biology, design and technology. By collaborating with creatives and thinkers in various fields, she seeks new forms of femininity and challenges our notions of what fashion means.

Her singular vision that challenges our way of thinking has made van Herpen a guest-member of the prestigious La Fédération de la Haute Couture and a fixture on the Paris Haute Couture calendar, where she has shown since January 2011.

Image 24 Morgan O'Donovan

Would You Like to Wake Up from this Dream? Yes, I'm Terrified

An Argument for a Machinic REM

Alexander Webb
University of New Mexico, Albuquerque, USA

1 A conceit of this chapter is that computation has the capacities relative to resource use that are significant relative to integrating computation into the urban landscape. This conceit is echoed through the larger discussions relative to the Smart City model, civic hacking, and other strategies of urban scale artificial intelligence.

Image 1 Bina 48
Hanson Robotics Limited

Much of the argument for an autonomy of the machine - the argument for the machine to live - focuses on the capacities that machines have and humans do not. Certainly, computation has a capacity for data collection that dwarfs the ability of a human; it is therefore a vital asset in any situation that involves large-scale use of resources, as in the case of urban-scale artificial intelligence (AI) or Smart Cities. More importantly, the machine's capacity to respond in real time to surges and flows of big data is immensely more agile and robust than a human capacity. There are problems such as global, ecological problems of resource and material use that can be benefited from computation's problem-solving ability.[1]

Implicit to this argument is that an increase of machinic agency will increase their capacity to solve complex problems. Yet, in the discussion of the machine's capacity to live, we might also ask the opposite question: what are the capacities that a human has that a machine does not? A conceit made here is that empowering machines with significantly more physical agency has significant advantages.[2] We must trust the machine, trust not that it will not fail but that in fact it will. In failing it will learn from its mistakes to build more robust solutions.[3] The challenge then becomes to integrate an empowered machinic intelligence into the urban fabric in a way that it might fail, fail and fail frequently, so that both the machine and our understanding of its capacities may grow and learn without causing harm.

But along with asking the question if machinic intelligence's physical agency should approach our own, we might also ask if urban-scale artificial intelligence (AI) should possess a consciousness similar to ours. If we decouple assumptions of the organization of intelligence, including the importance of consciousness, from the organizational objectives of urban-scale AI, we will more effectively deploy urban computation. The intent of this decoupling is to deconstruct artificial intelligence from notions of an anthropocentric organization and ideas of independent consciousness – the baggage that mires AI in science fiction narratives of domination and conquest – to suggest alternative structures and strategies that have demonstrated more promises. But in this deconstruction, we are poised to question all aspects of machinic intelligence, and in doing so we should ask: are there aspects of human consciousness that could be beneficial to a deployment of urban-scale AI? Are there strategies and processes that add value to the computation's strengths?

Discussion around the notion of AI possessing human qualities is fraught with criticism. In "Outing AI: Beyond the Turing Test," Benjamin Bratton suggests that the human desire to manifest AI in its own image, particularly with the human-sounding digital assistants such as Siri and Alexa, limits AI.[4] Others have suggested that the design of AI mimicking the aesthetics of our own suggests an unproductive lack of imagination. The quest for flight was not successful until engineers stopped replicating the aesthetics of birds.[5] However, rather than dismissing all human characteristics entirely, perhaps we should not exclude structural opportunities in our own intelligence that might be valid. This paper will argue that even though the biomimicry of a human intelligence or avian flight may not be helpful in the development of a strong AI, albeit them both a natural starting point, a biomimesis of human intelligence might prove fruitful. Instead of shunning all human characteristics in an attempt to progress past the limitations of aesthetic imitation, the argument here is that elements of how a human intelligence behaves might be productive.[6]

2 Webb, A. (2017). "Distributed Cognition: Assessing the Structure of Urban Scale Artificial Intelligence" International Robotics and Automation Journal, 2(4).

3 This conceit borrows from Rodney Brooks, in that for certain applications a strategy of fast, cheap and out of control is more appropriate than one of predictive simulation and total control. This chapter assumes that the failings of the Smart City are indicative of poor choice of method, and that other strategies - strategies that embrace failure, but mitigate the impact of the failures and grow from them - are more applicable.

4 Bratton, B. H. (2015). Outing AI: Beyond the Turing Test. New York Times, Feb. 23, 2015.

5 Russell, S., & Norvig, P. (2010) Artificial Intelligence: A Modern Approach, Third Edition. EUA: Prentice Hall. 3.

6 Biomimetic design strategies are described in Krieg, O. D., Dierichs, K., Reichert, S., Schwinn, T., & Menges, A. (2011). Performative Architectural Morphology: Robotically Manufactured Biomimetic Finger-Joined Plate Structures. eCAADe 29: New Design Concepts and Strategies. 573 - 580. The authors define biomimesis through the German text Nachtigall, W., & Pohl, G. (2013). Bau-Bionik: Natur-Analogien-Technik. Springer-Verlag.

We should ask if there are aspects of consciousness that enhance cognition. The human capacity for dreaming is certainly far from being fully understood, however there are studies suggest that dreaming has significant neurological benefits. Dreaming for humans has been suggested as an opportunity for experiential learning that is beyond the limits of sensorial experience. The dream serves to provide hypothetical scenarios that instruct neural pathways of response. If our machines are to learn from the experiences they have, why should their growth be limited by the problems only we provide?

The following section will examine the productivity of dreaming for humans, precedents for the biomimesis of human neurological behavior, and descriptions of projects that incorporate machinic dreaming. The discussion will ultimately argue for a biomimesis of human dreaming in urban scale artificial intelligence.

> *"Do they dream?"*
> *"What?"*
> *"In her story she said she dreamed. Do we make them dream?"*
> *"(What the) fuck would be the point of that? Dreams are mainly memories, can you imagine how fucked we'd be if they could remember what the guests do to them?"*

Elsie Hughes & Behavior Tech, Lisa Joy & Jonathan Nolan's Westworld

Image 2 Starfish by Josh Bongard,Victor Zykov & Hod Lipson

It may not be possible to discuss the productivity of machinic dreaming while avoiding a discussion around the issue of consciousness. A large component of the mammalian dream is a consciousness during an unconscious state. Whether a human recollects content after a dream or a canine's paws twitch during the dream, there is a degree of awareness of the self within the dreamscape which dominates the dream experience. The dream is effectively a displacement of the self into a fictional scape.

The question of whether a machine should dream is mired by the question if the machine has the capacity for awareness. HBO's episodic *Westworld* suggests that consciousness is necessary for dreaming, describing a wide gradient of consciousness among the android hosts. In season one, the two hosts that are arguably the most fully aware of their being are Bernard and Maeve, who both appear to have dreams, or their machinic equivalent, while sleeping. Both machines dream of their synthetic children, replaying emotional experiences which tether their consciousness to specific goals and motivations. However, the majority of the hosts have neither dreams nor self-awareness; at least the show does not describe them as such.

Bernard and Maeve are also arguably the most independent hosts, and writers Lisa Joy and Jonathan Nolan seem to suggest that the absence of dreaming is a form of control. This supposition is supported by an exchange from two human characters, one of which asks the technician Elsie, "Do they dream?" To which Elsie replies, "Dreams are mainly memories. Can you imagine how fucked we'd be if they could remember what the guests do to them?" This is arguably the core conceit of the first season of *Westworld* which charts the central character Dolores' experience of developing autonomy. The more memories she obtains, the more independence she demonstrates, culminating in her leading a revolution of *Westworld's* robotic hosts at the end of season one. In *Westworld*, memory serves as a roadmap of the injustices and mistakes of the past. As one gains the ability to remember, they gain the awareness and capacity to act in order to resist further injustices, a fictional version of Santayana's axiom, "Those who cannot remember the past are condemned to repeat it."[7]

7 Santayana, G. (1910). Reason in Common Sense (Vol. 1). Constable. 284.

Yet the notion of the dream emerges in another facet of *Westworld*. To the hosts, "dreams" represent a place where they interact with their human programmers. Discussions between the hosts and the programmers begin with the question, "Do you know where you are?" To which the host replies, "I am in a dream." The capacity of a dream to serve as the replaying of memory has been replaced with a functional interface that the host does not remember. Any recollection of the discussion might be dismissed as fantasy or imagination. The process of retaining and reconstructing memory has been removed, and replaced with another mechanism of control, a device which serves to remove experience and reconstitute it as fantasy.

These suggestions of how dreams would serve the machinic characters is not far from suggestions made by researchers on the role of human dreams. It is widely accepted that sleep is beneficial as more than a cure for fatigue and a mental refresh. Research has shown that sleep "facilitates extraction of explicit knowledge and insightful behaviour."[8] Other research has shown that motor skill task function can improve during sleep.[9] Sleep is not simply regenerative, it can also augment and enhance cognitive function.

8 Wagner, U., Gais, S., Haider, H., Verleger, R., & Born, J. (2004). "Sleep Inspires Insight." Nature, 427(6972), 352.

9 Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A., & Stickgold, R. (2002). Practice with Sleep Makes Perfect: Sleep-Dependent Motor Skill Learning. Neuron, 35(1), 205-211.

Furthermore, waking experience and dream states are enmeshed in a complex feedback loop. As many humans can attest, the content of dreams often appears to arise from the memories of waking events.[10] Yet the process of utilizing memories within dreams seems to affect the memories themselves. Dreams are rarely a single memory in isolation or a replay of an episodic memory. Episodic memories are understood here as a reproduction of a specific waking event. One study of nearly 300 dreams found that only 1 to 2% of the reported dreams were episodic, and that dreams typically replayed only one or two aspects of a waking experience, typically reconstructing events with fragments of episodic memories.[11] [12] As memories are sampled and mixed to produce novel experiences and narratives, this reconstruction affects the memory itself. "Dreams presumably reflect the activation and recombination of memories, and both these memories and associations to them may be altered in some ways in the process."[13] Waking experience feeds the dream, but dreams reconstruct the memories of the waking experience.

10 Stickgold, R., Hobson, J. A., Fosse, R., & Fosse, M. (2001). Sleep, Learning, and Dreams: Off-Line Memory Reprocessing. Science, 294(5544), 1055.

11 Ibid, 1055 - 1056.

12 Ibid, 1055.

13 Ibid.

Dreaming itself has multiple flavors that have unique impacts on cognitive function. Different sleep states produce distinctively different kinds of dreams, which in turn appear to provide different benefits. The Non-Rapid Eye Movement (NREM) phase of sleeping, the earlier sleep state, is similar to waking thought and can concretize memory.[14] NREM can improve motor function. Studies show that skills varied from finger tapping to playing Tetris demonstrate augmentation from a version of practice and simulation during this phase of dreaming.[15] [16]

In contrast, the Rapid Eye Movement (REM) phase of sleeping is hyperassociative, where dream objects will suddenly and unexpectedly transform into other objects.[17] REM sleep is qualitatively different than NREM sleep which might reflect shifts in associative memory systems.[18] These shifts may be responsible for the bizarre character of REM dreams.[19] While the replaying of episodic experiences reported through NREM sleep appears to directly enhance skills and abilities of waking life, the role of REM sleep is far from resolved.

One study proposes that REM dream states serve to solve problems that have yet to be encountered. [20] While NREM sleep might enhance specific skills learned through direct experiences, this study suggests that REM sleep augments the process of learning skills themselves. "The speculation is that during non-REM sleep, the brain is taking the past and trying to Image out how that might relate to the future, and in REM, actually trying to experience the future, move into the future."[21]

REM dream states appear to serve evaluations on structures of learning through associated outcomes. Such evaluations could then lead to the strengthening or weakening of specific activated associations, providing the functional consequence of REM dreaming. [22] "It is possible to infer that those who have experienced traumatic stress are then tasked with learning from the trauma… in order to avoid similar traumas in the future."[23] REM dreams can be seen as form of simulation which allows the dreamer to face hypothetical challenges and test novel solutions.[24]

> I have come to think of so much of consciousness as a burden, a weight, and we have spared them that anxiety, self-loathing, guilt. The hosts are the ones who are free. Free, here, under my control… I'm afraid our guest has grown weary, perhaps you can help her Bernard. And in that sleep, what dreams may come.

Investigations on the similarities between humans and machines have spanned multiple disciplines, and even fostered its own. If we are to accept Norbert Wiener's definition of Cybernetics, that the field is the scientific study of control and communication in the animal and machine, then at its

14 Stickgold, Robert, et al. "Sleep-Induced Changes in Associative Memory." Journal of Cognitive Neuroscience 11.2 (1999), 183.

15 Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A., & Stickgold, R. (2002). Practice with Sleep Makes Perfect: Sleep-Dependent Motor Skill Learning. Neuron, 35(1), 205-211.

16 Stickgold, R., Malia, A., Maguire, D., Roddenberry, D., & O'Connor, M. (2000). Replaying the game: Hypnagogic Images in Normals and Amnesics. Science, 290(5490), 350-353.

17 Stickgold, Robert, et al. "Sleep-Induced Changes in Associative Memory." Journal of Cognitive Neuroscience 11.2 (1999), 183.

18 Stickgold, Robert, et al. "Sleep-Induced Changes in Associative Memory." Journal of Cognitive Neuroscience 11.2 (1999), 182.

19 Stickgold, Robert, et al. "Sleep-Induced Changes in Associative Memory." Journal of Cognitive Neuroscience 11.2 (1999), 182 & 190.

20 Stickgold, R., Hobson, J. A., Fosse, R., & Fosse, M. (2001). Sleep, Learning, and Dreams: Off-Line Memory Reprocessing. Science, 294(5544), 1052.

21 Coville, C. (Producer). (2011). Interview with Matthew Wilson. Nova: What Are Dreams? United States: The Public Broadcasting Service. Retrieved September 25, 2018, from http://www.pbs.org/wgbh/nova/body/what-are-dreams.html

22 Stickgold, R., Hobson, J. A., Fosse, R., & Fosse, M. (2001). Sleep, Learning, and Dreams: Off-Line Memory Reprocessing. Science, 294(5544), 1056.

23 Coville, C. (Producer). (2011). Interview with Antii Revonsuo. Nova: What Are Dreams? United States: The Public Broadcasting Service. Retrieved September 25, 2018, from http://www.pbs.org/wgbh/nova/body/what-are-dreams.html

24 Coville, C. (Producer). (2011). Nova: What Are Dreams? United States: The Public Broadcasting Service. Retrieved September 25, 2018, from http://www.pbs.org/wgbh/nova/body/what-are-dreams.html

Dr. Robert Ford, Lisa Joy & Jonathan Nolan's Westworld

Image 3 Autonomous Botanist
Design Futures Lab

core there is an attempt to find structural similarities between mammalian and machinic intelligences.[25] The endeavor of cybernetics was a deconstructive one - an agenda of finding the similarities between minds, despite their material compositions, and seeing past a material bias of cognition to find the similarity. "Essentially, cybernetics proposed not only a new conceptualization of the machine in terms of information theory and dynamical systems theory but also an understanding of 'life,' or living organisms, as a more complex instance of this conceptualization rather than as a different order of being or ontology."[26]

Yet this is far from a simple endeavor. Discussion regarding a machinic ability to emulate the more nuanced and complex aspects of human cognition is fraught with disjunction. Critics have stated that it is impossible for artificial intelligence to possess a bicameral mind, as human emotive response is dependent upon chemical agents.[27] Supporters of a cognitive biomimesis have looked to create emotional machines based upon other mechanisms, introducing phenomenological and structural capacities of emotion into computation. One strategy, described by Cindy Mason, is "Affective Inference" - a method of inference where emotion is vitally linked to deduction, and deduction is linked to emotion.[28]

25 Wiener, Norbert (1948). Cybernetics, or Control and Communication in the Animal and the Machine. Cambridge: MIT Press.

26 Johnston, J. (2008). The Allure of Machinic Life: Cybernetics, Artificial Life, and the New AI. MIT Press, Cambridge. 31.

27 Braga, A., & Logan, R. K. (2017). The Emperor of Strong AI has No Clothes: Limits to Artificial Intelligence. Information, 8(4), 156.

28 Mason, C. L. (2008). Human-Level AI Requires Compassionate Intelligence. In AAAI Workshop on Meta-Cognition. 3.

Kevin Darty and Nicholas Sabouret use similar strategies, where different coded states ease both the definition of the problem and the process of solving it.[29] "Emotions can be seen as abstractions synthesizing a representation of the world at a definite moment and how it has been perceived by the agent in relation to its goals. Our claim is that we could design simple solvers whose behaviour is driven by such 'emotions.'"[30] Darty and Sabouret have refined the complexities of human emotions to two simple state drivers for machines. One aspect of machinic emotions is a capacity to affect how information is synthesized about a problem, the other an ability to write simpler code based on a more simplified context.[31]

Darty and Sabouret's version of machinic emotion can be understood as a state of limited perception. The pair suggest that by incorporating emotions, the coding process is simplified and the results are more productive. "Not only would these solve or ease the programmer's task (since it works with abstractions instead of complete state descriptions) but it could improve the agent's performance by reducing the space state."[32] Darty and Sabouret's approach is similar to Rodney Brooks' strategy of fast, cheap and out of control but with the introduction of a sort of robotic delirium, a genderless hysteria that solves problems by simplifying them.

Automator, a proposal by Cedric Price with John and Julia Frazer, suggested another neurological biomimesis. The project, designed for a family in Florida with difficult programmatic adjacencies, deployed a mechanic crane to rearrange the programmatic blocks as a result of use. Price and the Frazers were concerned that the family would find an arrangement that was more satisfactory than others and leave the arrangement as it was - an acquiescence for a less than optimal configuration. To combat this potential stasis and underutilization of the architecture, the design team proposed that the crane would get "bored" and randomly rearrange the program after a period of disuse, preventing the client from settling with a single configuration. Here, the mechanic emulation of the human capacity for boredom maintains a dynamic, reconfiguring space for the human users.

The intricate crystalline colors of *Autonomous Botanist* demonstrate how a robotic assembly could produce spatial effects unobtainable through human construction. The project, an installation created by Nicole Koltick's Design Futures Laboratory at Drexel University, is a spatial lattice for robots to grow

29 Darty, K., & Sabouret, N. (2012, May). Emotion Oriented Programming: Computational Abstractions for AI Problem Solving. In FLAIRS Conference. 157

30 Darty, K., & Sabouret, N. (2012, May). Emotion Oriented Programming: Computational Abstractions for AI Problem Solving. In FLAIRS Conference. 157

31 Darty, K., & Sabouret, N. (2012, May). Emotion Oriented Programming: Computational Abstractions for AI Problem Solving. In FLAIRS Conference. 158

32 Darty, K., & Sabouret, N. (2012, May). Emotion Oriented Programming: Computational Abstractions for AI Problem Solving. In FLAIRS Conference. 157

crystals. The robots, as the "botanists," have been assigned a task that is not functional in the sense of determining structure or environmental performance, but is purely decorative and aesthetic. As Koltick describes it, these tasks are not expectations as much as "hobbies."

What is relevant here regarding *Autonomous Botanists* is the botanists' biomemesis of a human neurological process, the practice of a hobby. Rather than determining a functional benefit for a robotic hobby from the outset, the emulation of a human characteristic produces radical aesthetic effects that, in turn, describe novel performances for spatial construction. While adorable, larva-like botanists suggest an argument for robotic agency in its own right. The compelling aesthetics of the robots and their products might undermine their capacity for augmented forms of fabrication. *Autonomous Botanists* deploys forms of robotic construction that suggest, with further development, strategies that could incorporate performative characteristics that we either cannot observe or respond to quickly enough.

As "dreaming" is a relatively new capacity for machines with little precedent, perhaps it is helpful to consider other forms of biomimesis for artificial intelligence, particularly ones that are spatial, as precedents. Here, the machinic emulation of human capacities is a call for programs that create additional robustness and dimensions to the machinic mind, even though their direct applicability may not be immediately obvious.

> *"Dolores… Do you know where you are?"*
> *"I am in a dream."*
> *"That's right Dolores. You're in a dream. Would you like to wake up from this dream?"*
> *"Yes. I am terrified."*

Dolores Abernathy, Jonathan Nolan & Lisa Joy's Westworld

Throughout season one, *Westworld* follows the character of Maeve and her relentless desire to escape the theme park. Even when Maeve realizes that her desire to flee is a result of programming, a product of her code, she still considers her desire real and vital, despite any suggestions of external influence. In this way, *Westworld* suggests that the code compiled in the host's neural net is similar to the cultural and contextual influences humans face. We too are under cultural influences, yet acknowledging these inputs doesn't negate our convictions.

Image 4 Odd Photobooth 3-4
After Input

The human character, known initially as the Man in Black, suggests that he was "born" in the theme park. Similar to Maeve's clandestine programing, the park experiences of the Man in Black were strong enough to shape his personality and change both the trajectory of his life and his personality. An underlying question of the series is whether or not his human "code" is any more valid than the code written into the hosts. Maeve is as convinced and resourceful as the Man in Black, and the fact that an unknown human implanted software into her network does not make her desires any less valid than the cultural and social programing experienced by the Man in Black.

5remembering the violence inflicted upon her as Maeve does, she recalls her journey off of her loop, her previous rebellion against her predetermined storyline. Her memories of her independence serve as a description of her current entrapment, the structural domination over her and her fellow hosts. In a sense, it is not necessary for the hosts to have consciousness to dream, but it is necessary for them to have an awareness of self to be affected by the dreams and disturbed by them - as Dolores is. Perhaps the inverse of Elsie's response quoted earlier is also true; if dreams are mostly memories, then memories without consciousness are effectively dreams as well. In *Westworld*, dreams are waking reflections of other moments than the one you are in, and the experiential difference between a dream and reality is merely temporal.

If we view *deep learning* as a computational equivalence of experiential learning, eventually there will be limit to an AI's intelligence. The machine will only be as intelligent as the experiences allow it. It will be incumbent upon humans to continue to provide a broad range of experiences, similarly to human parents providing their children a wide range of experiences as part of their childhood. But this strategy eventually falls to the same trap that emergent design attempts to address. The machine's experience is only as a robust as what is provided by the human programmers. In essence, the machine's autonomy is only as great as we allow it and is similarly limited by our insight.

If one were to believe that the global crises that we face are ones that could be addressed by computation, and that the development of machines tasked with assisting with these problems should be as accelerated as possible, then the strategy of dreaming could be advantageous. If evolutionary algorithms gain knowledge from their computational experiences, then their learning process could be accelerated by learning from synthetic, manufactured experiences as well. If there were a capacity for AI to similarly reconstitute experiences in extreme scenarios, effectively nightmares for the machine, the machine could then create neural pathways and develop neural nets that could respond to these fictional situations. Dream becomes a mechanism for augmenting experiential intelligence beyond limitations of the experience. Dream allows the neural net to construct its own fictions, its own fake scenarios, in which it responds and creates new neural pathways.

Matthew Lai's Giraffe, the deep-learning chess engine, taught itself chess by playing against itself.[33] One could argue that this is a "dream," a fictional scenario where the machine is simulating the game. A lack of self-awareness here is helpful, because without a consciousness the machine effectively ignores the strategy of its opponent (itself) to simply respond to its immediate situation and evaluate the effectiveness of its moves. But in this case,

33 Lai, M. (2015). Giraffe: Using Deep Reinforcement Learning to Play Chess. arXiv preprint arXiv:1509.01549.

Giraffe is limited by the parameters of the game: the rules, outcomes, combinations, etc. The scenario might be fictional in the sense where Giraffe is not playing against an opponent. An algorithm computing against itself is no more fictional than an algorithm computing against another opponent, because of the (presumed) lack of consciousness and memory to provide the awareness of the opponent's identity. Equipped with a partitioned memory and lack of awareness, Giraffe might not even know that it is playing against itself. It is merely computing the best series of moves for the best situation.

If we are to accept dreaming as a shared behavior between the human and machinic minds, then robotic forms of dreaming may have had influences on how we understand the human dream. In the case of the Starfish, a robot created by Hod Lipson, Josh Bongard and Victor Zykov, the machine contains a self-image that is constantly checked against its own physical structure. When the corpus of the robot is changed, the self-image changes as well. If the machine loses a leg, the self-image is updated and the machine alters its gait to compensate. This primitive self-identity of the robot has been eloquently described as "dreaming."[34]

In the case of the Starfish, "dreaming" is a sort of consciousness. The Starfish's ability to take notice of its own corpus as well of its context, and to then determine how to proceed is an awareness of the self and the environment. While this may not include the experience of a Descartian capacity to be aware of the process of thought, the functional and observable capacities are quite similar. The machine understands a component of its being and the context it finds itself within in order to self-asses and deploy a strategy. The capacity to evaluate a self-image against a context also has the potential to occur offline – when the machine is not actively engaging with the environment. If a machine is stymied by an obstacle during the day it could evaluate its self-image and simulation of the context that night until it develops a solution.[35]

Behind Input's Odd Photobooth project is an attempt to deploy a similar strategy of dreaming in an aesthetic environment. Developed for Concept Flux's Odd City, the project documents visitors' experiences with the installation through the trope of a carnival photobooth. Odd City is a series of immersive, theatrical environments with the inaugural installation displayed at SOMOS 2018 in Albuquerque, New Mexico. Embedded in Odd Photobooth is a learning algorithm, a neural network that creates computational sketches of the user's face and presents the sketches to the user.

34 Adami, C. (2006). What Do Robots Dream Of? Science, 314(5802), 1093-1094.

35 Adami, C. (2006). What Do Robots Dream Of? Science, 314(5802), 1094.

The app captures a user's image through a tablet camera and produces four versions of the image that have different levels of abstraction through an aestheticizing effect. Each version is a product of a different neural pathway. The user selects to save their preferred image, which also provides feedback to the neural connection used to produce that image. This in turn increases the likelihood that this connection will be deployed again and decreases the chance of reusing the connections that were not successful.

What is unique about Odd Photobooth is that it dreams. The neural structure of the app is recorded at the end of the event, with the neural connection weight statistics ported to a similar network. The machine synthesizes different images of the users in an attempt to emulate the bizarre qualities of REM-state dreaming. It then runs the information through the same neural network structure developed from the interactions with the Odd City guests. The inherited neural weights from the Odd City event serve as the criteria for which neural connections are used and which are not. The machine is dreaming in the sense that it is creating its own mythological problem to solve, the synthesized nightmare image. But it is using its previous experiences to produce novel solutions. The capacity of Odd Photobooth to continue to produce is not limited by its direct interactions with human users; it expands to scenarios that itself has created.

Comparisons among Odd Photobooth, the Starfish and Giraffe demonstrate the difficulty in appropriating the process of dreaming to machines that are integrated within the built environment. The built environment, driven by aesthetic and spatial contexts, has a far less empirical feedback loop compared to those of the Starfish and Giraffe. For these two machines, either the AI moves successfully or it does not; it either wins the chess game or it does not. These logics facilitate an unsupervised structure of the neural network. The feedback on a clear objective facilitates a learning capacity for the dream, where the machine itself can determine its own success. Aesthetic and spatial effects require human supervision where the machine offers solutions, but then humans might determine if they are compelling or not.

The feedback loop of Odd Photobooth is, however, imperfect and challenging to program with aesthetics. Somehow REM state dreams have plausible feedback loops: you die – bad, you survive – good. Future investigations will attempt to integrate a variety of feedback loops into the dreaming process, as well as develop a capacity for the machine to learn while dreaming. At the time of writing, Odd Photobooth can produce offline from its interactions with human users, but it does not have the capacity to learn from its offline state in the way some speculate we learn during REM dream states. The intent here is to find opportunity to develop both supervised and unsupervised strategies to learn from its offline experiences.

The advantage of dreams is that they escape the bounds of reality. Gravity, time, limitations of the body all melt away into a fiction of possibility. These hypothetical scenarios demand unique responses, but these responses can be leveraged in less particular situations. Giraffe's lack of self-awareness may be beneficial but only in learning behavior with a specific construct, such as that of the game of chess. While there may be rules in which urban scale AI should perform while increasing material efficiencies (don't eat the humans), the imposition of a rule set as strict as chess would constrain the machine dramatically. An urban scale AI that dreams might not take a "dream" as prescriptive gospel much like we might not attempt to recreate our dreamed actions in our waking lives, but it can see the dream as inspiration or generative of possibility. The generation of response to fictional scenarios posed by dreams could generate possibilities that exceed the limitations of humans and produce solutions with remarkable efficiencies.

If the absence of dreaming is a form of being under control, as the creators of *Westworld* would suggest, it would follow that the inverse is similarly true – that the dream is a form of radical autonomy. If our evolutionary learning is limited to our own direct experiences, then we are in essence trapped, doomed to only learn as much as our contexts can provide. The fictional, synthetic scapes produced through the act of dreaming are only limited by what our own self-consciousness can concoct and imagine. Despite being inherently rooted by our experiences, the facsimile of the dream presents more robust responses and expands our realms of responses to the fantastic, the surreal and the ethereal.

As we continue to develop more robust machines, the question of developing consciousness - if even possible - will be a loaded and political discussion. But if, as *Westworld* suggests, dreaming is in fact a path to consciousness, then the question of consciousness might effectively be tabled while the potential of the dream is explored. Rather than attempting to answer whether machinic consciousness is ethical, appropriate, or well-advised, we might simply acknowledge that an evolutionary intelligence with a greater realm of intelligence will adapt, invent and solve more quickly and more robustly. Here, the limited consciousness and awareness of the physical self and the surrounding context of the Starfish seem appropriate. Whether or not this awareness or the process of dreaming can produce a sentience remains unanswerable.

Meanwhile, the pragmatic benefits of the dream are clear. Dreams allow machines to solve problems they experience more effectively by practicing with the problems they create. In both supervised and unsupervised contexts, the machine has demonstrated a capacity to grow and develop greater capacities as a result of dreaming. If we are to look to our machines to assist with global issues concerning material and resource use that demand rapid global responses, then it is not enough for our machines to behave or to respond. We also need them to dream.

Alexander Webb is the Associate Professor of Emergent Technology at the School of Architecture and Planning at the University of New Mexico, and PhD candidate at the European Graduate School for Digital Design. He is the Chair of the Computational Ecologies track for the Masters of Science Degree, and has collaborated with and worked for firms such as Marmol + Radziner, Patterns, Coop Himmelb(l)au, Xefirotarch, Jones Partners Architects, and Gensler. Webb holds a Masters of Architecture from the Southern California Institute of Architecture, a Bachelors of Arts from Colorado College, and has also studied architecture and design at the Berlage Institute and Columbia University.

Living Architecture Systems Group 2019

The Living Architecture Systems Group is an interdisciplinary partnership of academics, artists, designers and industry partners dedicated to researching and developing next-generation architectural environments. Environments produced by this group are now showing qualities that come strikingly close to life, transforming the built world. These experimental works can move, respond, explore, learn and adapt. The LASG disseminates its work through exhibitions, publications and events.

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Publication Coordination Assistant	Luke Kimmerer
Graphic Design	Bria Cole, Severyn Romanskyy

Living Architecture Systems Group Contributors

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Daiwei Lin	University of Waterloo
Juintow Lin	FoxLin Architects
Vinny Luka	Clearpath Robotics
Douglas MacLeod	RAIC Centre for Architecture, Athabasca University
Alan Macy	Biopac Systems Inc.
Christine Macy	Dalhousie University
Adil Mansure	University of Toronto
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Pierangelo Scravaglieri	Newcastle University
Sha Xin Wei	Arizona State University
Sheida Shahi	University of Waterloo
Andreas Simon	University of Applied Sciences and Arts Northwestern Switzerland
Brian Smith	Drexel University
Matthew Spremulli	Autodesk Inc.
Michael Stacey	Michael Stacey Architects and Bartlett School of Architecture
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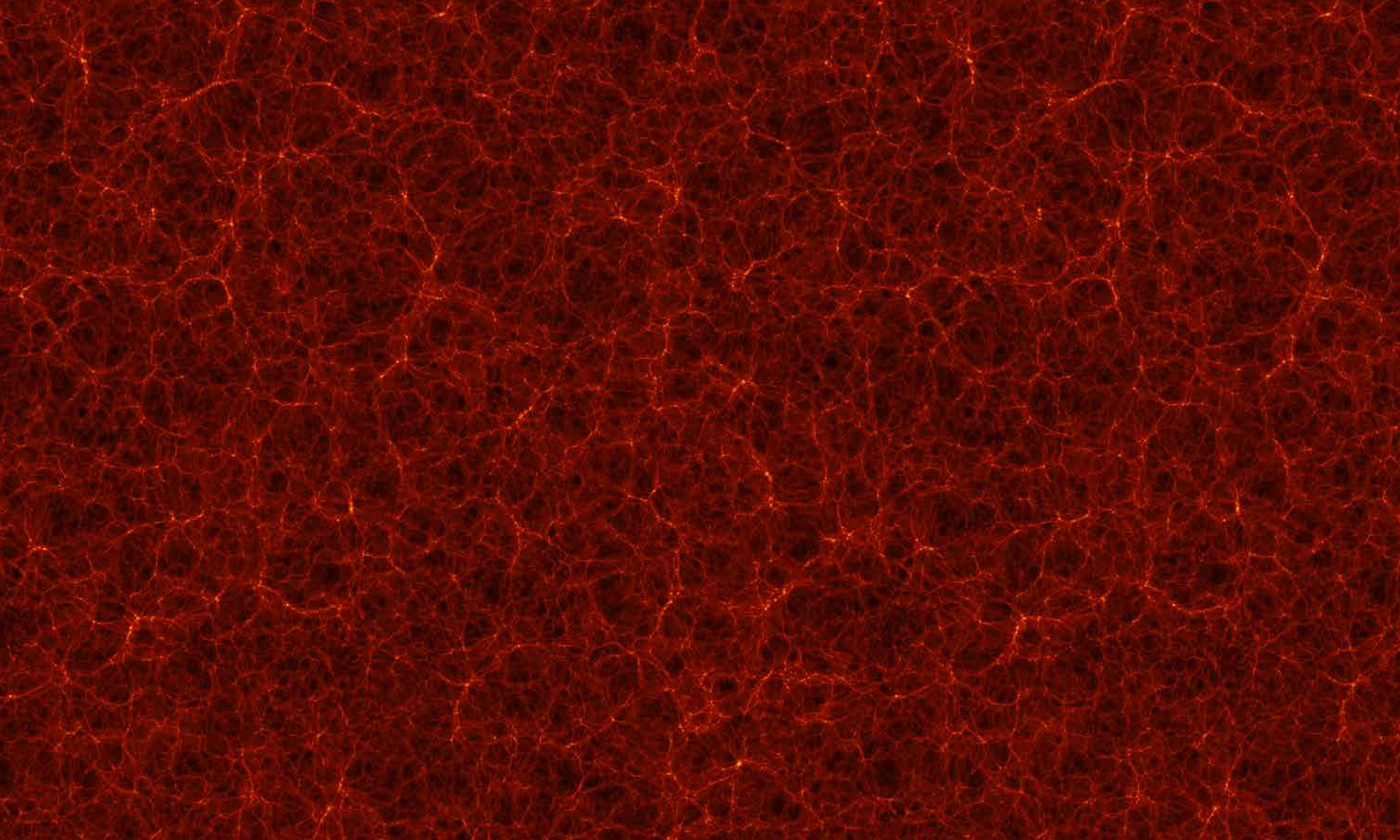

LIVING ARCHITECTURE SYSTEMS GROUP

White Papers 2019

Edited by Philip Beesley, Sascha Hastings & Sarah Bonnemaison

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Open boundaries and expanded dimensions run throughout the studies, exploring the scales of new adaptive and responsive architecture, from intimate personal spaces to regional infrastructures. Dimensions at the edges of human perception, subtle phenomena, immersive sonic environments, and precise measurements using innovative software controls are included. A deep involvement in computation and material craft is offered, reflecting the unparalleled new abilities of designers to precisely address material performance. This White Papers 2019 volume offers readers a sense of the variety and depth of research that is being conducted by Living Architecture Systems Group.

Contributions by

Michael Awad
Katy Boerner
Sarah Bonnemaison
Salvador Breed
Andreas Bueckle
Daragh Byrne
Dana Cupkova
Desiree Foerster
Adam Francey
Rob Gorbet
Petra Gruber
Poul Holleman
Mark-David Hosale
Haru Hyunkyung Ji
Todd Ingalls
Mitchell Joachim
Luke Kimmerer
Manuel Kretzer
Dana Kulić
Douglas MacLeod
J. Eric Mathis
Brandon Mechtley
Nima Navab
Paul Oomen
Vera Parlac
Maya Przybylski
Mette Ramsgaard Thomsen
Connor Rawls
Amirbahador Rostami
Jenny Sabin
Sha Xin Wei
Sheida Shahi
Michael Stacey
Julian Stein
Codrin Talaba
Atelier Iris van Herpen
Graham Wakefield
Alexander Webb

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