ARTIFICIAL LIFE APPROACH TO INTERACTIVE ARCHITECTURE

Metamaterial kinetic environments at the edge of chaos

Doctoral Thesis

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Abstract

This thesis examines the field of interactive architecture – that is spaces that engage in a communicative exchange with the inhabitants through a variety of sensory modalities. This thesis focuses on kinetic interactions, examining forms of non-verbal dialogue between human and architectural agency. The notion of agency suggests not simply an architecture controlled by human command, but rather an architecture with degrees of autonomy, a "life of its own". This thesis draws upon developments in the field of artificial life, that include topics of morphological behaviour, distributed control systems and soft robotics. Although there has been a great deal of development in technologies and methods in this domain, there are limited examples of architectural research harnessing the potential of these advances. This thesis explores three interlinked questions. How can the field of artificial life contribute to novel approaches to design of interactive kinetic architecture? How can recent developments in metamaterial structures be used to create novel transformable architectural surfaces and spaces? What types of actuation are most suitable for animating metamaterial structures in an architectural context? This thesis artificial life approach is developed through a 'proto-architectural' methodology of workshops and gallery installations. The major outcome I present, is the Edge of Chaos installation (Fig.1) that was internationally exhibited in France, Netherlands and Belgium in 2018. It

represents the synthesis of a series of physical experiments and academic workshops in soft actuators, metamaterial structures, and control systems that explore the potential of new technologies to realise novel forms of tactile, kinetic and interactive architecture. The results of the technical experimentation are presented sharing findings on the advantages and shortcomings of recent advances in soft robotic actuators and the metamaterial systems for architectural applications. The results of a series of public exhibitions are presented sharing findings on the aesthetic advantages and disadvantages of using artificial life techniques to drive an interactive installation. As a contribution, this thesis probes new emerging material and computational technologies and offers novel synthesis between fields of artificial life and architectural research.

Fig.1 Interacting with the Edge of Chaos installation exhibited at La Gaite Lyrique, Paris

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Research Context

The research in this thesis concerns the problem of interactive architecture – that is, spaces that enter into communicative forms of exchange with inhabitants through a variety of sensory modalities, that lead to changes in architecture and its inhabitants. This thesis focuses on kinetic interactions, examining forms of non-verbal dialogue between human and architectural agency.

The notion of agency suggests not simply an architecture controlled by human command, but rather an architecture with degrees of autonomy, a "life of its own". An architecture of indeterminate behaviour that can both lead to surprising and aesthetic spatial experiences for inhabitants, as well as adaptive behaviour that optimises building performance to changing conditions.

The potential for architectural agency is being advanced by developments in computational technologies, particularly the developments in sensing, actuation and information processing. The applications for artificial agency in the built environment are as diverse as the needs of human beings, buildings and ecosystems. Developments in the 'internet of things', by technology and communication industries, promise to soon saturate the built environment with responsive networked systems that will change our experience and conception of the built environment from inert and static, to lively and transformative. Such techno-optimism should be measured with some caution. Such terms as “smart”, “interactive”, and “intelligent” systems are common, and often used interchangeably and uncritically by technologist and architects alike. Marketing departments inflate expectations, and inevitably technologies fail to deliver.

Architects Michael Fox and Miles Kemp, in their book *Interactive Architecture*, describe the bringing together of fields of computation and architecture as motivated by desire to “create spaces and objects that can meet changing needs with respect to evolving individual, social and environmental needs”[i]. This leads to an architecture sensitive and adaptive to occupation and operation.

Today, however, there are differing and conflicting models in how to develop such intelligent systems. Contrasting approaches can be traced back to divergent practices emerging out of cybernetics and artificial intelligence research in the 1950’s and 60’s. Understanding the discourse in these fields and the evolution into interdisciplinary fields including artificial life, can help us develop a more critical awareness of the possibilities and short comings of current approaches and offer us a means to harness techniques within an architectural context.

Bringing AI into the physical, analogue world, situating it within contexts and changing conditions introduces new problems of computational complexity. Embodying AI in physical space necessitates an understanding that material systems themselves compute and are inherently behavioural. Even seemingly inert materials, such as wood or metals, are responsive to forces and changing environmental conditions, such as temperature and humidity. Today developments in synthetic composites, digital simulation and manufacturing techniques, and increasing collaboration between scientists, engineers and designers are leading to innovate 'programmable materials' that can be tuned to perform responsively to specific environmental stimuli. These developments suggest that a complete approach to building interactive architecture should embrace both the computational capabilities of the digital and the analogue.

Research Questions

Throughout the last couple of decades, the word *intelligent* has been applied to devices such as automatic doors, lighting and shading systems, becoming associated with any building that incorporates the faintest amount of automation technology. A variety of systems installed to enhance building performance are based on a fixed notion of an appropriate or maximum efficiency response. This lacks the awareness that what is appropriate changes with the building's use. As a consequence, the users are bound to live or work in spaces that are often rigidly pre-programmed rather than adaptive to changing needs.

The problem, I have argued, is rooted in the historic development of the field of artificial intelligence that was founded on the goal to replicate human intelligence in machines. This ambitious project was led primarily by the field of computer science. Alan Turing, John McCarthy and Marvin Minsky were among the pioneers of the endeavour to define the nature of intelligence and construct intelligent behaviour. Debates over the best methodology for the emergence of intelligence inhabited the scene for several decades leading to symbolic AI approaches (top-down), and artificial life approaches (bottom-up) rooted in cybernetic thinking.

Notable critiques of the top down approach include cognitive scientist Stevan Harnad, roboticist Rodney Brooks and architect and cybernetician Ranulph Glanville. The inability of symbolic top-down approaches to situate machine intelligence in the physical world was recognised by Harnad as their main “handicap” which he called the “symbol grounding problem”[ii]. Brooks criticised the decomposition of intelligence to processing modules where none of the modules themselves generates any behaviour but only their combination[iii]. As a response Brooks advocated for a distributed and adaptive control approach, demonstrating with his own machines, that some of the solutions to critical problems present in AI for robotics such as dealing with complex environments, robustness and cost, could be found in bottom up strategies. Glanville discusses AI in the context of architecture, critiquing the top-down control of so-called *intelligent buildings* that typically lack the ability to adapt, reducing intelligence to a computational box of reactive gimmicks[iv]. This thesis argues against these trends of centralised and reductive modes of control, instead embracing the unmanageable, with an artificial life approach that has its foundations in cybernetics. This bottom-up approach to design I suggest offers the potential to create spaces that manifests in complex and potentially intelligent interactions.

Applications of AI in architecture are diverse from design, to fabrication, to interaction, and so the scope of this problem could fill many volumes. This thesis focuses on the sub-domain of *interactive kinetic architecture*, involving physical transformation of surfaces and spaces in response to inhabitants. As there are a wide variety of approaches to creating kinetic motion, I have focused on recent developments in metamaterial transformable structures that show the potential of morphological and material intelligence to be programmed directly into architectural structures. As I have illustrated, they provide scope for exploring a variety of structural transformations based on simple building blocks, which enable playful exploration, repeatable experiments, and scalability.

With this approach the following questions have been asked.

1. How can the field of artificial life contribute to novel approaches to the design of interactive kinetic architecture?
2. How can recent developments in metamaterial structures be used to create novel transformable architectural surfaces and spaces?
3. What types of actuation are most suitable for animating metamaterial structures in an architectural context?

Methodology: A Proto-Architectural Approach

In Bob Sheil's edition of Architectural Design Journal titled *Protoarchitecture: Analogue and Digital Hybrids*[v], he argues that post-digital "designers more often design by manipulation than by determinism, and what is designed has become more curious, intuitive, speculative and experimental". Pushing beyond tired and predictable uses of digital technologies, hybrid material and digital technologies embrace emergent complexity. I propose, that if interactive systems should truly engage in a meaningful way with people, that this can only be done through a life of their own and they must be cultivated rather than controlled. Within the context of a school of architecture this thesis tries to tackle the monotony of product focused design of technologies and their dogma of user control. Instead, it utilizes prototyping and installation art to examine playful, artistic, speculative possibilities for artificial life techniques and metamaterial systems in future architecture.

This research is explored through:

- Physical prototyping
- Academic workshops
- Installation-based experiments in public spaces
- Scholarly publication

A proto-architectural approach emphasises the importance of physical testing, rebalancing against the increasing dominance of virtual and digital design practices, instead adopting hybrid approaches grounded in craft, model making, and 1:1 testing. The value in holding objects in one's hand and understanding how they transform in ways that simulations are yet to faithfully predict. Physical processing of prototyping explored through workshopping opens up room for the unexpected to appear in ways that are perhaps limited in the constraints of particular digital design spaces. If interactive architecture represents the embodiment of AI techniques into the space, design strategies of physical embodied experimentation are essential. Additionally, embodied prototypes address physical sensitivities of people in the most direct way – which is impossible to achieve through virtual simulation alone. Installation work enables the realisation of ambitious ideas as inhabitable constructs[vi]. It is a medium for designers to translate their spatial concepts into artefacts that communicate, through their physicality, aspirations and innovative propositions for future architecture. Fast iterative testing of hypotheses through the performance of installations can establish understandings that inform the integration of systems into more complex built environments. Installation work often gets associated with *experience* design, for its distinctive capability to engage the users or the viewers into an immersive atmosphere. As such, with an emphasis on viewer engagement and interaction, *installation as a* *proto-architectural methodology* has become a widely used medium for architects and designers to explore the advent of technological advances and their application. Using installation art as a presentation vehicle towards potential architectural use, architects evoke different perceptions of the future through bold and innovative statements. By captivating senses, provoking feelings, translating emotions and inspiring masses, progressive ideas are manifested but most importantly brought to life. Examples of key installation work related to the research focus of this thesis are discussed in chapter 2, setting the context for my own work. Important to note, are computational approaches that resist classical, reductive forms of control. Taking an artificial life approach offers a mode of resisting top-down cultures prevalent in current so-called 'intelligent building' design. Artistic, playful and speculative approaches are, I believe, a useful method for radically progressing future design approaches towards achieving spaces that are more responsive to individual needs of people and changing environmental conditions. This proto-architectural approach coupled to advancements in material technology offers some compelling possibilities for future kinetic architecture. The use of low-cost networkable hardware and low-cost networkable material systems creates a rich research space to find solutions to current problems of top down control, through distributed systems, material and computational.

Thesis Structure

Chapter 1. Introduction

The introduction gives an overall contextual review of the research space before identifying the research questions and methods chosen to tackle the thesis. I summarise the chapters and detail contributions of the research.

Chapter 2. Intelligent Kinetics

This chapter examines the interrelations between machines and architecture, further focusing on the interrelations between cybernetic systems and architecture, that inform the artificial life approach taken in this thesis. It recognises the historical relationship between machines and architecture and the influence these mechanical technologies had on shaping the visions for future architecture in the 20th century. It analyses buildings that have realised or feature some of the kinetic behaviours this architecture envisioned, foregrounding my *The Unexpected City* design project from 2014, that proposes an urban kinetic intervention in the city of Kotor, Montenegro. The second part of this chapter, examines the development of 'smart' or 'intelligent' architecture, arguing for their framing within the context of the foundations of artificial intelligence (AI), that has heavily predated and influenced its conception and design discourse. It discusses two competing design models of intelligence, starting with the birth of cybernetic thinking and computer science. First, an intelligence that is grounded in embodied and situated, sensor-motor feedback relationships, and second a 'representational' model of intelligence taken by computer scientists who have focused on computer logic and failed to include material, morphology or the environment. In this chapter, I argue for a bottom-up adaptive and distributed intelligence, instead of 'top-down' centralised strategies, setting the basis for this research's artificial life approach to interactive architecture.

Chapter 3. Softer Kinetics

This chapter, structured in two parts, examines the material softening of interactive architecture. It begins with an overview of the research between architecture and robotics, followed by physical experimentation and developments in soft actuators and metamaterial systems. Material experiments, notions of cybernetic systems and radical experimentation of inflatable, mobile and temporary structures of the 1960' and 1970's, influenced decades of research in leading schools of architecture and artist practises. Due to material challenges, there has been a limited range of commercial applications of soft architecture to date, however new developments are opening potential solutions to problems of durability. In this chapter, I review these developments that are contributing to the emerging field of soft robotics, by examining the current state of soft actuation, particularly alternative open source soft actuation approaches that are more accessible to wider research communities, unlike commercially available soft actuators. This chapter further focuses on study of advances in metamaterial research, bringing together programmable geometrical structures and soft actuation, that probe possible architectural applications. In order to gain understanding of their performance, I describe built prototypes harnessing some of the fundamental metamaterial structural units. I explain, how this research further led to an opportunity to collaborate with physicists based at Soft Robotic Matter group, AMOLF Institute of science, in Amsterdam. Finally, this chapter details series of workshops I ran with graduate architecture students exploring a range of applications and soft actuation techniques. It reviews workshop results through built prototypes that allow me to draw conclusions about the state of the art of soft actuation techniques and speculate on their future potential.

Chapter 4. Edge of Chaos

Following from theoretical research, physical prototypes and design workshops, this chapter describes a proto-architectural installation called the “Edge of Chaos”. This installation was a response to an international competition calling artists, designers and architects to offer their perspectives on technologically enhanced world, where once clear boundaries between living and synthetic systems are now dissolving. Edge of Chaos proposal, that I have developed with my collaborators, was successfully selected and awarded funds to deliver an exhibition for this European cooperation project run by Cinekid festival in Amsterdam, the Gaîté Lyrique gallery in Paris, and KIKK festival in Namur.

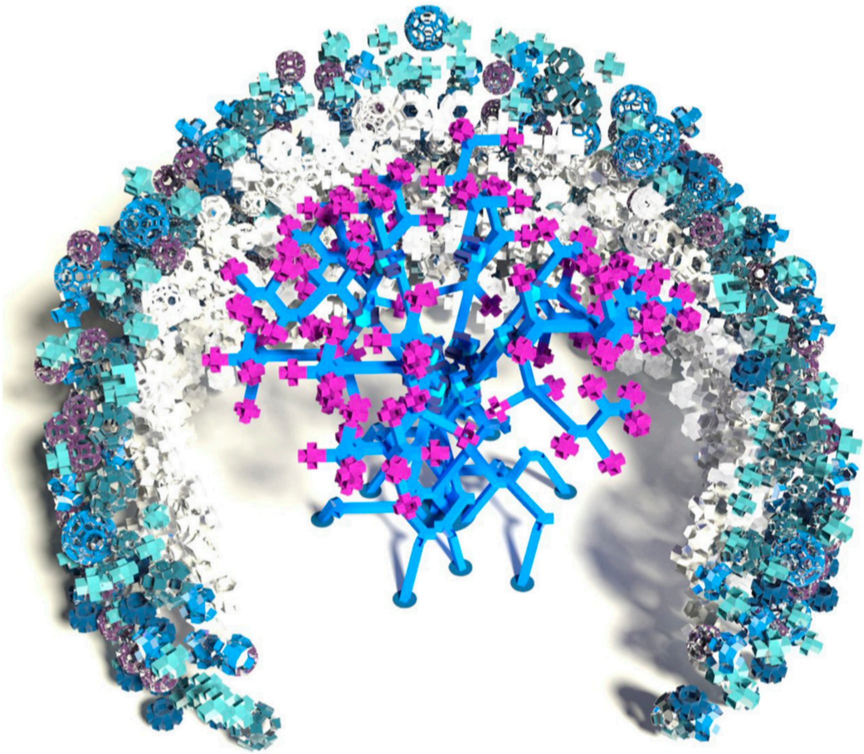
Metamaterials made of stamped polypropylene modules, previously used in Prague and Xuzhou workshop, served as the primary structural system for the Edge of Chaos while cellular automata techniques were chosen as a computational basis. This synthesis brings together findings from my research, making theories of emergent life tangible through an interactive installation that demonstrates complex kinetic behaviour.

Chapter 5. Conclusions

The final chapter states the conclusions to answering the research questions. It summarises and reflects on the research, making recommendations for future work on the topic and demonstrates contribution.

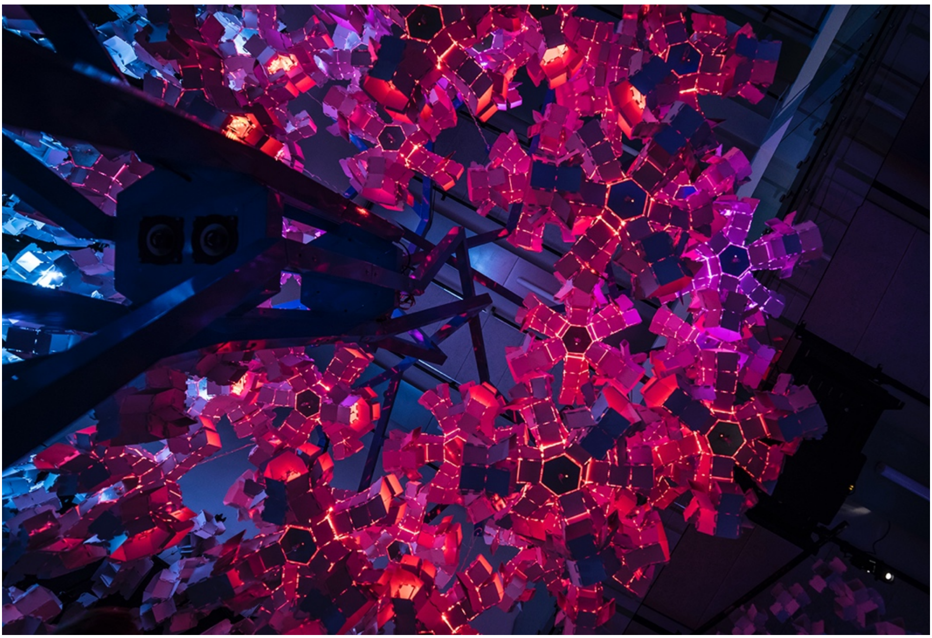
Edge of Chaos: Selection of Image Documentation

Competition Winning Concept Diagram

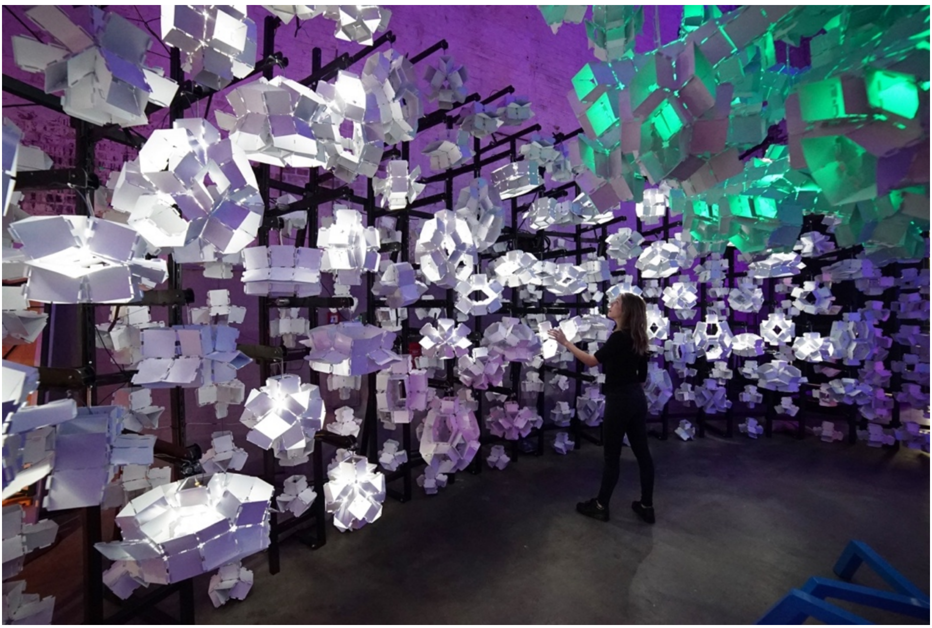


Tree Structure

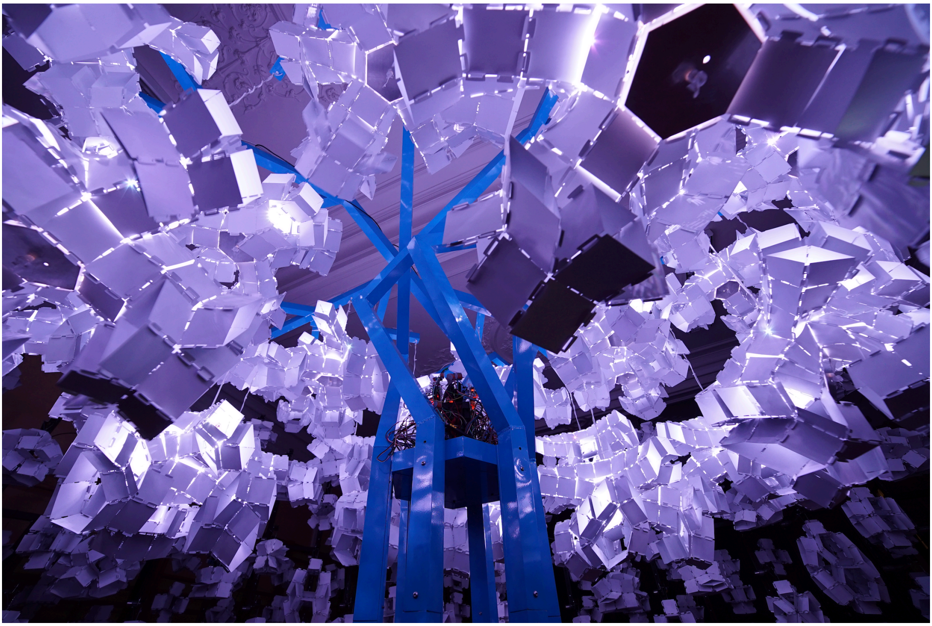
La Gaite Lyrique, Paris Exhibition



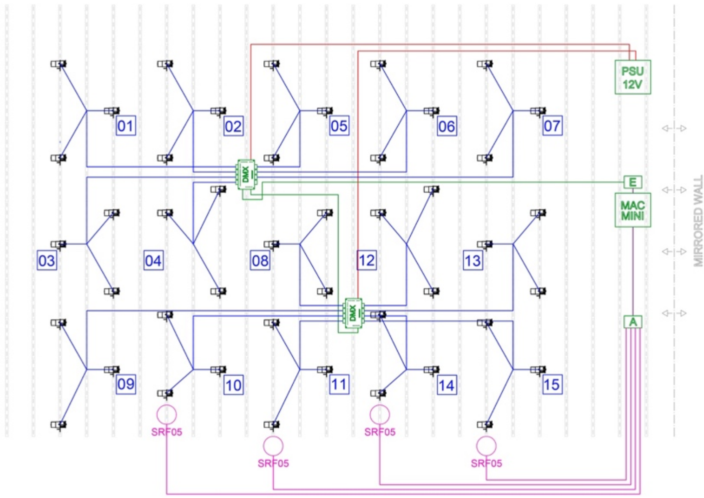
Cinekid festival, Amsterdam Exhibition



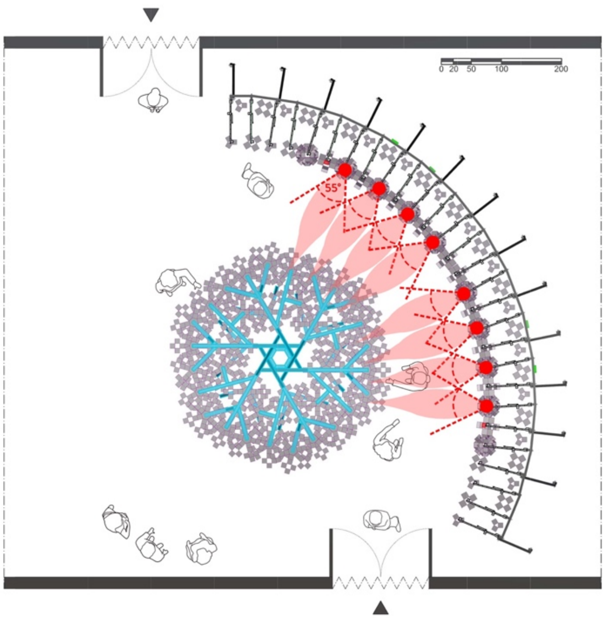
KIKK Festival, Namur Exhibition



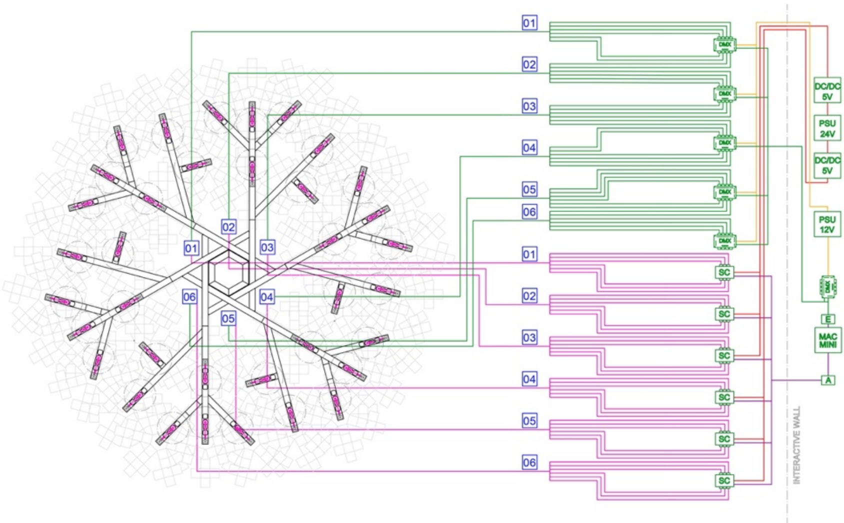
Circuit diagram of the Edge of Chaos wall



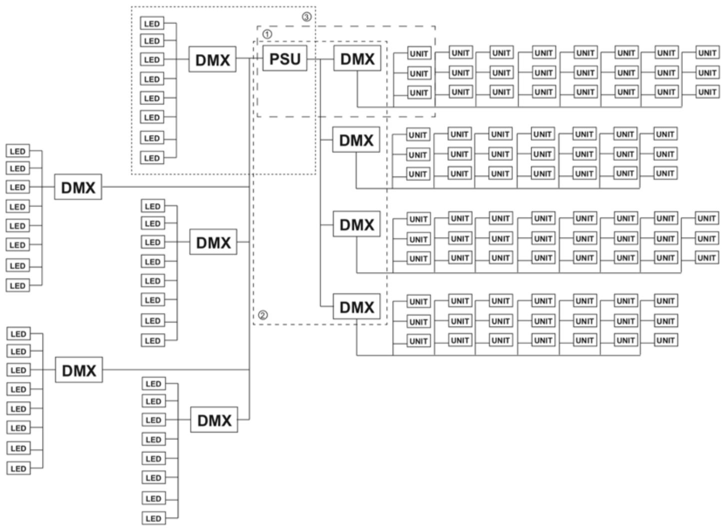
Sensing Map of 8 Proximity Sensors



Circuit Diagram for Tree of Life



Edge of Chaos Power Control Map



Conclusions

The thesis identifies and focused on two features of artificial life research that offer solutions to the current shortcomings of so-called ‘intelligent buildings’ specifically related to kinetic and interactive design. These are the use of distributed and situated computational techniques to create emergent interactive behaviour and the use of metamaterials to design intelligent behaviour into material structures.

We see a paradigmatic change today in the design of robotics away from rigid-body dynamics toward softer mechanical approaches that leverage material and morphological behaviour. Biomimetic robotics will inevitably begin to change our conception of kinetic design away from hard and uncompromising machines towards soft responsive bodies that invite a new intimacy between human and architectural interaction. This was very evident in the tactile and playful explorative behaviour of inhabitants of the Edge of Chaos installation.

My observations of the interaction from the Edge of Chaos confirm that there is functional and aesthetic potency in harnessing emergent patterns of behaviour from the interaction of individual agents. The indeterminacy of artificial life behaviour seems to trigger a deeper interest and intrigue to human behaviour than standard master-slave models of interaction typically found in the consumer technology we use on a daily basis. The human tendency to seek out control of a novel situation is more complicated when encountering an artificial form of life than for example a person controlling their phone or the lighting of their home. Artificial life creates a sensation of reciprocity between independent agents, that is compelling and, in some cases, emotionally affective.

The indeterminacy of Edge of Chaos was also seen to confuse visitors at times, leading to misunderstandings, particularly in groups, about the interaction model of the installation. Faced with the complexity of stimuli, it is human nature to hypothesise and test out assumptions. If the complexity remains too unpredictable visitors loose interest, but equally, if the hypothesis is too easily derived there is also a loss in interest. From my observations, it appears that a 'sweet spot' exists in between predictable and unpredictable behaviour. The task of designing with an artificial life approach is to tune the variable of these bottom up systems to create sustained dynamic and seemingly animate behaviour. I would argue that the Edge of Chaos cellular automata algorithm is a successful example of this balancing act.

Metamaterials are an attractive approach for a number of reasons including their potential scalability, their structural programmability, and the modular approach to design they enable. Through various design experiments and workshops, this modular approach enabled repeatable experiments, utilising creation of simple kinetic components made at low cost, allowing for rapid distribution of ideas.

The successful running of the Edge of Chaos installations, for months at a time, also demonstrates considerable robustness to continuous transformation. From these observations, I would support Dr Overvelde and his colleagues' views that metamaterials have potential applications in architecture. However, substantial environmental testing of materials would be necessary, particularly for external use but based on the state of the art and the inherent behavioural features of soft metamaterial, they provide a range of useful characteristics that currently lend themselves towards applications in interior space. During the workshops with graduate architecture students I found that solar shading, and deployable thresholds for creating temporary spaces were popular concepts harnessing metamaterial's modularity. The Edge of Chaos demonstrates successful use of metamaterials in close proximity to human bodies. Due to its scale, it also demonstrated potential of metamaterials for large spatial applications, offering character, behaviour and animacy to otherwise inanimate elements within the space.

Metamaterial approach allows for design of hybrid rigid and soft structures, as apposed for example to an inflatable architecture approach. This hybrid approach resembles the structure of the bodies and their movement through a combination of elastic soft elements and rigid structural components, and as such sits within the context of artificial life and biomimetic research. In order to test these ideas, I have been prototyping a wide variety of soft actuators, testing their applications alongside the metamaterial structures.

The future of robotics is looking increasingly soft. A paradigm shift in the design and control of machines intended for close proximity to human beings, and for tasks not well suited to traditional rigid body dynamics is occurring in engineering supported by advances in material and actuation technologies. In just the short period of this doctoral thesis there has been rapid developments in the fabrication of low-cost pneumatic actuators that open up fertile ground for designers to explore the advantages of soft kinetics. In this thesis a wide variety of soft actuation methods have been physically tested, including McKibben muscles, origami muscles, pouch motors, silicone muscles and 3D printed bellow muscles. The advantages and disadvantages of such systems are discussed and demonstrated in a series of workshops. It is my view that soft actuated architectural machines are still some way from being realised due to issues of reliability but the lowering of cost any growing research in the field suggests robust solutions are coming soon. Electric motors were ultimately the better choice of actuation for kinetic interactive environments at present.

Contributions

Published peer reviewed papers

- Abramovic, V., Glynn, R. (2019). *Edge of Chaos: Artificial Life based interactive art installation*. Proceedings of the 2019 International Conference on the Synthesis and Simulation of Living Systems (ALIFE 2019), published by MIT Press, Newcastle upon Tyne, UK, from 29 July - 2 August 2019.
- Abramovic, V., Glynn, R., Overvelde, B. (2018). *Edge of chaos: Towards intelligent architecture through distributed control systems based on cellular automata.* In: Anzalone, P. and Del Signore, M. and Wit, A.J., (eds.) ACADIA 2018 Recalibration: On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture. (pp. pp. 226-231). ACADIA: Mexico City, Mexico.
- Abramovic, V. (2018). *An Artificial Life approach to Interactive Architecture*. In: Proceedings of the 1st Conference of Design Computing 2018 – Navrhování pomocí počítače, Faculty of Architecture, Faculty of Civil Engineering, Czech Technical University in

Prague, Conference, 11 October 2018. Exhibition 10-17 October 2018.

- Abramovic, V., Glynn, R. and Achten, H. (2017). *Roamniture - Multi-Stable Soft Robotic Structures,* Proceedings of the 35th eCAADe Conference - Volume 1, Sapienza University of Rome, Rome, Italy, 20-22 September 2017, pp. 327-336.
- Abramovic, V. (2017). *Plug-In Home.* Proceeding of the 4th International Conference S.ARCH-2017 07-09 June 2017, Hong Kong.
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- Abramovic, V., Achten, H. (2016). *Flexible, Interactive Structures for Future Visions: A Case Study.* International Journal of Contemporary Architecture" The

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- Abramovic, V. (2016). *The Unexpected City by Vasilija Abramović*. Pogled 19- PERSPECTIVE. The Journal of Engineers Chamber of Montenegro Year 7 / No. 19 january 2017. pp. 86-92, ISSN 2336-9175 (Printed) ISSN 2336-9183 (Online)
- Abramovic, V. (2018). *The future are spaces and buildings living and breathing at our own pace*. The Journal of Engineers Chamber of Montenegro Year 8 / No. 24 may 2018. pp. 90-96, ISSN 2336-9175 (Printed)

Workshops

- Workshop "Metamaterial based interactive installations" (2018). Abramovic, V., Glynn, R., Faculty of Architecture, China University of Mining and Technology, Xuzhou China
- Workshop "Interactive Soft Actuated Environments" (2019). Abramovic, V., Petrš, J., Faculty of Architecture, Czech Technical University, Prague, Czech Republic

Exhibitions

- La Gaîté Lyrique, Paris,
  France, April – July 2018
- Cinekid Festival, Amsterdam, Netherlands, October 2018
- KiKK Festival, Namur, Belgium, November 2018

Notes

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[ii] Harnad, S. (1987). *Category induction and representation*. In S. Harnad (Ed.) Categorical perception: The groundwork of Cognition. New York: Cambridge University Press.

[iii] Brooks, R. A. (1991). *Intelligence without representation*. Artificial intelligence, 47(1-3), pp.139-159.

[iv] Glanville, R. (2001). *An intelligent architecture*. Convergence, 7(2), pp.12-24.

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