Morphing Architecture
with Responsive Material Systems

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Morphing Architecture

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Abstract

My research focuses design issues in architecture that can change its shape and other properties in response to changing external stimuli. Previous research has considered whether architecture can morph using ‘hard’ mechanical hinges, components, and systems for actuation and kinetic transformation. Few have explored the ‘soft’ alternatives. In my research I explore whether there is an opportunity for using a ‘soft’ system approach that exploits the performance of responsive materials when applied to lightweight, flexible and adaptive architectural designs that respond to environmental and lighting stimuli. I investigate unexplored approaches using responsive and ‘soft’ form-changing materials. This investigation presents opportunities for designing responsive morphing architecture with ‘hingeless’ actuation and transformation.

My research aim is to investigate novel design strategies for responsive kinetic architecture through the exploration of alternative material systems and design tools with sensing and responsive capacities. This aim is investigated and evaluated through a ‘Design Tetralogy’, of four experimental design investigations in the form of architectural skins and envelopes as project works, namely Tent, Curtain, Blind and Blanket. Each focuses on an individual research area: elasticity, Tensegrity, kinetic materiality and sensitivity. The investigations were conducted using a rigorous method called responsive kinetic material system (RKMS), based on the concept of soft kinetics. This concept served as the ‘guiding principle’ for using the interchange of elasticity and memory in the properties of form-changing materials to affect physical transformation and kinesis in architecture.

All four design investigations involved a series of conceptual prototypes as ‘reciprocal interventions’ to retrofit existing buildings. These prototypes serve as novel hybrid material systems, and as evidence to demonstrate the potential for practical applications of responsive morphing architecture with minimal, mechanical and discrete components that sense real-time data, manipulate daylight effects and perform active illumination. The outcomes and findings of my project-based design investigations contribute to early-stage design strategies for architects and designers to model morphing architecture through parametric design processes with responsive material explorations and accessible technologies.

I conclude from my research that through the exploitation of alternative form-changing material systems with responsive capacities and novel tools, an alternative design paradigm for responsive morphing architecture can be conceived. This paradigm is based on anticipation of a new material culture in which physical computation is synthesised with dynamic material properties. This synthesis produces an atypical model as an alternative to mainstream architectural design research and practice for responsive kinetic architecture.
List of abbreviations

AA: Architecture Association
ABS: acrylonitrile butadiene styrene
CRG: Cornerstone Research Group
DARPA: Defense Advanced Research Projects Agency
EAP: electroactive polymer
ESD: Environmentally Sustainable Design
ETFE: ethylene tetrafluoroethylene
IPO: input-process-output
LED: light-emitting diode
MAS: morphing architectural skin
MDF: medium-density fibreboard
PCM: phase-change material
PTFE: polytetrafluoroethylene
PWM: pulse-width modulation
RKMS: responsive kinetic material system
SMA: shape memory alloy
SMP: shape memory polymer
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Introduction

An animate approach to architecture subsumes traditional models of statics into a more advanced system of dynamic organizations.1 —Greg Lynn

When Greg Lynn published his seminal book, *Animate Form*, in 1999, it inspired an entire generation of architects to conceive of architecture as highly elastic, flexible and malleable. As an architecture undergraduate when Lynn’s book was published 13 years ago, like many of my contemporaries I was immediately drawn to this fascinating paradigm of architecture that could change shape, morph, deform and, ultimately, transform. However, after further reading, I came to agree with Michael Chapman’s view of Lynn’s work, that the outcomes of Lynn’s methods ‘are intended to induce the feeling of animation while remaining essentially static’.2 In addition, in one of Michael Speaks’s essays, the author concludes that Lynn’s work ‘is only able to offer animate techniques which produce, in the end, forms which seem no more animate than those he sets out to surpass’.3 Although Lynn produces ‘static’ architecture with ‘animated’ experience through animation techniques, his computer-generated shape-changing blobs or fluid particle systems raise a question that remains unanswered: How is it possible to achieve an actual transition from digital to physical, to develop a potential animated or dynamic architecture with materials, structure and construction implementation?

Since then, after seven years of involvement in the architectural animation industry, and as a co-founder of Metamosaic,4 my conviction regarding the significance of digitally animated architectural forms and surfaces (as initially inspired by Lynn) morphed into a fascination with architecture that could move and change shape physically. This fascination led to my investigation of digital animated surfaces, which led me to consider how to turn them into physically ‘morphing’ architectural surfaces as an extension to the current body of knowledge regarding responsive kinetic architecture.

My personal background in the architectural animation industry allowed me to digitally morph objects and forms in the context of architectural visualisation. I began to imagine that processes of

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virtual morphing could eventually transfer to physical architecture that could respond and change shape beyond the digital realm. I wondered whether this transition was possible, and, if so, how it could be achieved. Could there be a morphing architecture? These were my initial enquiries after reflecting on my previous experiences of architectural animation, prior to the commencement of this PhD study. Departing from these early analogies between virtual and physical, the initial purpose for undertaking this PhD research was to investigate the possibility of applying the digital morphing idea to designs for kinetic and form-changing architecture constructed with physical materiality and responsive capacity.

Based on this rather optimistic hypothetical idea, I began an initial review of current literature and precedents regarding similar research approaches. However, all the closest current built precedents to this responsive kinetic architectural vision were designed with mechanical components. Although I was aware that architecture with retractable roofs, mobility and rotating ability might fall into a similar category as ‘kinetic architecture’—a term coined by William Zuk and Roger H. Clark in the 1970s—it this was beyond the scope of my research. In contrast, my research is concerned with the kinetic design of continuous architectural surfaces with seamless transformable and responsive capacities, such as the Hyposurface designed by dECOi a decade ago. The findings of my initial research, particularly regarding the state of responsive kinetic building skins, reinforced my eagerness to commence my PhD research. Part of the motivation to commence this study began with my curiosity about new possibilities and alternative design paradigms for responsive kinetic architectural applications. This curiosity existed in the context of animated architectural surfaces or envelopes that can morph and respond to environmental stimuli—a kinetic vision quite alternative to the prevalent convention of using mechanical kinetic components.

The idea of a responsive and form-changing architectural surface challenges the materiality of a physical architecture. Current approaches to the design of these architectural features, such as kinetic façades, include the predominant use of mechanical systems, often borrowed from mechanical and electrical engineering. Reacting to this context, there are potential design possibilities in using ‘soft’ and form-changing materials to fabricate kinetic and responsive architectural components. Although the ‘soft’ approach in architecture was introduced during the 1960s and 1970s, there has still not been much progress in this domain. In order to realise this vision, further exploration with kinetic mechanisms and materiality is required. In recent material research, soft matter is becoming a novel approach for applications such as biomimetic sensing and actuation. By synthesising and

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5 However, through literature, kinetic architecture remains one of the closest relevant precedents in this research. These precedents are discussed in detail in Chapter 2. For further information regarding kinetic architecture, see William Zuk and Roger H. Clark, *Kinetic Architecture* (New York: Van Nostrand Reinhold Company, 1970).

6 The term ‘soft’ used in this context is referred to the softness of deformable material properties, and of systems that can be easily deformed and changed in shape when external forces are applied.

manipulating these soft materials, they can be given a unique capacity to respond to external environmental stimuli.\(^8\) By taking the position that a more organic, less mechanical approach capitalises on material properties, rather than the technologies of connections, the initial aim of this research is to address performance and aesthetic demands in soft responsive architectural design.\(^9\)

I began studying the soft approach by reviewing current technological advancements in appropriate and accessible materials, and exploring new analogue and digital tools. The primary outcomes of this initial study led me to develop material systems that use passive and active form-changing materials, such as elastic silicone polymers and shape memory alloys (SMAs). When integrated with and controlled by parametric design tools, application of these materials suggests a new possibility for responsive architectural designs. When integrated with other sensing and actuating components, these soft material systems have the potential to provide an alternative as multifunctional material systems that address the current brittleness of mechanical and sensing systems. The soft approach in these material systems, in general terms, exploits the nature of the soft material properties. In my experiments, the soft materials were integrated with other hard materials to form them. I took advantage of the flexible and elastic nature of the material systems to perform ‘organic’ deformation and actuation. This soft approach develops new architectural meaning for the term ‘morphing’ that is inspired by recent soft mechanical approaches in aerospace engineering, particularly in morphing wing technology.

In computer graphics and motion pictures, the term ‘morphing’ refers to a visualisation whereby one image is seamlessly transitioned into another. In recent aeronautical and automobile research, the term has often been applied to morphing wing design and to new shape-changing material development.\(^10\) ‘Morphing’ is used within the scope of my research to describe a seamless and continuous shape-change deformation.

1.1. Responsive architectural skins

Development of the initial motivation to commence this PhD study began with an enquiry into the absence of new architectural design approaches for responsive kinetic architecture. Broadly speaking, responsive kinetic architecture is mostly assembled from various discrete components that perform sensing and actuation to control external environmental conditions.\(^11\)

Kinetic architectural design has been explored since at least the 1920s. An example is Angelo Invernizzi’s Villa Girasole, built in

\(^11\) This area of kinetic architecture is discussed extensively in Chapter 2.
The design of such kinetic architecture often includes complicated, intricate and heavy mechanical elements, such as joints, actuators and control systems for dynamic responsiveness. This approach almost inevitably produces brittle and vulnerable kinetic systems. This problem established another line of enquiry for me and a significant research motivation to investigate new possibilities to displace conventional mechanical component operations. In common practice, these solutions involve conventional mechanical components that are often borrowed from other disciplines—mostly engineering. Examples are multiple pistons or actuators to enable transformation, which require designers to manage high energy costs and complex mechanisms. These mechanical kinetic design approaches also presented another set of frustrations to me, which subsequently led to another research motivation. This involved investigating new alternatives to the conventional mechanistic operation approach with contemporary tools and materials.

The above questions established the trajectory that motivated me to investigate these hindrances and alternative approaches by using contemporary materials and tools to develop new potentials for the implementation and application of morphing architecture. I have investigated this through responsive architectural skin designs. Current research and designs are mainly focused on improving responsive kinetic architecture in the form of the façade to respond to changing environmental conditions via existing engineering design approaches. In some cases, studies and research have involved developing the efficiency of the responsive architectural skin by building energy performance. Although I am concerned with the important considerations of energy usage and maintenance costs for existing responsive kinetic architecture, these are not within the scope of my research. Instead of attempting to improve existing systems to investigate responsive kinetic architecture in terms of its operational energy consumption and sustainability issues, I considered research that investigates the potential applications of kinetics beyond simply kinetic building façades. I consider these kinetic façades part of responsive kinetic architecture; as Mike Davies suggested in 1981 in regard to his polyvalent wall:

a dynamic processor should not only be the logical response to a dynamic environment at a technical performance level but also fulfill the role of magician in its visual potential and virtuosity.

Davies’s ambitious vision for multifunctional architectural design is still considered paramount, even in today’s context, and remains an underexplored research territory after three decades. This vision is full of potential for these architectural elements, not restricted to the form of ‘façades’. It responds to a changing environment, but is implemented in other design elements, such as autonomous architectural skins for visual, performance, communication and

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experience features. From my perspective, there is a distinguished fundamental difference between a façade and an architectural skin. A façade solely serves as the exterior face of a building. In contrast, an architectural skin portrays a potentially reciprocal and independent architectural feature that either serves as an autonomous exterior or interior element beyond the typical functions of a façade. My interpretation of architectural skin is encompassed by similar characteristics to those of the polyvalent wall envisioned by Davies.

Having been motivated by various initial frustrations and lines of enquiry, I began to ask: Can these responsive architectural elements be applied to architecture beyond conventional kinetic façades? Are there any alternative design implications of soft kinetic systems for responsive architectural features? If so, what are the architectural materials and new tools to apply for their design? I decided to frame the scope of this research within the enquiries mentioned above and to investigate the possible design implications and implementations of morphing architecture, represented in the form of responsive architectural skin designs.

In response to these enquiries, I conducted a series of design investigations. Recent material technology advancements—particularly in accessible sensing and actuation technologies—provided an alternative avenue to explore the possibility of developing a materially kinetic system with embedded physical computing. Within this opportunity, a new potential design paradigm for responsive kinetic architectural designs with minimal or no discrete operable mechanical components has arisen.

1.2. Research aim

The aim of this research is to investigate novel design strategies for responsive kinetic architecture through the exploration of new material systems and tools with sensing and responsive capacities. I begin by framing my research within the scope of architectural skin design explorations that encompass new material developments. The goal is to develop and evaluate early-stage responsive architectural prototypes that can morph in response to environmental stimuli.

1.3. Research question and hypothesis

Technological advancements in designing dynamic architectural skins present new opportunities for designers and architects. Kinetic architecture was introduced by William Zuk and Roger H. Clark in the early 1970s, when dynamic spatial design problems tended to be explored in mechanical systems. Precedents in these architectural approaches often involve the design of kinetic architectural skins that are transformable and responsive. These architectural skins also provide a screen between people and the natural environment, and offer rich possibilities for visual expression and new architectural vocabulary. This design approach has been

16 Zuk and Clark, Kinetic Architecture.
explored since the 1960s, with one of the first examples being the responsive brise-soleil of the Los Angeles County Hall of Records, designed by Richard Neutra in 1962. The design of such kinetic skins often includes complicated, intricate and heavy mechanical elements, such as joints, actuators and control systems for dynamic responsiveness. The kinetic skin of L’Institut du Monde Arabe in Paris, designed by French architect Jean Nouvel in 1987, is a salient example of this approach. These solutions involve conventional mechanical components, such as multiple pistons to actuate transformation, and they require designers to manage high energy costs and complex mechanisms. These piston components were found to be prone to fatigue failure, causing gasket leakage from the pistons.

The approaches and precedents briefly mentioned above often produce brittle and vulnerable kinetic systems in responsive architecture. Thus, the unreliability, lack of longevity, and high energy consumption of these systems are the main hindrances to responsive kinetic architecture becoming a mainstream approach in architectural design. Furthermore, conventional mechanical actuation technologies are inherently stiff elements or require many actuators and large stiff pumps in the case of hydraulic or pneumatic solutions. Is there an alternative to these conventional approaches for designing responsive kinetic architecture? Instead of dismissing the well-established conventional mechanical systems applied in the fields of engineering and manufacturing, my research seeks to explore an alternative by exploiting the conventional mechanical principle partially but using fewer discrete components, which integrate with soft materials to achieve a hybrid mechanical system. The current ‘soft robotic’ research provides some appropriate insights for this alternative that focuses on soft materials such as polymers and nanocomposites. This approach anticipates near-infinite degrees of deformable and transformable freedom if compared to conventional rigid, jointed mechanical systems. Based on the motivations and aim I have outlined above, I ask:

How can soft material systems be used to design responsive morphing architecture?

This key research question leads to the path that I undertook during this three-year, full-time PhD study: a series of project-based design investigations in conjunction with a literature and precedent review. The underlying method was to conduct my research through a series of interrelated experimental project works and practices. These

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21 Ibid., 9.
project works served as design investigations in the form of an innovative technique applied to achieve a specific sub-goal. They were progressively developed into a rigorous method to investigate individually focused implementation in specific research areas. Complemented with the model of reflection-in-action, I undertook the experimental project works in order to generate new understandings and enable changes in the situation to inform further action for every design experiment.

I do not intend or anticipate that my research question will lead to the perfect technology. Rather, in this research I am seeking to establish a perimeter to shape my initial framework to allow potential design possibilities as outcomes and to allow results to emerge at the end of the research. The outcomes generated in this research are qualitative. The research aim is met and the research question is addressed by demonstrating feasibility and early-stage designs for morphing architecture, and by using novel responsive material systems and design tools. I hypothesise that by using emerging form-changing materials and alternative tools, a responsive morphing architecture can be achieved with fewer mechanical components and devices. By developing a consistent experimental framework in which to design, prototype and evaluate applications through these materials and tools, a new design approach for responsive kinetic architecture can be realised. This hypothesis is tested by the results generated from the design investigations, as project works represented in various scales of operational digital and physical conceptual prototypes. These research findings are consistently qualitative, rather than quantitatively measurable. By proposing, refining and testing a rigorous method applied systematically to a series of project-based design investigations, I provide architects and designers with a mix of passive and active design strategies to apply responsive material systems in the early-stage design of morphing architecture.

In my research I investigate the application of alternative multifunctional material systems with possible form-changing and responsive capacities. These are integrated with physical computational processes for responsive morphing architectural design as an ‘integrated’ and ‘synergetic’ entity identical to single-moulded devices such as the solid-state door handles developed by the automobile industry. This approach is inspired by material research and physical computing advancements that are currently adopting inexpensive materials and methods. This inspiration suggests a design approach that focuses on the mechanical and responsive properties integral to composite materials, to replace the functionality of mechanical components for actuation and sensing purposes in order to achieve responsive morphing architecture.

Thus, my research expands the repertoire of current responsive architectural design research through demonstrated investigation processes and prototypical design outcomes that use accessible soft
and morphing elements, such as elastic and form-changing materials, integrated with sensing devices and parametric design tools.

1.4. Methodology
As stated in Section 1.2, this research aims to investigate novel design strategies for responsive kinetic architecture, and their implications, by exploring new material systems and design tools with sensing and responsive capacities. To achieve this aim and address the research question, I take several steps in my research to produce design knowing through the design investigation process. From the initial motivations and enquiries, to exploring alternative design implications of responsive kinetic architecture, I develop this pathway. I undertake my research journey in my PhD study through a series of project-based design investigations in conjunction with a literature and precedent review. This underlying strategy is conducted through the interrelated experimental design investigations as project works and practices. The PhD by project programme offered by RMIT University, provided an appropriate platform and opportunity to allow me to explore my research strategy as discussed above. Since this PhD programme is concerned with projects coupled with an exegetical reflection for knowledge production, I employ a project-based research approach to develop a series of design investigations to provide clearer evidence and outcomes.25 At RMIT University, project-based research is distinguished from conventional thesis-based research. While thesis-based research is an extended, logically constructed argument using well-established epistemological and methodological conventions, project-based research employs a variety of additional methodological heuristic modes, which include modes of research based on creative, design and professional practice.26

Instead of taking the theoretical research approach explored by aforementioned researchers such as Greg Lynn, this project-based research adopts an alternative mode that potentially seeks to address my research question through a range of digital models and physical conceptual prototypes. It also allows me to directly engage with materials and tools during the design investigation process and practice. I perceive the real challenge of animated and kinetic architecture not as conceiving it but rather as realising it. This perception is best demonstrated by the shortcomings and mechanical issues that are revealed in the facade of L’Institut du Monde Arabe, which reinforce the importance of a practical design implementation. The shortcomings of this ‘hard’ mechanical system only become apparent through design practice and physical realisation. Thus, this precedent became part of the inspiration for me to initiate the project-based research approach that allowed me to test my hypothesis with physical practices and project investigations.

25 The PhD by project is a project-based doctorate programme of RMIT University, Melbourne, concerned with the design processes of projects that reveal the shape and nature of enquiry through design. For further information, see Peter Downton, Design Research (Melbourne: RMIT Publishing, 2004), 127.

While complemented by Donald Schon’s ‘reflection-in-action’ concept, my project-based research strategy generates a method as a system of conducting a series of ‘evolving’ design investigations. Schon’s concept is relevant as a complementary element to my research strategy due to its knowing-in-action potential for combining reflection and action. In Schon’s words:

> When someone reflects-in-action, he becomes a researcher in the practice context. He is not dependent on the categories of established theory and technique, but constructs a new theory of the unique case. His inquiry is not limited to a deliberation about means which depends on a prior agreement about ends. He does not keep means and ends separate, but defines them interactively as he frames a problematic situation. He does not separate thinking from doing, ratiocinating his way to a decision which he must later convert to action. Because his experimenting is a kind of action, implementation is built into his inquiry.  

According to the statement stated above, I interpret the integration of doing and thinking-that-becomes-an-action in relation to the design context. In the context of design, Schon further introduced the idea of designing as a reflective conversation with situations, which suggests that designing is a process that allows changes ‘in the situation by forming new appreciations and understandings and by making new moves’. Schon’s idea provided the framework that enabled me to critically reflect upon my own actions and findings during the process of project-based design investigation, to generate tacit and explicit knowledge. This knowledge forms the crucial point of departure from which to commence the subsequent design investigations as project works. Bryan Lawson further describes this approach in the context of designing ‘a model the designer is more or less continually reflecting on the current understanding of the problem and the validity of the emerging solution or solutions’. This suggests that designing is part of the research process if reflection is employed during the design action. Considering my design investigations are project-based, the argument of Peter Downton becomes relevant:

> Designing is also a way of conducting research of the kind that design undertakes and, by this means, of producing knowledge for use in designing.

Downton interprets the idea that knowing, knowledge production and knowledge are at the centre of discussion of designing, especially in the context of architectural design research. He further argues that the design process tests existing knowledge in order to produce new knowledge through the application of skills. In this context, by doing, making and fabricating—often in the production of design projects—products or projects generate design knowing and knowledge. Nigel Cross suggests a similar way to generate knowledge through designing. He proposes that there is a ‘designerly way of knowing’.

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27 The concept of reflection-in-action is introduced by Donald Schon in 1983 is an extraordinary process of continuous learning engages with reflective action and experience. For further information, see Schon, The Reflective Practitioner, 61.
28 Ibid., 68.
29 Ibid., 78–9.
31 Downton, Design Research, 56.
32 Ibid., 72.
He argues that a significant branch of designerly ways of knowing is the knowledge that resides in objects or products created by designers. Designers are immersed in material culture and use products as their primary source of thinking. Through ‘communicating’ with the products, they create new objects that embody new knowledge. Cross also warns that normal works of typical architectural practice are not regarded as works of research:

I do not see how normal works of practice can be regarded as works of research. The whole point of doing research is to extract reliable knowledge from either the natural or artificial world, and to make that knowledge available to others in re-usable form. This does not mean that works of design practice must be wholly excluded from design research, but it does mean that, to qualify as research, there must be reflection by the practitioner on the work, and the communication of some re-usable results from that reflection.

Thus, reflection is prominent when employing design in research. The reflecting process distinguishes a researcher from a normal design practitioner engaged in non-research activity. All the arguments by Schon, Lawson, Downton and Cross discussed above anticipate a notion of the design investigation approach as a research practice that combines a project basis and reflection process. They provided insight and inspiration regarding how my research should be conducted. In order to address my research question and test the hypothesis, this approach of design investigation involved reflection-in-action on ‘doing’ and ‘making’ that directly engaged with novel materials and tools. Instead of making commercially viable products, as design or architectural practitioners do, all the project investigations (from Chapters 4 to 7) generated in my research aim to produce new knowledge through the reflection process for the research and practice fields. The contribution of this design investigation process demonstrates developmental works that go beyond just the refinement of an existing architectural product.

Figure 1.1: Continuous and evolving design investigations as part of a research methodology within the reflection-in-action model. Reflection-in-action is represented as a continuous iterative cycle that indicates the design process provides insight, knowledge, findings and reflections on the basis of which to undertake subsequent design investigations springing from a prior individual predecessor. Source: Author.

34 Ibid., 102.
Figure 1.1 is a diagram that summarises my research methodology inspired by Schon’s concept, as an alternative to investigating through segregated individual projects. It further develops that methodology by involving four interrelated and evolving project-based design investigations in a continuous and iterative reflection-in-action process. Each design investigation is conducted with the iterative cycle in action through identical evolving stages, including initial research enquiries, prototyping, testing and analysis. Prior to the commencement of these design investigations, I developed a pilot system as a method of action generated from the research methodology along with the reflective input of my early research aim, hypothesis and critical summary of the current literature review. This step-by-step and systematic process acts as a rigorous pilot method I developed, called a ‘responsive kinetic material system’ (RKMS), based on the soft kinetic concept. It consists of four stages of the design development process: skeleton, skin, transformation and responsiveness. This process is applied to four design investigations as a Design Tetralogy—namely, Tent, Curtain, Blind and Blanket—with rigorous speculative and reflective action to produce experimentally responsive material systems as prototypes focused on specific research areas, including elasticity, Tensegrity, kinetic materiality and sensitivity. The outcomes of these design investigations become the physical working evidence presented alongside the reflective process. This evidence is embodied and represented in the form of conceptual prototypes. These serve as a proof of concept in support of the research argument, and embody knowledge more efficiently and appropriately than a textual description.

In the core chapters of my exegesis, the series of design investigations are presented to test the limits of their technical feasibility by using proposed and developed material system designs. Most importantly, they are proffered to capture the imagination and project a future architecture that is close to being grasped. The design investigations are representative of reciprocal morphing architectural skins (MASs) retrofitted to existing buildings as ‘reciprocal interventions’. They perform as lightweight, transformable, elastic, flexible, sensing, adaptive and luminous architectural apparel that focuses on the lighting aesthetic as its integrated response.

Instead of obtaining quantitative feedback through an analytical approach, the results of these research project outcomes are evaluated through qualitative feedback. This design investigation process acts coinced the term ‘Design Tetralogy’ based on the nature of the four interrelated design investigations, which form a compound project work conducted within my PhD by project research. This term will be further discussed in Chapter 3.
as an interactive and observant design development strategy. The results generated by these project-based design investigations are used to interrogate original ideas, test the hypothesis and pose a new set of questions through the evaluation and discussion of the various aspects mentioned above.

1.5. Exegesis structure

Following Chapter 1 (this introduction), Chapter 2 introduces selected precedents and literature across various disciplines, ranging from kinetic architecture to responsive building skins and morphing technology in the aeronautical field, to ground readers within the relevant contemporary architecture discourse. The end of Chapter 2 provides a summary that suggests why the work of this research is different and introduces the conception of a novel aspiration: soft kinetics.

Chapter 3 further describes and enacts the soft kinetic concept as a guiding principle underpinning a method based on the methodological framework developed in Chapter 1. This method serves as a pilot system, RKMS, that is applied to every practical design investigation. This is a method for a systematic research exploration using digital and physical prototyping.

Chapters 4 to 7 consist of four project-based design investigations as a Design Tetralogy. Named Tent, Curtain, Blind and Blanket, as research techniques they are applied through the method of action (RKMS) individually, each emphasising a specific research area: elasticity, Tensegrity, kinetic materiality and sensibility.

Design investigation one, Tent, starts with an elastic and soft architectural skin design as a real-time responsive working prototype, to demonstrate the possibility of application as a responsive architectural element that performs passive and active elastic deformation within its material properties. Design investigation two, Curtain, takes advantage of the compression and tension principle in the elastic pneumatic system developed in Tent to further explore a Tensegrity material system. This serves as a more appropriate approach for larger scale architectural design solutions, while using form-changing materials to integrate a tetrahedral skeleton and skin with an elastic modular system. The reflections of these two project works initiated design investigation three, Blind, which is a modular system demonstrating the implementation of form-changing materials, such as SMAs and silicone polymer, as the actuator, as well as part of the skeleton structure, of the morphing skin. The final project work of the Design Tetralogy, Blanket, investigates silicone rubbers integrated with glowing pigments to absorb solar energy and glow in the dark, within a focused area of sensitivity. This fourth investigation explores the new potential for form-changing materials with capacitance sensing, energy absorbing and illumination capabilities to respond to proximity and lighting stimuli. These materials include glowing pigments and conductive paints, which can be used to integrate a composite material system as a responsive MAS. This lightweight, flexible, economical sensory morphing skin
is designed to minimise the use of discrete components, such as sensing and lighting devices. It moves towards an integrated ‘synthetic’ morphing architecture that can sense and respond to environmental and occupant stimuli. This series of design investigations is represented as conceptual prototypes that are tested and evaluated during the reflective design process in terms of their implementation and application. I reflect further and collectively on these outcomes at the end of this exegesis to reach a conclusion in response to the initial hypothesis and in answer to the research question. The results contribute insight and knowledge that generates recommendations for the development of future work.

The results and outcomes generated from these investigations are evaluated and discussed in Chapter 8 in terms of their implications and limitations. This chapter reflects on the overall research journey, its outcomes, and the outcomes’ relevance to the contemporary architectural discourse, particularly in the context of responsive architecture. It discusses five specific aspects of the outcomes: architectural design investigation, materiality, technology, environment and lighting aesthetic. This leads to an initial outline for the following concluding chapter.

The concluding chapter, Chapter 9, presents the summaries and reflections from Chapter 8 to reach the conclusion that morphing architecture—with responsive material systems that sense, respond and actuate as new design strategies—offers a positive potential future in responsive kinetic architectural design for architects and designers. My research approach tested this potential through novel tools and materials that demonstrate a promising method for designing responsive morphing architecture.

The appendices at the end of this exegesis contain the progress images and figures of all the design investigations, the Arduino codes used in every investigation, and the selected full articles of refereed journals and proceeding publications. These documents serve as the supporting material to the main body of text, to provide further information about the technical issues and detailed process of the project development.

39 For full progress images of all design investigations, please refer to Appendix G.
40 For detailed information regarding the general timeline of this research process, please refer to Appendix H.
Background research

My research began with relevant literature and precedent reviews from various disciplines. One of the main purposes of this review study is to ground the reader within the contemporary architecture discourse relevant to responsive and kinetic architectural designs. This review includes five main areas proposed as background study: kinetic architecture, responsive building skins technology, materials technology, physical computing and aerospace engineering. This chapter presents a discussion of the overall background research of contemporary responsive kinetic designs within interdisciplinary fields. It consists of five sections to discuss various aspects of the literature and precedents related to this research investigation (see Figure 2.1). These are interrelated and eventually provide the critical reflections and summaries that suggest a new alternative for the opportunity of morphing architectural designs with responsive materials and systems. Based on this opportunity, the novel theoretical concept of soft kinetics is conceived at the end of this chapter and its implementation is further discussed as a basis for developing a rigorous method in Chapter 3.

Figure 2.1: The chorographical mapping of selected literature for each section. Source: Author.

The first section of this chapter briefly discusses the kinetic approach in architectural design since the beginning of the twentieth century. Section 2.2 explores selected contemporary responsive kinetic architectural skins, with approaches ranging from hard mechanical to soft material properties. Section 2.3 further discusses the new possibilities of kinetic materiality to design responsive architectural skins, and Section 2.4 enters new territory by suggesting the applicability of integrating physical computation and kinetic materiality in responsive architectural skin designs. The fifth section, Section 2.5, focuses on the inspiration of soft mechanical approaches in aerospace engineering, particularly morphing wing technology, for
the potential to apply this to the design of architectural-scale morphing skins.

Each section provides critical, insightful knowledge and arguments that emerge from various fields related to this research and to how and why this PhD study should be conducted. A brief summary and a theoretical concept are presented in Section 2.6, the final section of this chapter. This reflective summary allows me to begin developing the rigorous method and system used in subsequent chapters to conduct the design investigations.

2.1. Kinetics in responsive architecture

In this section I discuss how kinetics is applied in responsive architectural design. This design approach is not new, with the first relevant architectural design realised as early as the first quarter of the twentieth century. Kinetic architecture was introduced by William Zuk and Roger H. Clarke in the early 1970s, when dynamic spatial design problems were explored in mechanical systems.41 Zuk and Clarke generally summarised kinetics in architectural research during the 1960s through discussion and classification of a series of design prototypes and actual projects. In general, according to Zuk and Clarke, kinetic architecture is not static, giving it the capability to adapt to changing environmental conditions, which enhances its aesthetic qualities through moving parts.42 After five decades, there is limited literature on which to base discussion of their ultimate definitions. This section provides a brief overview of the contemporary development of kinetics in architecture, based on Zuk and Clarke’s legacy. In addition, it discusses ‘responsive architecture’, which was coined by Nicholas Negroponte in the same period, when spatial design problems were explored in digital technologies.43

41 Zuk and Clark, Kinetic Architecture.
42 Ibid., 4.

Prior to their manifestations in the 1960s and 1970s, there were precedents for kinetic architectural spaces that could be transformed and reconfigured to accommodate different usage. The first precedent was that of Villa Girasole—the rotating house built by engineer Angelo Invernizzi during 1929 to 1935 in Marcellise. This was a completely revolutionary idea—a rotating building designed to constantly capture sunlight and use an eco-compatible energy source (Figure 2.2).44 Earlier in the same period, in 1924, Gerrit Rietveld used sliding partitions to allow spaces to respond to different uses in

44 Randl, Revolving Architecture, 84.
his Schroeder House (Figure 2.3). Although these two prominent projects used kinetics in responsive architecture almost a century ago, there are few recent projects that go beyond their visionary implication in terms of responsive and kinetic architectural designs.

In addition, during a similar period, László Moholy-Nagy took another approach to designing a kinetic space that focuses on the exploration of light. As a teacher at the Bauhaus, he designed a Light Space Modulator (1922–30), in which perforated metal discs and grates are moved by motor. When spotlights shine on this modulator, it casts continuously changing shadows and reflections on its surrounding environment. Unfortunately, his exploration of kinetic space did not continue after the rise of the Nazis and the outbreak of the Second World War. After the war, the kinetic architectural movement ceased for almost two decades until the beginning of the 1960s. This is arguably why there are no significant precedents related to kinetic architecture between the 1940s and the 1960s.

The architectural scene has progressed since Zuk and Clark’s manifestation of kinetic architecture four decades ago. Contemporary kinetic design in architecture focuses on adaptable entertainment venues that can accommodate various functions and outdoor and indoor activities by being covered with large retractable roofs for particular weather conditions. An example of this is the first retractable roof, at the Civic Arena in Pittsburgh, United States (US), built in 1961 (Figure 2.4). It has also moved forward from the reconfigurable approaches of Archigram’s theoretical Walking City (1964) and Cedric Price’s Fun Palace (1961), and towards kinetic design with a responsive agenda on architectural surfaces or envelopes. These design approaches provide a flexible, reconfigurable space that is capable of responding to participants and adapting to various events and activities (Figure 2.5).

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47 Ibid.


Recent kinetic architectural design strategies can be categorised in the way that Caroline Stevenson has suggested, as deform, fold, deploy, retract, slide and revolve. Based on Stevenson’s kinetic transformation categories, I further discuss the following selected precedents that relate to these categories from different contemporary contexts.

Hyperbody Research Group developed the MuscleBody project in 2005 by using the ‘deform’ strategy embedded with pneumatic muscle actuators to create a deformable architectural envelope that responds to the behaviour of the players (Figure 2.6). In contrast, Michael Jantzen’s mechanically transformable M-Velope uses ‘fold’ as the strategy for achieving various spatial configurations (Figure 2.7). Chuck Hoberman’s transformable structures manifest the ‘deploy’ strategy well in recent kinetic architectural context. The Expanding Video Screen developed by Hoberman and used in a U2 concert can change its size and shape—it represents one of the largest architectural transformable structures constructed today and demonstrates the great potential for kinetic transformable structures in architecture (Figure 2.8). The Ocean Dome, the world’s largest


retractable roof, which housed the world’s only indoor beach in Japan, is an extreme example of using the ‘retract’ strategy to adapt to changing environmental conditions (Figure 2.9). ‘Slide’ is best represented by Shigeru Ban’s 9 Square Grids House (Figure 2.10). This is a contemporary interpretation of the conventional Japanese house, with sliding partitions as large cabinets to store blankets and mattresses during the day and provide privacy at night. However, several shortcomings in the Grids House have restricted its implementation. In general, there are only limited possible configurations, and, because the partitions are produced to be as lightweight as possible in order to allow inhabitants to move them manually, this makes them poor thermal and sound insulators. In addition, the process of reconfiguring a space is still reasonably labour intensive. The last strategy used in kinetic architecture, ‘revolve’, can be represented in the contemporary built project, the Suite Vollard revolving apartment (2004) designed by Bruno De Franco in Curitiba, Basil. Each floor of this 11-storey building rotates independently to allow inhabitants to experience different views and fulfil their individual needs (Figure 2.11). It is considered a contemporary interpretation of Invernizzi’s Villa Girasole, discussed in the earlier part of this section.

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54 Randl, Revolving Architecture, 186–7.
mechanical operations with discrete components. These design strategies, although employed with contemporary technology, are still considered identical to the mechanical design strategies coined by Zuk and Clark’s manifestation of kinetic architecture more than 40 years ago. There is potential to explore design strategies with the current responsive material advancement for kinetic architecture.

In parallel, computationally generated transformable structures have also been a focus of the current digital era. When considering responsive architecture composed by a transformable structure, it is necessary to confront issues of human power, space control, environmental manipulation, material economy, operational effectiveness and energy investment. Furthermore, contemporary responsive architecture is generally built on the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental responsiveness. The integration of these two areas provides an environment that is capable of reconfiguring itself and automating physical change to respond, react and adapt. This metaphor leads to a purpose; structure can be reduced for space-making through the ability of a singular system to facilitate multiple uses via transformative adaptability.

Physical kinetic motions play an important role in responsive architecture. Responsive architecture is not necessarily physically kinetic—for example, the virtual motions of the responsive media façade represented are not kinetic. However, when humans respond to onscreen motion, it is only seen as filtered through the conscious mind. An object that has its own physical mass moves; however, it triggers a more visceral reaction. Thus, physical kinetic motions in responsive architecture are more than just for operational purposes—they offer a new architectural experience that people have never encountered before and form part of the future direction in architectural design. These experiences are best appreciated in Hoberman’s works that has been discussed previously, and further enhanced through the notable example of the moveable wing-like sunscreens atop the Milwaukee Art Museum designed by Santiago Calatrava. The wing-like sunscreen composed of fin-shaped purlins operates like the independent feathers on a bird. These fin-shaped purlins demonstrate poetic shadow play of the screens serving as a large-scale kinetic brise-soleil beyond the sunscreen’s original shading function. The works of Hoberman and Calatrava established a benchmark for what responsive kinetic architecture can achieve.

Discussion of the influences and theories of kinetic arts in responsive architectural designs is beyond the scope of my research. However, the works of selected kinetic artists (works that are relevant to kinetic architecture)—including Ned Kahn, Reuben Heyday Margolin, Theo Jansen, George Rickey and Len Lye—provide certain inspirations and realistic possibilities for architects and designers interested in kinetic designs.

One of the provocative works of Ned Kahn is *Wind Arbor* (2011) at the Marina Bay Sands Hotel, Singapore. This work demonstrates the possibilities of kinetic architectural designs (Figure 2.12). This is a passive, wind-powered, less mechanical kinetic skin that runs along the façade of a hotel atrium. It consists of 260,000 metal ‘flappers’ that perform various patterns via the movement of wind and reflections of sunlight. In addition to reducing solar gain and allowing transmission of air and light into the atrium space, *Wind Arbor* converts a solid building skin into an amorphous and liquid-like surface to create a visual system that combines ambient reflected light and wind patterns in a new and glittering spectacle. This kinetic artwork has architectural functionality and certainly provides insight into the potential of kinetic architectural design. It generates potential for further exploration, particularly in terms of the visual malleability of architectural skins through kinetic movements and morphing effects.

In contrast, the works of Reuben Heyday Margolin and Theo Jansen take a more mechanical approach by creating complicated kinetic machines that are passively powered by natural forces and partially by active forces. Their intriguing kinetic sculptures involve complicated mechanical components that cleverly produce spectacular ‘living machines’ that have stimulated the imaginations of architects and designers. The ‘wind-walking’ Strandbeest project (2010) by Jansen is one of the crucial works that manifests the beauty of ‘living machines’—the integration of art and engineering. It demonstrates that it is possible to use simple materials (plastic yellow tubes) and passive energy (wind) to create a large-scale kinetic structure without heavy and expensive machinery (Figure 2.13). Margolin is interested in a similar approach, but focuses on mechanically driven animated waveform kinetic sculptures. Most of his works are installed in high ceilings; however, his spectacular Nebula project (2010) is suspended from the ceiling of the atrium in the Dallas Hilton hotel and is perhaps the most ambitious kinetic design work of all.

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sculpture ever commissioned. This amazing ‘kinetic ceiling’ is composed of bicycle reflectors, custom anodised aluminium cones and rods. It brings a new life to the existing hotel atrium through its constantly transforming structures and lighting effects (Figure 2.14). It is the largest kinetic surface that Margolin has ever constructed and is an encouragement for architects and researchers to explore large-scale kinetic architectural designs beyond ‘local’ transformations (such as façade openings) and move towards the possibility of ‘global’ transformations (the entire structure or skeleton).

Instead of solely focusing on creating large-scale kinetic sculptures, George Rickey is interested in the theory of motion in kinetic sculptures. His significant theoretical text, Morphology of Movement, argues that the ontology of kinetic arts is best addressed by dealing with actual movement directly, rather than with optical effect. This is best illustrated by his articulation of the classic movements of a ship at sea, including pitch, roll, fall, rise, yaw and shear motions. This study eventually intends to develop a possible ‘syntax’ for kinetic art.

One of Rickey’s contemporaries, the New Zealand-born artist, Len Lye, was also convinced that motion could be part of the language of kinetic art. This led Lye to early experiments with kinetic sculpture. His experimental kinetic sculptures are set apart from the previous examples because Lye was less interested in the mechanical motion in the artificial world than he was in the raw kinetics of nature. This idea is represented in two of his early works, Blade (1976) and Trilogy (1977). The kinetic motion of the homogenous material (steel sheets in this context) created a near-natural movement by deforming the material itself (Figure 2.15). Two significant projects were not realised in his lifetime: the 48-metre-high Wind Wand (2000) and Water Whirler (2006). These demonstrated that materially kinetic sculptures are suitable for large-scale implementation (Figure 2.16 and 2.17). These kinetic sculptures were fabricated with fibreglass and metal to show alternative kinetic motions by material

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64 Ibid.
67 Ibid.
properties. Beyond mechanical components, kinetic operation within material properties becomes feasible and applicable on a single large-scale integrated structure. Since architecture is a large-scale material and structural practice, Lye’s kinetic sculptures are extremely relevant in providing precedents and suggesting novel possibilities for designing kinetics in responsive architecture, at least during the early stage of design experimentation.

Generally, kinetic sculptures do not always influence kinetic design in architecture directly; however, they have the potential to influence kinetic architectural design in the future. Further cooperative works in this particular discipline will test the boundaries of designing kinetics in architecture. All the kinetic sculptures discussed above have opened new windows of opportunity for architects and designers to consider large-scale physical kinetic design in responsive architecture. They have also provided feasible technical and fabrication knowledge that is helpful for architectural applications.

Figure 2.15: Left: Blade, 1976. Right: Trilogy, 1977. Source: Govett-Brewster Art Gallery.

Figure 2.16: Wind Wand, 2000. Source: Corrie Linnell. Right: Figure 2.17: Water Whirler, 2006. Source: Grovett-Brewster Art Gallery.

Kinetics remains one of the crucial elements in responsive architectural designs. It is expressed in the selected precedents discussed in this section, which provide a brief overview of feasible implementations in a contemporary technological context. To form part of the extension of this topic, the next section focuses on a much-narrowed, related area by discussing current applications and implementations of kinetics in contemporary responsive architectural skins. This subsequent section also provides early suggestions of how the kinetic motion of materials might apply to architectural skin designs in the near future.
2.2. Responsive kinetic skins

Architecture has typically resisted kinetic motion; however, technological advancements in designing dynamic screens and animated surfaces present new opportunities for designers and architects. This section discusses the precedents in these architectural approaches, which often involve the design of kinetic skins that are transformable and responsive. In addition, these architectural skins provide a screen between people and the natural environment, offering rich possibilities for visual expression and new architectural vocabulary. They not only have the potential to deliver a new aesthetic for architecture, but are also bioclimatically devised. They are technically competent, and take advantage of advancement in materials. These material-orientated, ambitious ideas for architectural skin designs were envisioned by Mike Davies in the early 1980s. He proposed dynamic change systems that operate on the chemical nature of materials and at a molecular scale. After three decades, due to the accessibility and better economies of advanced materials, his visions can now be realised, at least in terms of producing experimental physical prototypes for research investigation purposes. This section reviews a series of architectural kinetic skins, ranging from hard (mechanical components) to soft (material properties) design approaches. While the hard design approach in this context literally refers to kinematic operation through discrete mechanical components, the soft approach performs transformation by changing the materials’ properties.

The following subsections discuss responsive kinetic building skins in two categories: mechanical skins and soft skins. Mechanical skins represent the existing precedent of responsive kinetic façades and skins using mechanical components to perform sensing and actuations. Soft skins are alternative contemporary design approaches for responsive building skins, and the design experiments use soft and elastic materials.

2.2.1. Mechanical skins

The mechanical responsive kinetic skin design approach has been explored since the 1960s, with one of the first examples being the responsive brise-soleil of the Los Angeles County Hall of Records, designed by Richard Neutra in 1962. The designs of such kinetic skins often include complicated, intricate and heavy mechanistic elements, such as joints, actuators and control systems for dynamic responsiveness (Figure 2.18).
Another contemporary example is the responsive kinetic façade of L’Institut du Monde Arabe in Paris, designed by French architect Jean Nouvel in 1987. This is a significant precedent that is known for its mechanical failure. However, despite its unsuccessful mechanical approach, this beautifully composed mechanical ‘moire pattern’ façade once created a ‘malleable’ interior atmosphere by changing shadow castings (Figure 2.19). It has been a benchmark for the capabilities of responsive kinetic façades for the last 25 years. This façade was one of the pioneer examples of the actual application of responsive kinetic façades. It continues to provide inspiration for contemporary young architects interested in responsive architectural design.

In addition to the two significant precedents discussed above, more than a decade ago, dECOi integrated two facets of architecture—responsiveness and kinetic skin—to create and investigate responsive architectural surfaces and installations. The Aegis Hyposurface, created in 2001, uses high-tech mechanical solutions, such as multiple piston components, to actuate transformation. It is the world’s first functioning physical prototype of its kind at the architectural scale, and it has fulfilled and intrigued the imaginations of many architects and design researchers. Since its construction, architects and design researchers no longer shy away from designing physical prototypes or experiments for kinetic skin designs—the Aegis Hyposurface has set a benchmark for what is possible, even in large-scale structural transformation. Despite its success, the fascinating dynamic surface display system is far from perfect. Its piston components have been found to be particularly prone to fatigue failure, causing gasket leakage from the piston. However, it remains one of the most inspiring precedents for mechanical architectural kinetic skin design.

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75 Ritter, Smart Materials, 6–7.
77 Chun, “Investigation into the Cause.”
In 2008, another similar approach of using pneumatic pistons to control a kinetic façade prototype was seen in the Flare media façade developed by WHITEvoid in Germany. This is a modular visual façade system consisting of several tiltable metal flake bodies supplemented by individually controllable pneumatic cylinders.\(^{78}\) It acts like a ‘living skin’ and seeks to allow the building façade to express, communicate and interact with its surrounding environment (Figure 2.21). Although the reflective surfaces of the kinetic Flare reflect the sky light and environment to generate interesting pattern compositions, its shortcoming is that the porosity and fenestration of this surface do not consider the relationship between the exterior and interior environments.

In contrast, the dynamic façade of the Kiefer technic showroom (2007) by Ernst Giselbrecht + Partner uses the folding technique for perforated aluminium panels to generate various configurations that show a new ‘face’ every hour each day for daylight control.\(^{79}\) Energy performance is not the primary focus for this ‘performative façade’ approach, because it is a showcase to demonstrate that technology can adapt to individual needs and changing conditions (Figure 2.22). However, architectural critics are always concerned about this kind of architectural approach because of its long-term maintenance and longevity issues.

These issues were recently tested by perhaps the largest mechanical kinetic façade ever built—the polytetrafluoroethylene (PTFE) (Teflon) membrane-clad kinetic façade system of the Abu Dhabi Investment Council Headquarters tower, designed by Aedas in 2010. This system—the Dynamic Mashrabiya (a wooden lattice shading screen, particular to the Middle East)—includes 1,049 units fitted to a 150-metre tower covering the east, south and west zones. These units open and close according to the position of direct sunlight.\(^{80}\) The giant hydraulic actuation system for each Dynamic Mashrabiya inevitably creates a slow transformation process to achieve dynamic shading effects. It might be a subtle change in the context of the responsive sunshading approach, but since programmed shading devices follow the sun path throughout the year, individual

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preferences for various comfort settings are unlikely to be possible in such a huge kinetic façade treatment (Figure 2.23).

Figure 2.23: The PTFE (Teflon) membrane-clad kinetic façade system of the Abu Dhabi Investment Council Headquarters tower, by Aedas, 2010. Source: Aedas Architects.

On a smaller scale, one of the recent projects equipped with a proclaimed ‘smart skin’ as a second-layer façade is the newly completed Design Hub (2012) by RMIT University, Melbourne. The original idea proposed an innovative ‘green kinetic façade’ composed of 16,000 sandblasted glass discs as an automation system to help shade and power the building with harnessed solar power (Figure 2.24). However, the completed façade performs none of the responsive abilities mentioned above—at least in its current state of completion. Melbourne planner and blogger Alan Davies argues that the ‘smart skin’ is no better or worse than a conventional shading device:

It seems the Design Hub’s outer wall wants to be something it isn’t and may have ended up doing neither very well. It would be unfortunate if it turns out the environmental performance of such a self-consciously ESD [Environmentally Sustainable Design] building is no better, or possibly even worse, than conventional solutions. I hope not.81

Davies continues to argue that only one quarter of the discs are kinetically operable for the entire façade, and that it is almost impossible to claim that they can perform sun tracking and fully harvest solar energy without embedding photovoltaic cells into each disc. In fact, the discs can only rotate on vertical axes, and even if they could rotate in both horizontal and vertical axes, this would still not be sufficient to fully harvest passive solar energy. Possibly the actual feasible function of the rotating discs is to provide occupants with a view. Since the discs are made from translucent sandblasted glass, there is concern that the nature of this material might jeopardise even its basic shading ability—it might not minimise the direct hot summer sunlight striking the inner glass wall.82

82 Ibid.
In contrast, the west-facing ‘green façade’ of Melbourne Council House 2, Melbourne, built in 2006, provides a more feasible implementation for its climatic façade approach. This green façade is fabricated in untreated recycled timber forming louvres that are kinetically moved by a computer-controlled hydraulic system to manage penetration of the harsh western sun and facilitate views for occupants.\(^{83}\) This outer movable pivoted façade is part of the building’s ‘green’ features, used to achieve energy optimisation and sustainability (Figure 2.25). These particular kinetic louvres are programmed to maximise penetration of sunlight during winter and minimise direct sunlight penetration during summer. However, there is no indication that that they are responsive to unprogrammed situations, such as cloudy days during summer. They remain programmed kinetic louvres instead of responsive ones.

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After the completion of Nouvel’s responsive kinetic façade of L’Institut du Monde Arabe in Paris two and half decades ago, it is surprising that there has not been much progression in this kind of design approach. The current selected precedents discussed above demonstrate this underdeveloped architectural design paradigm. Architects remained fascinated by designing responsive kinetic façades with conventional mechanical methods borrowed from other disciplines, especially from mechanical engineering. The two selected projects in Melbourne, discussed above, are evidence that contemporary kinetic façades still adopt mechanical operation techniques similar to Nouvel’s approach. Although contemporary technology might provide lightweight, durable and faster mechanical devices, the fundamental problems of maintenance and energy consumption remain unexplored and unresolved. The proposed mechanical ‘smart skin’ of the Design Hub serves as another approach to develop this idea, but has not been fully implemented. While the green façade of Council House 2 performs according to its
initial proposal, there is a lack of information and data evaluation of
the energy consumption of these mechanically driven façade systems
after the building’s six-year occupation period.

All the projects mentioned above involve mechanical components
that require designers to deal with a certain degree of hard mechanics
that often produce brittle and vulnerable kinetic systems. These
approaches often involve conventional mechanical components, such
as multiple pistons, to actuate the transformation. These require
designers to manage high energy costs and complicated mechanisms.
As aforementioned in this section, piston components have
disadvantages in terms of leakage and maintenance issues. The
reliability and longevity of these systems is always criticised by
sceptics, who question their eligibility for designing kinetic skins.
The next section reviews the soft approach as an alternative to the
mechanical skins used by researchers and architects to demonstrate
feasible implementations of kinetic skins with fewer or no
mechanical components.

2.2.2. Soft skins

This subsection reviews the selected precedents of kinetic
architectural skins with fewer mechanical operations. Most of these
explore the potential for soft materials to be used as an alternative
design approach, and consider their implications compared to
existing kinetic façade applications. The examples below demonstrate that beyond the conventional mechanical kinetic
façades, soft kinetic skins are possible. This is demonstrated by
exploring soft, lightweight, flexible and elastic materials embedded
with computational abilities that enable the design of responsive
kinetic architectural skins serving as a reciprocal architectural element to existing buildings.

Although soft architecture is a concept introduced in the 1960s and
1970s, there is still limited progress in this domain.84 In order to
achieve the vision, further exploration with soft materials for
architectural designs is required. This subsection explores the
precedents of responsive kinetic architectural skins that use soft
elastic and form-changing materials for fabrication and construction.
One of their purposes is to address performance and aesthetic
demands in soft responsive architectural skin designs.85

The famous climatic skin of the Biosphere at the Montreal Expo of
1967, designed by Buckminster Fuller, sets the first precedent for this
type of soft architectural skin approach (Figure 2.26). It is considered
a pioneering use of soft materials (fabrics) in the design of the
shutters on its geodesic dome steel structure, and its acrylic cell
envelope. These shutters are soft in nature and operated through
individual mechanical motors that function similarly to the roller
blinds used in domestic houses. The purpose of these automated
shutters is to control the temperature and modulate sunlight for the
internal space. They are in the shape of triangular repetitive
components, similar to the pores of human skin. They can open or

85 Khan, “Elasticity.”
close individually in order to create almost infinite patterns through this operation. Although this is a fascinating and novel idea developed almost four and a half decades ago, this soft design approach for responsive architectural skin has not been widely implemented and there have been few further research explorations. Part of the reason for this is the fragile and complex mechanical system, which uses conventional motors and mechanisms to control the rolling of the shutter fabrics. By taking full advantage of soft material properties with current technological advancements, Fuller’s visionary automated shutters have the potential to develop a new kind of responsive architectural skin with fewer or no mechanical components.

There have been several contemporary approaches that further explore these kinds of soft architectural surfaces and skins. Omar Khan’s Gravity Screens are an elastic architectural envelope that provides a novel active response in which surface form results from gravity’s effect on the soft and elastic material patterning (Figure 2.27). These elastic, mutable screens provide possibilities for a responsive space that can mutate from circulation corridors to room clusters. However, Khan’s work provides only a starting platform for soft responsive architectural ideas; there is still unexplored territory in the attempt to expand the potential of moving from the hard to soft approach.

Current projects seek to investigate the softness of kinetic architectural skins in various ways. The recently completed Media-ICT

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87 Khan, “Elasticity.”
ICT building, designed by Cloud 9 Architects in Barcelona, takes the softness metaphor further by demonstrating energy efficiency and implementation of the soft approach to kinetic architectural skin. This pneumatic façade, made of ethylene tetrafluoroethylene (ETFE), responds to the user’s needs. The ETFE skin protects the interior from too much direct sunlight (Figure 2.28). When light is needed, it opens to allow daylight in. This pneumatic kinetic shading device is a crucial example of the practical implementation of the ‘soft skin’ that I focus on in this subsection. Other relevant projects, such as Kukkia and Vilkas, designed by Joanna Berzowska and Marcelo Coelho, investigate the soft approach of kinetic electronic garments that integrate Nitinol and custom electronics to move and change the body in a slow, organic motion. Coelho further explores this idea in the project Shutter, as a permeable surface for environment control and communication.

Although these projects provide knowledge of using active form-changing materials to design soft kinetic textile skins, further investigation is required, particularly in terms of the responsiveness, adaptability and scalability of these systems (Figure 2.29). Another similar work, the Living Glass project by David Benjamin and Soo-in Yang, integrates a Nitinol actuator and sensor to form a responsive kinetic skin. It focuses on transformation within local openings for ventilation purposes. There is an unexplored area for global topological transformation on the entire surface of this project (Figure 2.30).

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91 David Benjamin and Soo-in Yang, Life Size: Volume 2 (New York: Graduate School of Architecture, Planning and Preservation of Columbia University, 2006).
conditions. Their research provides insight into the initial soft approach for responsive architectural skins. However, there is a lack of further research, especially in terms of the porosity of soft architectural envelopes that respond to environmental and communication inputs.

The recently completed South Korean Thematic Pavilion in Expo 2012, designed by SOMA, has a biomimetic media façade that demonstrates a soft approach for large-scale implementation is possible. Instead of adopting conventional media façades based on an orthogonal grid of pixels that permits the display of images or text messages, this soft kinetic skin performs real-time visual content—choreography replaying abstract performances, including patterns of colour, different speeds of movement, and variation in the angles of openings (Figure 2.32). This novel design strategy sets an alternative precedent beyond the contemporary electronic digital media façade by using physical transformable openings (or apertures) to represent abstract visual content.

The water wall of Carlo Ratti’s water pavilion is another soft architectural skin; however, its ‘liquid’ form distinguishes it from the other soft material approaches discussed above. It has a permeable screen with ‘liquid curtains’ of falling water with gaps at specific points to form patterns of pixels created by water and air, instead of conventional light-emitting diode (LED) light points (Figure 2.33). It can be programmed for images and message display, and sense proximity of objects at the same time. By exploring ordinary and simple materials, such as water, in a novel way, this project demonstrates the possibility of creating softness in responsive architectural design without needing new materials and technologies to achieve the soft-skin architectural vision.

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In addition to reviewing the soft-skin precedents discussed above, during the early stages of this PhD study, I found several hands-on experiences of soft architectural skin design. I was selected to attend the SmartGeometry workshop in 2011 and 2012 to study the topic of contemporary materialisation in architectural skin design. The cluster of 2011—namely, Performing Skins, led by Mette Ramsgard Thomsen and Ayelet Karmon—investigated the fabrication of three-dimensional (3D) knitted surfaces that provide an intelligent skin, and are structurally performative and behaviourally responsive.\(^9\) The outcomes of this workshop tested knitted skins that can sense and respond to external environmental stimuli (Figure 2.34). The cluster of SmartGeometry 2012 took another approach, called Bio-responsive Building Envelopes, and was headed by Anna Dyson, Bess Krietemeyer, Neil Katz and Satoshi Kiyono. This cluster investigated the possibility of harnessing the behaviour of electopolymeric display technology to design mediated bio-responsive building envelopes that negotiate aesthetic and cultural desires with bioclimatic energy flows.\(^9\) In this cluster, a new form-changing polymer developed by Elliott Schlam of New Visual Media Group was introduced. This is considered the first near-commercial product available to apply to physical media skins in a building context. The contraction and expansion (in roll form) of this electroactive polymer (EAP) is controlled by the amount of electricity charged to the material (Figure 2.35). One of the shortcomings of this novel material is that it must be contained within concealed double-glazing and does not work in exposed environments.

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Both workshop clusters provided insight into contemporary research and practice development of soft architectural skins. The feedback from these clusters suggests a positive future for this kind of soft approach, especially for responsive architectural skin design. The technical and design knowledge I gained from these two workshops allowed me to further investigate the soft approach of responsive skins. This approach is later expressed through the experimental design works discussed in Chapters 4 to 7.

This section would be incomplete without discussing one of the most significant books about contemporary kinetic building skin design: Designing Kinetics for Architectural Facades: State Change by Jules Moloney, published in 2011. Although this book focuses on the issue of the morphology of kinetic façades, independent of scale or materiality, it provides a comprehensive review of kinetic architecture and makes sense of its existence in terms of theory and design.\(^98\) Part of Moloney’s enthusiasm about the kinetic movement for the transition states of façades is derived from 1960s artist and theorist George Rickey’s works.\(^99\) Rickey’s nautical metaphors form part of the influence for Moloney’s kinetic pattern of façades, discussed in a later section of his book. These works provide a significant framework for the design of kinetics in building façades on a theoretical and conceptual basis. An area that remains unexplored in his research is the implementation and application of materiality in this type of kinetic design approach. My research further investigates this potential area through exploring actual materiality and testing the limits of its possibilities for kinetic skin design.

Building on the success of previous approaches to responsive kinetic architectural skins, I argue that there is a need to explore new materials with form-changing ability in current material engineering to advance the idea of responsive materiality, as discussed in Section 2.3. This is a more organic approach with less mechanical components, which can benefit from materials’ mechanical and responsive properties to produce transformations in designing responsive MASs.

\(^{98}\) Moloney, Designing, 8–9.
\(^{99}\) Ibid., 66–7.
2.3. Responsive materiality

An active material, however, contains both sensors and actuators, with a feedback loop between the two, and is capable of complex behaviour—it can not only sense a new condition, but can also respond to it.  

Branko Kolarevic

My review of the literature on soft skins, as discussed in a previous section, triggered an interest in further investigating soft material that can perform deformation and perhaps function as an actuator and sensor itself. I wanted to investigate whether this kind of material exists. In addition, if it did, I wanted to know how to apply it in a responsive architectural context. These early enquiries formed an initial investigation into the potential of existing form-changing materials to design responsive architectural skins. This investigation eventually generated the concept of ‘responsive materiality’. Responsive materiality offers an initial concept of movement and change in response to material properties, rather than changes in mechanical components, such as actuated motors and gears, in the kinetic architectural context. Current material advancements have allowed this concept to become a reality. Contemporary architects and designers can now reconsider the traditional relationship between architecture and material practice.

Achim Menges’s recent project, HygroScope: Meteorosensitive Morphology, at the Centre Pompidou in Paris, demonstrates a materially actuated responsive skin without any kind of mechanics, electronic control or supply of external energy (Figure 2.36). It creates a new range of possibilities that propose that materials can actuate as well as sense. This purely passive approach suggests that zero-energy responsive architecture is possible. However, one of the shortcomings of this approach is that once the material is ‘programmed’ during the fabrication process, the passive behaviour of the material properties is fixed and unchangeable. Instead of being a negative issue, this shortcoming provides an opportunity for this research to further explore a possible hybrid approach that includes passive and active responsive abilities within the materials’ properties, which can control various states after they are manufactured.

Figure 2.36: Left: ‘Closed’ state of HygroScope: Meteorosensitive Morphology. Right: ‘Opened’ state of HygroScope–Meteorosensitive Morphology. Source: Achim Menges.

Another similar approach is the project Bloom, designed by Doris Kim Sung. This is an architectural installation for sunshading and air

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ventilation, composed of 14,000 pieces of thermo-bimetal. This responsive material is fabricated with two thin sheets of metal. Each sheet contracts and expands at a different temperature rate when heated by sunlight (Figure 2.37). Identical to the HygroScope project, Bloom adopts a purely passive and zero-energy approach through material actuation that focuses on 'local' openings or apertures on its surface. There is an outstanding opportunity to explore this passive approach in the transformation of its overall ‘global’ surface.

In addition to the two projects discussed above, there is another approach that uses passive material actuation through phase-change materials (PCMs), developed by Chris Leung. Leung explores the dynamic façade of a shipping container pavilion by using paraffin wax and passive environmental technology to move between open and closed states of the openings. This process allows daylight fenestration and minimal heat loss. It is a novel method that takes advantage of the phase-changing process of paraffin wax (from liquid to solid and vice-versa) within a narrow temperature band to achieve actuation (Figure 2.38). However, this passive ‘hydraulic’ actuation only occurs within a concealed hydraulic pump system using a piston rod and cylinder head. The paraffin wax is not autonomous and does not work as an independent actuator exposed to the external environment. This is a limitation of some contemporary PCMs in current research. A passive form-changing material that performs actuation as well as sensing independently is required to address the shortcoming of PCMs in the context of designing responsive architecture.

The Hylozoic Ground project by Philip Beesley sets another precedent in which material actuation is applied in the context of architectural installation (Figure 2.39). This Hylozoic environment...
includes several materially actuated elements. The SMA-actuated pores and lashes are driven by Flexinol wires that contract when an electrical current runs through them. This form-changing material is controlled by software that channels electric current to individual SMA wires using a transistor switch. The control system introduces an active material actuation on a small scale by using leverage to amplify the contraction and expansion of the lashes. Although SMAs were invented in the 1960s, this versatile material is still full of potential, especially for responsive architectural design. This material provides room to further develop the architectural-scale application for responsive morphing skins, as discussed in Section 3.2.

ShapeShift is a project that takes another approach to Beesley’s works. A group of students and Manuel Kretzer from ETHZ (the Swiss Federal Institute of Technology, Zurich) used kinetic membranes with EAPs to develop this project as a prototype of an air control and shading system. It performs actuation by an electromechanical process within the materials’ properties. This early exploration of active kinetic materiality is a novel approach; however, further development is needed, especially in the context of architectural-scale implications and potential applications (Figure 2.40). There is also potential for this project to further develop the porosity and permeability of the membrane itself to respond to environmental and communication inputs.

While Menges, Sung and Leung focus on the passive approach to designing responsive architectural elements, Beesley’s works and his project ShiftShape move towards an active actuation and sensing approach by using several form-changing materials and an electronic control system. I wanted to investigate whether there is a system that exploits both passive and active approaches. There is an opportunity to create a hybrid system that involves passive and active implementation to fully exploit the advantages of both approaches. This hybrid system is expressed and partially explored through the design investigations conducted in this research.

Responsive materiality anticipates a novel form of architectural design, particularly in responsive kinetic architecture. By using materials with responsive capacity, this different approach hints at

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the great potential in a material system to perform transformation and other adaptive abilities through the material’s properties. This design revelation establishes an initial step for the design investigations in this research to further explore the full potential of this new paradigm with responsive materiality.

2.4. Physical computing in architectural design

Whereas previous paradigms of cyberspace threatened to dematerialise architecture, pervasive computing invites a defense of architecture.  

—Malcolm McCullough

The previous section discussed novel approaches for materials that are transformable and function as actuators applied in a responsive architectural context. I also sought to examine whether these materials could respond to external stimuli with integrated computational systems. Thus, this section discusses the potential for physical computational processes embedded in these materials to investigate new possibilities to achieve a responsive form-changing material system in architectural design.

In its most simple terms, physical and pervasive computing is about creating a conversation between the physical world and the virtual world of the computer. The process of transduction, or the conversion of one form of energy into another, enables this flow. I sought to examine whether this process can create a conversation between physical material and external environmental data through a computing process in an architectural design context. It is a core enquiry in this section to explore the idea of embedding physical materiality with computation to design responsive architecture.

One of the first approaches that physical computing applied in architectural and engineering practice was Ove Arup’s model experiments on the roof shells of the Sydney Opera House during the 1960s. These experiments tested and collected data from physical scaled models and sent them to a computer for analysis and processing. This innovative approach created a set of new possibilities for architects to design architecture with physical models and digital data (Figure 2.41). This was considered a pioneering use of physical computing in architectural design and provided a platform for provocative experimental design between physical and computation designs.

Three decades later, in his seminal book, An Evolutionary Architecture, John Frazer discusses some of his students’ works from the Architecture Association (AA) in London. He claims that evolutionary architecture should be responsive to evolving in not just a virtual, but also in a real, environment. Some of the works included in this book act as pioneering uses of physical computing in architectural design. The Universal Constructor developed by AA

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107 O’Sullivan and Igoe, Physical Computing, xix.
108 Ibid.
Diploma Unit 11 in 1990 is a significant example of these works (Figure 2.42).

Frazer and some of his students (from 1989 to 1996) at AA also cooperated with the late Gordon Pask. They related their work to cybernetics and architecture. These works included building new design tools and making models of intelligent responsive systems that went beyond the algorithmic approach to generative self-organising architecture to investigate systems that can learn through the basis of feedback. Cybernetics in architecture began to appear in the 1960s, almost in parallel with the concept of kinetic and responsive architecture, as was discussed in Section 2.1. Cybernetics is relevant to kinetic and responsive architecture because it typically requires a feedback and control system. Since this section focuses on physical computing in architectural design, this topic is relevant to this discussion. A control system with feedback ability including sensors and actuators is considered a fundamental physical computing process that inevitably establishes cybernetics as a point of reference. There is also the possibility for cybernetics to be applied in kinetic materiality, as discussed in a previous section. This approach served one of the main investigations of this research.

During the 1960s, avant-garde architectural thinking flourished with provocative ideas involving flexibility, mobility, computers, prefabrication and robotics, as well as energy and resources. These ideas inevitably embraced the cybernetics concept, and it was no surprise that Gordon Pask became one of the pioneers who adopted the cybernetics concept in architecture. Pask was recognised as the source of inspiration for speculative cybernetics ideas in architecture during his teaching at the AA during the 1990s, particularly in terms of his contribution to the responsive architectural theory explored with physical computation technology. According to Pask in 1969, cybernetics was an architectural design paradigm:

> Let us turn the design paradigm in upon itself; let us apply it to the interaction between the designer and the system he...

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designs, rather than the interaction between the system and the people who inhabit it.\textsuperscript{114}

This paradigm, proposed by Pask almost four decades ago, is still considered valid, especially for designers and researchers who investigate the design of responsive architecture with physical computing. It is thus important to consider how Frazer’s works and Pask’s cybernetics in architecture, conceived in the 1960s, relate to current research in responsive architecture in today’s digital and physical computing technology. Frazer and Pask’s contributions are significant because they allow contemporary young designers and researchers involved with responsive architectural research to further their explorations. With current affordable and accessible electronics, such as the Arduino microcontroller with plug-and-play programming software, designers and even architects can achieve Pask’s vision of an architectural design paradigm for more interactions during the design process between the designed systems and the designers. It is considered a novel bottom-up design paradigm even in today’s context, in contrast to the traditional top-down design process that lacks feedback, as Pask suggested.

Ranulph Glanville, a student of Pask, is a champion of second-order cybernetics\textsuperscript{115} that explores the area of communication. Glanville argues that the design process (in architecture) is a form of communication (with designers) that indicates a cybernetic process at work. This cycle of conversation in the design process with designers (the observers) is perhaps the epitome of second-order cybernetic systems, as Glanville claims.\textsuperscript{116} Glanville argues that this process is a cybernetic system with circularity that is embodied in the role of the active observer (designers) in this system—otherwise it would not be a cybernetic system.\textsuperscript{117}

Most contemporary interactive or responsive architecture that involves design (design process) with physical computing is also considered, under certain circumstances, the epitome of second-order cybernetic systems. The feedback loop design process involving the design of physical prototypes and the designers through physical computing (microcontroller, programming software, sensors, actuators and so forth) is a similar system to that which Glanville proposed. Michael Fox and Miles Kemp, in their latest book, \textit{Interactive Architecture} (2009), state that contemporary interactive architecture is the complex physical interaction of the designer’s creative fusion of embedded computation with a physical, tangible counterpart (actuators and sensors).\textsuperscript{118} They also claim that, without simultaneous physical change and embedded computation,

\begin{itemize}
  \item \textsuperscript{115} Second-order cybernetics investigates cybernetics with awareness that the investigators are part of the cybernetic system. The investigators observe the system that they affect, and are affected by it. For more detail, see Francis Heylighen.
  \item \textsuperscript{117} Ibid., 1183.
  \item \textsuperscript{118} Michael Fox and Miles Kemp, \textit{Interactive Architecture} (London: Prince Architectural Press, 2009), 12.
\end{itemize}
responsive adaptability is impossible. This ‘conversational’ design process was initiated by Pask and further developed by Glanville. As Pask describes it, the conversational design process is the basic form of genuine interaction and is important in creating a good model for design. This brief description can be interpreted and suggested as stating that current design processes with physical computing through constant feedback with designers is paramount when designing contemporary responsive architecture.

Physical computing in architectural design has become a popular avant-garde design phenomenon, especially among schools of architecture during the last decade. As aforementioned, the accessibility and affordability of hardware such as the Arduino microcontrollers provides opportunities for non-specialists to design architectural prototypes with basic electronics and software (Figure 2.43). Open-source parametric software such as Grasshopper and Firefly also creates a user-friendly design environment, even for designers without any knowledge of mechatronic or electronic engineering. The current accessibility of this form of design approach was unimaginable for architects and designers a few decades ago.

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119 Ibid., 96.
120 Glanville, “Try Again,” 1185.
121 This design process is inspired in all the experimental design investigations explored in Chapters 4 to 7.

2.5. The inspiration of morphing technology

While the previous four sections discussed the issues of kinetics in architectural materiality and computational design, this fifth section focuses on the disciplines that are inspired by nature and biology, related to engineering technology. The review of this literature provides some inspiration, adding to the possibilities for designing morphing architectural skins (MASs) in full scale, and reveals certain considerations involved in implementing existing technology to achieve realistic possibilities.

Architectural design is always inspired by either the systems or mechanisms of nature. In nature, there are myriad organisms with transformation or deformation abilities that enable them to adapt to changing environmental conditions. It is almost inevitable for architects and designers who are interested in kinetically responsive
architecture to draw certain influences or inspiration from the fascinating creatures and plants capable of morphing or transforming their forms to respond to changing situations. Although current technological advancements have been made with a bio-inspired approach, nature is still far superior to that which humans are capable of making and adapting.\(^{122}\)

Morphing adaptation has been found in nature. In 2007, Roger Hanlon, from the Marine Biology Lab in Massachusetts, revealed the combination of shape malleability and optical transformation found in octopi and cuttlefish.\(^{123}\) The morphing and visual transformation of the skins of octopi serve as their primary defence camouflage from predators (Figure 2.44).\(^{124}\) This provocative revelation of adaptive morphing ability in nature provided the idea that artificial surfaces designed with synthetic responsive materials might perform similar effects.

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\(^{123}\) Mather, “Responsive Materials,” 94.


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One of the areas, aside from architecture, that has adopted the initial morphing concept is the soft mechanical approach used in aerospace engineering, especially for morphing wing technology.\(^{125}\) In the field of engineering, the word ‘morphing’ is used when referring to continuous shape change—when no discrete parts move relative to each other, but one entity deforms upon actuation.\(^{126}\) For example, on an aircraft wing, this could mean that a hinged flap would be replaced by a structure that could transform its surface area and camber without opening gaps in itself and between itself and the main wing.\(^{127}\) Current research programmes include the Morphing

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\(^{127}\) Leonard D. Wiggins et al., “A Design and Analysis of a Morphing Hyper-elliptic Cambered Span (HECS) Wing” (paper presented at 45th
Aircraft Structure programme by the Defense Advanced Research Projects Agency (DARPA). This programme is working in this research direction with newly developed smart materials.128 This fascinating concept of morphing skin as an emerging aerospace technology has inspired aircraft wing design, yet has remained unexplored in terms of MASs.

Leslie Momoda, the director of the Sensors and Materials Laboratory, HRL Laboratories, argues that to achieve this kind of morphing structure on a large scale, a multifunctional material system is required. This material system would require a combination of three or more functions, including logic, sensing, energy storage, structure and actuation.129 It is considered an extended discussion of Section 2.3 (kinetic materiality) to further study the material system, especially in sensing and flexible capabilities that can be applied in large-scale structures. Momoda’s proposal for a multifunctional material system would be easily integrated into larger engineered structures because it would be lighter, smaller, less difficult to interface with and easier to maintain than mechanical systems.130

Since architectural design practice normally deals with large-scale structures, the success of implementing this concept in engineering provided the initial idea of designing a full-scale MAS.

Most current smart materials are not multifunctional. They normally perform singular functions, such as actuation or sensing, but not both. Since this section focuses on the morphing technology that can be applied to the design of the structures and skins of responsive architectural surfaces, the materials that perform morphing and actuation with transducer elements are included here. Shape memory alloys (SMAs) are considered one of the most common actuation materials used in aeronautical engineering because of their technological maturity in terms of reliability and performance limits.131 However, they are still considered a one-direction active form-changing material with no sensing ability. One of the main tasks of the project work (from Chapters 4 to 7) in this research is to explore the possibilities of integrating these two abilities (actuation and sensing). There is another class of morphing material—electroactive polymers (EAPs)—that are potential actuation materials for designing responsive architectural skins. However, these are not included in this research exploration because they are only capable of small-scale actuation and can only be actuated by the application of a strong electric current.132

The morphing concept with responsive ability, in engineering, emulates the mechanics of biology. For example, the muscle of

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130 Ibid.
131 This application of SMAs in this research will be further discussed in Chapter 3, thus it is not reviewed in detail in this section.
animals or humans is an adaptive morphing component composed of sensors, actuators and structure as one integrated entity. The multifunctional muscle system is considered a holy grail in the development of large-scale responsive morphing structures. Current research in aeronautical engineering includes that of Cornerstone Research Group (CRG), which is investigating the Veritex artificial muscle for military purposes, especially to morph aircraft wings of unmanned combat aerial vehicles.\textsuperscript{133} This prototype hints that the artificial muscle-like actuation and sensing system is suitable for large-scale implementation (Figure 2.45). The early success of this experiment encourages responsive architectural skin designs to adopt a similar design approaches in terms of structure, sensing and actuation as one integrated surface. This idea is further developed and discussed in Chapter 3 and is thus not reviewed in detail in this section.

![Figure 2.45: The Veritex artificial muscle developed by CRG for potential use in the morphing aircraft wings of unmanned combat aerial vehicles. Source: CRG.](http://www.crgrp.com/technology/overviews/morphing.html)

In addition to current research on morphing technology from aerospace engineering, there are numerous experimental morphing design ideas from the automobile industry. The GINA Light Visionary Model is an innovative concept automobile with a morphing ‘fabric skin,’ designed and built by the BMW group in 2008. This manifests a future design direction for automobiles, particularly regarding the idea of surfaces. The vehicle has an external ‘envelope’ made by polyurethane-coated Lycra—a resilient, durable and water-resistant material. It is flexible and elastic, stretched by a form-changing aluminium frame underneath that is controlled by electric and hydraulic actuators allowing drivers to change the body shape to adapt to road conditions (Figure 2.46).\textsuperscript{134} Another innovative idea is the eye-inspired morphing headlamp that can open and close to achieve an optimal aerodynamic vehicle shape in various driving situations (day and night). This provided imaginations that such an approach could be applied in the context of architectural openings such as windows and doors. This is considered an important piece of innovative engineering with the purpose of inspiring designers. Such creativity is not limited to the automobile industry; research in this area is expanding in new directions, especially for responsive kinetic architectural skins. As stated by Chris Bangle, a former chief designer of BMW Design and GINA Light Visionary Model, the speculative form-changing surfaces or skins in the automobile industry provide new challenges to both automobile designers and architects.\textsuperscript{135} These challenges will motivate current architects and design researchers to investigate new


possibilities for form-changing surfaces to be applied in the design of architectural skins.

Figure 2.46: GINA Light Visionary Model designed and built by BMW group in 2008. It demonstrates the morphing polyurethane-coated Lycra bonnet skin in ‘closed’ and ‘opened’ state. Source: BMW.

All the morphing technologies in various disciplines reviewed above are still considered in their early stages and we are at the beginning of a long journey towards fully exploiting their potential. This provocative and inspiring approach is moving towards using responsive materials to create a system that can respond to its surroundings and adapt for optimal performance as a synthesised entity. This is an innovative and challenging research area in the aeronautical and automobile industries, and in architectural design. However, this area lacks research exploration, and this shortcoming provides an opportunity for MAS design to grasp these challenges through design. A new design paradigm will inspire future research. This frames a core research area by using current morphing technologies to inspire this research investigation.

2.6. Towards a responsive soft kinetic approach

This section summarises the five focused research areas in the literature review that generated insightful background knowledge for this study. These research areas served as a ‘mini categorisation’ to unite various fields and disciplines that individually seem separate, yet are related. They also reinforce the scope of my research and enhance the methodology proposed in the previous chapter. Most of these resources were selected and reviewed through books, journals, papers and the internet, as well as my personal experiences attending international workshops and conferences, such as Smartgeometry 2011 and 2012. These experiences provided first-hand knowledge of the most current research outcomes and directions related to this research, prior to their publication. They were a valuable source of up-to-date resources and knowledge that was extremely helpful while writing this chapter, as was information publicised on the internet. In addition, constructive conversations with peers such as researchers and other PhD candidates with similar research interests at international conferences contributed a great deal of knowledge and helped narrow the scope of and literature selected for my research.

This chapter began by discussing the issue of kinetics in responsive architecture, then discussed current morphing technology from various industries. This diverse review of literature appears to be composed of separate, individual topics. However, these served as interrelated critical reviews of the literature and precedents that grounded this study’s initial direction for method development. They eventually shaped a system to design the series of experimental design projects used as the form of enquiry. They do not represent a linear process and stand-alone component of this chapter—each section draws on background knowledge and relates to the issue of...
designing architectural skins with responsive material systems. For instance, Section 2.2 focused on responsive architecture skins. This was a further development of a previous section regarding kinetics in responsive architecture. Another example is that, without Sections 2.3 and 2.4, which discuss kinetic materiality and physical computing in architectural designs, no proposed design system to control materials’ properties through physical computing could be realised in Chapter 3. As mentioned in an earlier part of this chapter, the main aim of Section 2.5 was to review the possibilities for large-scale morphing structures to be applied in responsive architectural skin designs. These possibilities could not be explored further without the background knowledge generated from the previous four sections. Thus, each section has an irreplaceable role and serves to achieve critical review and reflection.

The critical reviews of the five areas in this chapter provide a summary that indicates the potential for passive and active design strategies taken from various disciplinary practices and fields. These can create kinetic architectural designs with or without complicated mechanical actuations and transformations, to respond to external stimuli. Based on this context, the concept of soft kinetics is conceived to investigate the design paradigm for responsive morphing architecture. It offers kinetic movement and shape change in response to material mechanical properties through a computational process, rather than changes in mechanical components. This concept eventually led to the development of a rigorous method as system to apply in all the project-based design investigations embodied in responsive material systems.

In the next chapter, the soft kinetic concept is discussed in detail and subsequently used to develop a systematic and step-by-step rigorous method of action—a responsive kinetic material system (RKMS)—as a pilot design system to apply to every design investigation to test the initial research hypothesis. These design investigations consist of four project works as a Design Tetralogy: Tent, Curtain, Blind and Blanket. They focus on the individual research areas of elasticity, Tensegrity, kinetic materiality and sensibility. Each of them has the identical design implications of lighting, visual and illumination effects in an architectural context, is are applied as reciprocal interventions to existing buildings’ environments. Their results serve as ‘artefacts’ embodied in the form of a morphing architectural skin (MAS) to demonstrate new possibilities and potentials, especially for the early-stage design of morphing architecture that responds to various environmental conditions and serves as research evidence and proof of concept. The application of these MASs, represented as material systems generated through the project-based design investigations, is exhibited through the soft kinetic concept, as discussed earlier, for fabricating conceptual prototypes with modular systems.
This chapter introduces the proposal of the method derived from the design research methodology as shown in Figure 1.1, that was discussed in the introductory chapter, in conjunction with the critical review of literature and precedents in the previous chapter. As discussed in the introduction, the methodology involves the reflection-in-action process of ‘designing’, ‘doing’ and ‘making’. In contrast to some less action-based research methods, this project-based research is conducted and rigorously evaluated to extend current design knowing and knowledge. By ‘doing’ and ‘making’ within the context of a critical review of selected precedents and literature, this approach forms an alternative and crucial quest for knowledge in my research. By employing contemporary technology in terms of materials and tools, this process explores four experimental design investigations as part of research techniques derived from the proposed method.

My research approach expects that the project-based design investigations, when explored with current existing technology, will allow new knowledge to emerge. These investigations are conducted through individual design enquiries with a series of experimental conceptual prototypes that sit on a continuum with prior and subsequent prototypes. This is not done to check the initial results, but as a recognition that the first enquiry resulted in a worthwhile outcome with the potential to again produce a valuable outcome. In this chapter, I further discuss this form of enquiry in order for an appropriate rigorous method to be conceived for this research. The next section discusses this enquiry through the theoretical concept of soft kinetics, conceived in the previous chapter as a guiding principle, prior to using it to develop a rigorous method as a system to apply to every design investigation for the following four chapters.

### 3.1. Soft kinetics

I believe that the ‘softs’ are an important vehicle to responsiveness, but they must be studied with great caution. —Nicholas Negroponte

Almost four decades ago, Nicholas Negroponte envisioned soft materials as the most natural materials for designing responsive architecture because they exhibit and can perform motor reflexes within their properties, even through simple controls. In a similar period, Warren M. Brodey coined the term ‘soft architecture’, which...
is a design concept for intelligent environments. For Brodey, soft architecture is an alternative to hard architecture because it explores the use of soft materials, sensors and feedback loop circuits in the design of an intelligent environment.141 Three decades after Negroponte’s and Brodey’s vision and prediction for soft responsive architectural design, Stanford Kwinter argues that an architectural system is soft when:

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\text{it is flexible, adaptable, and evolving, when it is complex and maintained by a dense network of active information or feedback loops, or, put in a more general way, when a system is able to sustain quotient of sensitive, quasi-random flow.} \quad 142
\]

Kwinter’s idea of a soft system is complementary to both Negroponte’s and Brodey’s visions; however, it moves towards an electromaterial environment from small- to large-scale design in a ‘soft’ world where everything flows seamlessly in real time.143 I further this investigation by exploring the soft concepts discussed by Negroponte, Brodey and Kwinter for architectural material systems in terms of physical materiality and digital responsiveness, particularly in kinetics and actuation for physical transformation purposes. As briefly discussed in the introduction, this soft approach resonates with another term—‘morphing’—that has similarities when referring to seamless, flexible and transformable capabilities.

When the term ‘morphing’ is applied here to architectural design—particularly in the form of a membrane or skin—it is inspired by the reflection in Section 2.5, which reviewed morphing technology in various fields, such as the aeronautical and automobile industries. Architecture is commonly recognised as static form and is built to last. Thus, the idea of having morphing architecture constructed from soft and elastic materials seems contradictory. It does not intuitively seem feasible, because soft materials, let alone those required for morphing purposes, do not generally possess robust structural properties. However, advances in soft and form-changing material technology have revealed their relevance to responsive architecture, especially when integrated with other composite materials, such as those used in aerospace technology. These materials include SMAs and the silicone rubber used in the design investigations within my PhD research study. Current technology in aircraft morphing wing design, as discussed in a previous chapter, indicates some of the potential of these materials to be implemented in MAS design. It is timely to investigate how smart materials can now be applied to designing architecture, particularly for MAS design. The term ‘morphing’ also indicates the potential for passive and active design strategies that can generate kinetic architectural designs with minimal or no complicated mechanical actuations and transformations.

Based on the soft and morphing architectural context discussed above, in conjunction with the critical reviews in Chapter 2, the concept of soft kinetics was conceived. This eventually led to the development of a method as system to apply to all project-based
design investigations, embodied in responsive material systems. This theoretical concept is considered a guiding principle—to use the interchange of elasticity and memory in form-changing materials to affect physical transformation and kinesis in architecture. In contrast to conventional kinetic systems, soft kinetics offers kinetic movement and shape change in response to the thermomechanical properties of materials, rather than changes in mechanical components, such as actuated motors and gears. This shift challenges the current notion of kinetic structure relying on external actuation; in soft kinetics, the transformed surface becomes the actuator itself. This approach—similar to soft mechanical approaches in aerospace engineering, but not yet appropriated in architecture—liberates the transformable skin from a heavy structure. The main idea behind deploying this concept to investigate morphing architectural designs is that the exoskeleton structure and surface is also the actuator, with sensing ability. Hence, soft kinetics does not require mechanical pivot joints, hinges or motors. The kinetic actuation also takes place in the overall system with the use of form-changing materials and little use of mechanical components. It is ‘soft’ in system control as well as in material properties.

Based on this theoretical concept, I begin to explore deformable materials with passive and active form-changing capabilities as part of a design investigation strategy. This is done to develop responsive architectural morphing prototypes through design investigations that minimise the need for complex mechanical actuations. All the experimental works that have been prototyped in various scales combine material explorations, and digital and physical computing techniques. These will be discussed in Chapters 4 to 7.

One of the opportunities offered by soft kinetics is to explore the application of architectural morphing designs and exploit the elastic nature of material systems in architectural structures and skin design. Based on this concept, these material systems are able to accommodate responsive mechanisms with passive elastic memory, while minimising the energy and weight required for actuation. While this approach has general implications for energy usage and the cost of maintenance, these areas are beyond the scope of this research. I argue, as an early hypothesis, that the soft kinetic concept can afford designers a mix of passive and active design strategies with novel material systems and tools for architectural morphing designs. I test this argument through experimental works from small scale to architectural-scale design investigations in this research. The results and outcomes of these investigations describe a new repertoire of responsive morphing architectural design ideas using accessible soft components, such as elastic (passive) and form-changing (active) materials, integrated with contemporary sensor devices. The passive and active deformation of these materials is developed using parametric and physical computing design tools. The following subsections further discuss deformations of these materials through passive and active strategies that eventually lead to devising a material system, as discussed in Section 3.2.
3.1.1. Passive deformation

The purpose of obtaining the passive deformation ability of materials within the overall concept of soft kinetics is to take advantage of their elastic nature for actuation with stored elastic energy. The passive deformable and form-changing materials explored through this research include silicone rubbers, polypropylenes and elastic strings. Passive deformation ability is not limited to these materials—it is expanded to the entire material system composed by these materials in terms of structures and surfaces. This approach is first explored in Chapter 4, which focuses on the research area of elasticity.

3.1.2. Active deformation

In this subsection, active deformation concerns the shapes or forms of materials that can be changed by external active energy—for instance, electricity—as a thermomechanical approach. These actively deformable materials could potentially be used as material control actuators for transformation purposes in responsive kinetic architecture. As discussed in Section 2.3, the materials with these kinds of mechanical properties and abilities are categorised as having ‘responsive materiality’. When integrated with passive deformable materials, these materials serve as the active components for actuation when necessary. The integration of active and passive deformable materials is a novel and tangible way of embodying the concept of soft kinetics to develop a design system as a rigorous method, as discussed in the next section. The purpose of these selected materials, including shape memory alloys (SMAs), implemented in the final three experimental design investigations is to use a passive and active design strategy to minimise energy usage in the transformation and actuation processes.

Exploiting the passive and active deformable capacity of form-changing materials through the soft kinetic concept subsequently develops a systematic and step-by-step method of action—namely a responsive kinetic material system (RKMS). This is discussed in the next section as a rigorous pilot design system to be applied in every design investigation to test the initial research hypothesis. These design investigations consist of four project works and focus on individual research areas. Each has identical design implications of lighting, visual and illumination effects in architectural context, and each is applied as a reciprocal intervention to the existing buildings’ environments. The results serve as conceptual prototypes embodied in the form of MASs to demonstrate new possibilities and potentials, especially for the early stage of design of morphing architecture. These respond to various environmental conditions and serve as research evidence and proof of concept. The application of these morphing architectural skins (MASs) represented as material systems generated through project-based design investigations is exhibited through the soft kinetic concept, as discussed earlier, for fabricating conceptual prototypes with a modular system to test the research hypothesis.
3.2. RKMS

While the previous section provided an overview of the soft kinetic concept, in this section I discuss the implications of this concept for developing a rigorous method. This method is developed in conjunction with the critical reviews in Chapter 2, to conduct design investigations through the reflective and systematic ‘action’ process. The action process in this context not only expressed as ‘doing’ or ‘making’; rather, it allows change and improvement during the design investigation process. I develop this open-ended method of action as a rigorous design system. This method serves as a pilot system and is eventually represented as a responsive kinetic material system (RKMS), as is discussed in detail in this section.

Chapter 2 provided a critical review of the background knowledge needed to understand the responsive and kinetic fields in various disciplines to develop initial knowledge for a rigorous system to be realised. This system is used as the method for the pilot tests. It uses the concept of soft kinetics for design enquiries involving a series of experimental design investigations. These are initiated by exploring how the proposed pilot system provides a crucial rigorous design investigation process to be conducted individually. These design investigations are not reviewed in this section because they are discussed in detail in Chapters 4 to 7. As aforementioned, each of these design investigations focuses on a specific research area. Elasticity, Tensegrity, kinetic materiality and sensitivity are the areas investigated by the enquiries to determine the possibility of designing responsive morphing architectural prototypes.

In his most famous work, *On Growth and Form*, published in 1917, D’Arcy Wentworth Thompson argues that form and mechanical efficiency in the skeleton systems of animals comes from having soft and hard parts, and rigid and flexible parts, in one integral and individual whole.\(^{144}\) He states:

> Muscle and bone, for instance, are inseparably associated and connected; they are moulded one with another; they come into being together, and act and react together.\(^{145}\)

Thompson’s interpretation of the skeleton system study provides ideas and inspires the further development of the proposed concept of soft kinetics. This development is embodied as a design pilot system that is eventually applied to every design investigation project. It is a flexible, integrated kinetic material system, similar to that described by Thompson in that it is composed of hard and soft components. These components potentially achieve transformable and morphing capabilities to initiate a large-scale kinetic structural system for designing responsive morphing architecture. This approach, although identical to soft mechanical approaches in aerospace engineering, such as that used in morphing wing design, does not liberate the

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\(^{145}\) Ibid., 1019.
transformable skin from the requirements of a sturdy structure. Modular components that are also explored in this system act as a lightweight structural support and a spatial envelope in order to achieve large-scale architectural implementations.

The development of the RKMS presented in this section is used as a pilot system for morphing architectural design in the form of skins and envelopes that use the soft approach in a simple yet efficient manner. This system is applied through a series of design investigation processes that require iterations of physical and digital modelling, electronic prototyping and fabrication. Through four stages of the development process—skeleton, skin, transformation and responsiveness—data is exchanged between digital and physical models (Figure 3.1).

The four stages of the process of RKMS design that are applied to each design investigation, as discussed in this section, include:

1. **Skeleton**: the first stage of the design requires the modular components of the skeleton to be sketched, modelled and fabricated. These components are represented in the form of parametric digital and physical tetrahedral modules as part of the experimentation process.

2. **Skin**: the second stage investigates accessible elastic and form-changing materials, such as silicone rubber, nylon coated stainless steel string, SMAs and phosphorescent materials for physical implementation.

3. **Transformation**: the third stage focuses on the new possibilities of the form-changing materials and their elastic nature to emulate simple transformable mechanisms, such as joints, actuators and hinges, to create an alternative toolkit to conventional mechanical components.

4. **Responsiveness**: the last stage of the system discusses the responsiveness of the project work in order to achieve morphing skins that display elastic properties, as well as being able to respond to digital and physical stimuli, and facilitate a feedback loop to the system.

Figure 3.1: The overall structure and four stages of RKMS design. Source: Author.
Reflecting upon Section 2.4, the overall structure of the system conforms to a simple one way input-process-output (IPO) process that is generally the responsive set-up within the RKMS, applied to all four design investigations as project works, as discussed in Chapters 4 to 7. First, the sensors receive the analogue data that is sent to an Arduino microcontroller with Arduino code for processing. Then, the Firefly plug-in embedded in the Grasshopper programme under the Rhinoceros software platform reads the processed data and produces the values that activate the form-changing materials for actuation through pneumatic and material heating systems. The contraction and expansion of the actuated form-changing materials produce kinetic movement in the models as they respond to the external stimuli (Figure 3.2).

To complement this IPO process, virtual parametric models can be associated with real-time data from sensors that stream data from the physical environment as input to drive the parametric variations in the model. The IPO process is considered form-fostering, and enables interoperation and integration of digital, physical modelling and computing through associative design. This form-fostering process facilitates parametric modelling and computing as the platform to simulate the behaviours of the RKMS (physically and digitally) in the early design phase of each experimental design investigation. The following subsections discuss the issue of implementing this design phase with modelling and computing, RKMS and the IPO process, physically and digitally.

3.2.1. Physical and digital modelling

The modelling part of the RKMS with the IPO process is an early-stage design study of the physical and digital models that respond to external environmental stimuli. I use these modelling processes as physical and digital representations to understand the behaviour and performance of the responsive models while designing. The parametric design tools—such as Rhinoceros, Grasshopper (a free

147 In general, the input-process-output process is derived from the architecture-related cybernetic system of Gordon Pask and Ranulph Glanville that is discussed in Section 2.4. For more detail, see Usman Haque, “The Architectural Relevance of Gordon Pask,” *4dsocial: Interactive Design Environments, Architectural Design* 77 (2007): 56.


plug-in for Rhinoceros) and Processing—are used in this process for their robustness in terms of digital modelling and capability of being physical fabricated. The early stages of the experimental digital modelling and physical fabrication processes involve using materials such as medium-density fibreboard (MDF), elastic string and silicone rubber to demonstrate their behaviour and performance through the IPO process. This is demonstrated in Chapter 4. These modelling processes allowed me to compare and evaluate any variation in the physical and digital models during the early design phase.

3.2.2. Physical and digital computing

Physical components embedded with digital computing processes are not uncommon in architectural design. As some projects and precedents were discussed in Section 2.4, this subsection emphasises physical digital computing related to the reaction within material properties. Conventional physical computing experiments mostly involve interaction between the sensors with discrete mechanical devices, such as servomotors for actuation purposes, through a microcontroller. I propose a novel approach that goes beyond discrete components to directly control the material properties for potential form-changing and actuation purposes through the physical and digital computing process. The IPO process discussed above is the embodiment of this approach for the RKMS, which bridges and ‘communicates’ between the physical (materials) and digital (sensing data) entities through Firefly software in real time. Firefly is a physical computing software tool dedicated to bridging the gap between Grasshopper and the Arduino microcontroller. It enables real-time data flow between the physical and digital worlds in order to explore the design potentials of physical and virtual conceptual prototypes. Due to the accessibility and accountability of this software, it is used in the early and final stages of all the experimental design investigations in this study, and serves as a crucial digital element for testing and designing.

3.2.3. Focused research areas related to the RKMS

The process of developing the RKMS requires research to be performed in four distinct, but overlapping, areas: elasticity, Tensegrity, kinetic materiality and sensitivity. This subsection introduces and discusses these four focus research areas, which are eventually tested and implemented in individual experimental design investigation work through the RKMS to generate appropriate prototypes and working models, as demonstrated in Chapters 4 to 7.

Elasticity is the initial focused research area, investigated in the first design investigation. It refers to the ability of a body that has undergone deformation caused by applying force to return to its initial size and form once the distorting force is removed. At a micro scale, elasticity is a result of chemical bonds between the atoms from which a material is made. During deformation,
potential energy is stored within the material, which activates the acceleration back to its original state. This offers new forms of flexibility, adaptability and passive deformation by using the memory effect in morphing architectural skin designs.

The subsequent focused area, Tensegrity, was coined by Buckminster Fuller by combining the words ‘tensional’ and ‘integrity’. It is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such way that the compressed members do not touch each other and the pre-stressed tensioned members delineate the system spatially. Thus, the Tensegrity structural approach reduces the friction between mechanical joints and achieves a lightweight structure that is particularly interesting when considering the development of responsive systems, especially in kinetic operation. Due to the interdependent nature of all the compressed elements, a slight change in any of these parameters can result in significant form transformation. The Tensegrity structure was chosen as the main research area in Chapter 5 due to its flexibility and lightweight components.

The third research area, kinetic materiality, was inspired by Section 2.3. There are several selected responsive materials with form-changing capabilities for actuation and deformation purposes. However, there has been little investigation into the use of these materials as active and passive actuators for structural adaptation and transformation, especially in the design of architectural skins. As a result of comparing multiple form-changing materials, SMAs and silicone rubber were selected to investigate the research area of kinetic materiality presented in Chapter 6. This was done due to these materials’ accessibility for achieving possible active and passive materially actuation in morphing architectural design. Prior to the full implementation and exploration of SMAs in Chapter 6, I have embedded them into the Tensegrity skeleton of Curtain in Chapter 5, to test their deformation capability for material actuation.

The last research area, sensitivity, focuses on exploring the potential for developing responsive synthetic materials with sensing, kinetic and luminous capacity for application in the design of MASs. In this area, I compose sensing devices and morphing architectural skins as one integrated entity, thereby eliminating the need to embed discrete components in a vulnerable system. This research area also explores the properties and performance of a new material, Lumina, for application as a lightweight, flexible and economic luminous MAS that responds to proximity and lighting stimuli. I do not review the details of the design process for this material here because they will be fully discussed in Chapter 7.

These four focused research areas are eventually embodied and investigated through four experimental design investigations as

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project works. These design investigations serve as the research techniques of enquiry in the form of responsive MASs. The next section introduces these experimental design investigations within the four focus areas as a Design Tetralogy. Their implementation and goals generate outcomes that serve as proof of concept and evidence to test the hypothesis and address the research question.

3.3. Research technique: Design Tetralogy

This section begins with two enquiries:

1. What would be lost in this research without the project-based design investigations?
2. If these investigations form a significant part of this research, what is their essential research function?

These enquiries are the early motivation, along with the research methodology discussed in the introductory chapter, to initiate this research with a project-based design investigation approach. These design investigations as project works are critically examined in the subsequent four chapters of this exegesis, to generate a discussion of their legitimacy and efficacy, which is a crucial part of my research. They are conceived in terms of the individual design contexts and implications embodied in the form of responsive morphing architectural skins (MASs). I plan these investigations as research techniques generated from the proposed system as a rigorous method that accounts for half of the time spent in this PhD study. These investigations justify and test the new approaches of morphing architectural designs through a series of continuous and evolving design investigations, consisting of four main project works that use a responsive kinetic material system (RKMS) as their overall method of investigation.

As described in Section 3.2, the investigation of morphing architecture in the form of responsive skin designs is represented as a Design Tetralogy—a research technique composed of four experimental design investigations: Tent, Curtain, Blind and Blanket (Table 3.1). A tetralogy is a compound work that consists of four distinct works, a form originally found in literature and drama. I use this term to describe collectively the four design investigations of the Design Tetralogy, based on their evolving and relating nature during the process of investigation. The outcomes of the experimental design investigations explored in the next four chapters, in the form of conceptual architectural prototypes, reveal new possibilities for modular systems in MAS designs. They respond to various environmental conditions and serve as research evidence and proof of concept. All are conducted through the rigorous method of the RKMS. The input-process-output (IPO) process discussed in Section 3.2 is integral to the RKMS, within the focused research areas of elasticity, Tensegrity, kinetic materiality and sensitivity in the context of responsive morphing architectural designs.

Table 3.1 summarises each of the design investigations, focusing on individual goals, research areas and implementation. Each

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155 The term ‘tetralogy’ has been widely applied to a series of four related works in films, movies, novels, plays and dramas. For further details, see Rush Rehm, Greek Tragic Theatre (New York: Routledge, 1994), 16.
subsequent project is based on reflection and evolving the previous design outcomes to answer specific research area enquiries through a rigorous RKMS, which included four stages, as shown in Figure 3.1. These stages are skeleton, skin, transformation and responsiveness, which are used to generate comparable results in the conceptual prototypes. In this section, I introduce their goals and implementation, but do not review their focused research area because this was discussed in Section 3.2.3.

<table>
<thead>
<tr>
<th>Design Investigation (Project work)</th>
<th>Research areas</th>
<th>Implementation focus</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tent</td>
<td>Elasticity</td>
<td>Architectural skins</td>
<td>Flexibility</td>
</tr>
<tr>
<td>Curtain</td>
<td>Tensegrity</td>
<td>Structures</td>
<td>Transformation</td>
</tr>
<tr>
<td>Blind</td>
<td>Kinetic materiality</td>
<td>Actuators</td>
<td>Actuation</td>
</tr>
<tr>
<td>Blanket</td>
<td>Sensitivity</td>
<td>Sensors / Lighting</td>
<td>Sensing / Illumination</td>
</tr>
</tbody>
</table>

Table 3.1: Design Tetralogy: Four experimental design projects focused on individual goals, research areas and implementation. Source: Author.

The first design investigation, Tent, serves as the interior ‘space divider’ to explore the research area of elasticity by using an assembly of passive tetrahedral elastic modules to represent the overall skeleton and skin components of MAS. It investigates the performances, capacities and behaviours of this system under integrated pneumatic actuation.

The second and subsequent investigation, Curtain, a vertical ‘second skin’, serves as a lighting regulator between the exterior and interior space, and further develops the elastic modules of the first investigation to minimise the number of components and reduce the weight of the module by exploring lightweight and flexible materials. It demonstrates the transformable capability via assembly of the Tensegrity exoskeleton of the overall morphing skin.

The transformable capability of this is further developed in the third investigation, Blind, which is represented in the form of a canopy focusing on kinetic materiality, which emulates and implements form-changing materials to become the actuator, as well as part of the skeleton structure, of the morphing skin.

The penultimate investigation, Blanket, a responsive morphing ‘lantern’, focuses on sensing and illuminating capacities as a reciprocal intervention to improve an existing ill-designed building environment. It embodies an ultimate form of responsive MAS inherited from the capabilities and constructive reflections on the three previous design outcomes. A new type of material is also developed for responsive MAS through this particular project. This material performs sensing, actuating and illuminating, as one integrated entity.

The outcomes of these exploratory design investigations serve as evidence in the form of conceptual prototypes. They are the proof of concept that intends to address and fulfil the requirements of the research question asked in the introduction of this exegesis. These outcomes also demonstrate that the RKMS used in these investigations can provide designers and design researchers with design strategies through novel tools and materials. This strategy
enables mixing of the passive and active transformable capacity of materials in the design of morphing architecture.

The next four chapters discuss these experimental design investigations in detail, and each concludes with a summary as an early individual reflection that initiates the subsequent investigation. These project-oriented investigations embrace technological exploration engaged with a certain level of existing technology in terms of materials and tools to fulfil the technological requirements that anticipate the development of physical conceptual prototypes. Instead of adopting the purely digital animated simulation approach, which is generally less constrained, physical working models and prototypes are used to reflect the harsh constraints of implementation in the physical world.156

These experimental design investigations are understood as expedient forms of research that can inspire innovative approaches from small-scale to full-scale architectural design implementations. These experiments enable speculation on and testing of the new possibilities of material use, fabrication techniques and assembly methods that can eventually translate to larger architectural scale.157 Instead of a conventional top-down approach, they represent a bottom-up design enquiry process. Every design investigation begins with an initial exploration involving a certain level of physical materials, fabricating modular design components to test their feasibility. These are eventually integrated as a series of prototypical working assemblages. The outcomes of the design investigations derived from these assemblages are a physical representation that responds and reflects on the focused research area set by each individual project. These investigations provide a platform for experimentation. They produce exhibition-quality outcomes that can be exhibited and presented in a recognised venue as part of the examination process of my PhD by project research.

Design Investigation 1
Design investigation 1: Tent

This chapter begins with a discussion of elasticity in material as the focused research area for investigating morphing architectural skin (MAS) design using the rigorous method of the responsive kinetic material system (RKMS). As the inaugural design investigation project of the Design Tetralogy at the heart of this exegesis, Tent is a responsive elastic MAS assembled by series of elastic tetrahedral modules that perform form changing between a vertical and horizontal shape.

This is a somewhat primitive first approach at a design investigation for a morphing skin that contracts and expands without mechanical components such as motors and pistons. Tent is a reciprocal ‘luminous space divider’, embodied as a kinetic tent-like skin that changes shape to meet various needs and environmental conditions for an existing interior space. For example, it responds to proximity and changeable spatial qualities by altering the lighting atmosphere. Its shape-morphing capability occurs through a pneumatic air ‘muscle’ in a linear balloon form fabricated with silicone polymer for actuation, in order to manipulate various spatial conditions. Elasticity serves as a key factor in this operation to achieve transformation, especially given the passive energy stored in the material system for actuation and transformation purposes. Based on this potential, the next section discusses the relationship between the design investigation of Tent and elasticity as a material property.

4.1. Elasticity

Elasticity refers to the ability of a body to resist a distorting influence or stress and then return to its initial size and shape once the stress is removed. —Hensel and Menges

According to the theory of elasticity, all solid material systems exhibit a certain level of elastic behaviour if sufficient force is applied. A solid material system is considered elastic if it recovers to its original form or shape upon the removal of the applied forces that caused the deformation. In the context of mechanical engineering, the mechanics of a material system in terms of its properties can be classified into ‘mechanics of solids’ and ‘mechanics of fluids’. Mechanics of solids can also be divided into ‘mechanics of rigid bodies’ and ‘mechanics of deformable bodies’. This section is only concerned with the latter, as it is relevant in the context of this chapter, particularly for investigating the applicability

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161 Ibid., 3.
of deforming material systems with passive energy in the design of the first experimental design project, Tent.

The idea of using soft and elastic material systems to design responsive architecture was introduced in the early 1970s. However, there has not been much progress in this architectural research area by way of exploring alternatives, even after four decades. In contrast to supple materials, the advantage of elastic materials is that they are able to return to their original form without additional external force being applied. However, despite the obvious opportunities of this material system, it is not commonly applied in architecture due to issues of reliability and durability. Aside from uses such as damping and sealing for architecture and construction, elastic materials such as silicone and rubber are often neglected, especially for large-scale architectural designs such as architectural skeletons and skins. Despite their potential, these material systems have not found widespread application—architects and designers tend to shy away from them, cowed by questions of liability and lack of experience.

The initial idea of the early experimental design investigation is to explore the potential of elasticity within structural and material properties that allow physical change as a response and adaptation to external inputs. This idea needs further exploration, especially in terms of energy and weight. This section describes how I conduct the early experiment prior to the design initiation of Tent. It also addresses the issues of energy and weight by using lightweight, simple, elastically transformable modules that respond to stimuli by changing their state and form. It develops one module—an ‘elastic tetrahedron’—as is discussed further in the next section. This aim provides the central hypothesis that an elastic modular system can exploit the advantage of using elastic passive energy in materials to design MASs.

The intention of this early design experiment is to discover general directions to apply to future soft solutions for responsive design and transformability. The elastic experiment focuses on new possibilities of elasticity for MASs in the following areas:

- Elasticity as structure: The structural, architectural components for architectural skins can expand and contract (Figure 4.1).

Figure 4.1: Early physical experiments for the elasticity-as-structure idea, fabricated with hollow plastic tubing connected with elastic rubber strings. Source: Author.

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164 Hensel and Menges, eds., Morpho-Ecologies.
Elasticity as surface: A soft architectural surface is explored by harnessing elastic silicone polymer properties. This tests aspects of the feasibility of implementing passive amorphous building membranes or skins that respond to external and internal environmental stimuli (Figure 4.2).

Figure 4.2: A series of elastic surface structures form a transformable cube that can change its form when forces are applied, and return to its original state when the forces are released. Source: Author.

Elasticity as actuation: This is the novel application of elastic material as an actuator. It excels due to its light weight and its potential to act as a substitute for mechanical joints and actuators. An example is a pneumatic ‘muscle’ in a linear balloon form for global actuation, which reduces weight and friction between parts, compared to equivalent mechanical systems.

The areas described above are the fundamental design implications of elasticity that form the basis of the experimental design investigation of Tent. The following sections discuss the four stages—skeleton, skin, transformation and responsiveness—within the RKMS in order for the overall design enquiry and process to take place. They also further investigate the implementation of the focused area of elasticity for the design implications of Tent.

4.2. Skeleton

First, the assembly skeleton components of Tent include accessible, basic, economical materials, such as elastic strings, as primary elements, and hollow straw-like plastic tubes, used to fabricate the first Platonic polyhedral—a tetrahedron (Figure 4.3). Partially inspired by the work of Buckminster Fuller, in particular the Octahedron-tetrahedron (Octet) truss designed in 1959, this elastic tetrahedron is the basic module forming the overall skeletal structure of Tent, derived from the outcomes generated through the early elasticity experiments discussed in the previous section. Due to its elastic nature, it is expandable and deformable when forces are applied.

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165 These design implications of elasticity were first published in one of my refereed papers—see Chin Koi Khoo and Flora Dilys Salim, “Designing Elastic Transformable Structures: Towards Soft Responsive Architecture” (paper presented at the 16th International Conference on Computer-Aided Architectural Design Research in Asia, New Castle, New South Wales, April 27–29, 2011).

166 The ‘Octet’ truss is a structural system developed through Fuller’s earlier work on the Tensegrity tetrahedron. There is a further discussion regarding Tensegrity and tetrahedron works by Fuller in Chapter 5. For further information regarding the ‘Octet’ truss, see Robert Marks and R. Buckminster Fuller, The Dymaxion World of Buckminster Fuller (Anchor Press, 1973), 172.
applied, thereby allowing transformation to occur even at a local scale.

The series of elastic tetrahedral modules eventually form the supportive and expandable elastic skeleton for the overall backbone structure of Tent (Figure 4.4). This elastic skeleton demonstrates the capability for overhanging and flexible movement that allows the overall structure to contract and expand. Due to its lightweight and elastic physical properties, a small load or force triggers large-scale state change in this skeleton. This structural behaviour implies interesting potential by suggesting that the morphing process of this elastic skeleton uses less force or load with less energy active actuation than conventional mechanical approach.

Aside from its elasticity and lightweight characteristics, this deformable elastic skeleton is also capable of serving as a long-span structure when minimum tensional elements, in cable or wire form, are embedded in its overall fabric (Figure 4.5). These tensional cables act as supportive structural components, change their length and strength, and trigger various deformations of the elastic skeleton. This operation can potentially be used for kinetic and actuated movements of the elastic skeletal structure, even when using only minimum energy. By changing a small amount of the tensional forces and lengths within the local elements (cables), a greater scale of deformation of the global elastic structure can occur. This deformation constrains the contraction and expansion due to its continuous surface structure. These constraints serve as a challenge, yet are a controllable parameter for the elastic skeleton to perform a series of systematic transformations that take advantage of leverage when a small load is applied to the tensional components (Figure 4.6). Although recently a more sophisticated version of a flexible tetrahedral structure—Senspectra—has been developed at the Tangible Media Group, MIT Media Laboratory, it functions as a physical modelling toolkit for real-time sensing and visualisation of structural strain. Instead of serving as a physical visualisation toolkit, the elastic tetrahedral skeleton of Tent is developed to

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explore the potential for full-scale deformable architectural structures with minimal friction between joints.

Figure 4.5: Testing the ability of the overhang of the elastic skeleton with only one tensional wire linked to all elastic tetrahedral modules. Source: Author.

Figure 4.6: Initial transformational test of an elastic skeleton that performs as a contracting and expanding structure when changing the length of the tensional cables. Source: Author.

4.3. Skin

The stage after the development of the skeleton explores the skin of Tent to investigate an inflatable elastic silicone elastomer in a linear ‘balloon’ form integrated within the elastic skeleton to serve as actuator and skin. This approach creates novel effects that mimic organic movement and behaviour. The skin itself is elastic and expandable, thereby achieving a high degree of flexibility and adaptability. I call this actuated skin a ‘balloon skin’. This approach is similar to the Tensegrity system because the air inside the balloon skin serves as the compressional force and the skin acts as the tensional element.168 While changing the pressure of the compressed air inside the balloon, deformation occurs in the overall balloon skin in order to allow kinetic operation and actuation. Based on this context, the balloon skin serves two fundamental purposes—it is an actuator as well as a skin of the transformable Tent.

Two steps within the experiment are undertaken to develop the balloon skin as an actuated structural system for Tent. Step one demonstrates the initial physical experiment by using seven linear balloon-form elastomers tied together. This is done to test their shape-changing ability and loading strength by adjusting various level of compressed air within them (Figure 4.7). By adding loads on the surface of the balloon skins in the form of a suspended structure, the compressional forces (air) and tensional elements (elastomer skins) create strength to uphold certain weights (Figure 4.8). The horizontal surface of these balloon skins also becomes convex and concave vertically, depending on the changing level of air pressure inside the elastomer skin (Figure 4.9). This first experimental step demonstrates that soft and elastic materials can provide structural strength and perform kinetic actuation if the advantages of their

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168 I am not reviewing the Tensegrity system in detail in this chapter because there is an extensive discussion of this system in Chapter 5. For more detail, please refer to Chapter 5: Design investigation two: Curtain.
material properties and behaviour are exploited and a novel structural system is adapted from them.

Figure 4.7: Left: Inflated linear balloons tied together to form a skin actuator and part of the supportive structure. Right: A close-up view of the skin performing bending deformation. Source: Author.

Figure 4.8: A series of tests for the balloon skin as actuator to carry loads and perform contraction and expansion. Source: Author.

Figure 4.9: The balloon skin performs horizontal transformation in convex and concave shapes through realization of different air pressures within the skin. Source: Author.

After successful testing of the load-bearing and deformable abilities of the balloon skin, step two uses three elastomer linear balloon skins integrated within the modular tetrahedral elastic skeleton developed in Section 4.1 as the integrated skeletal skin of Tent. Not only does each linear balloon skin serve as an ‘organic’ muscle-like actuator with skin characteristics, the inverted conventional ‘skeleton and skin’ relationship pierces the elastic exoskeleton of Tent so that it acts as one integrated material system forming an elastic surface (Figure 4.10). This step allows the skeleton and skin framework to form the overall ‘backbone’ of Tent, prior to embedding sensing and responsive abilities. After several initial tests for possible transformations and actuations, this structural skin already begins to show greater strength and kinetic performance than the first-step experiment. The novel approach of inverting the skeleton–skin relationship provides a lightweight and flexible structural system that needs no movable joints to perform kinetic movements, and uses minimal materials used.

Figure 4.10: Modular tetrahedral elastic skeleton integrated with the balloon skin actuators controlled by an electric air pump to form the initial ‘backbone’ of Tent. Source: Author.
4.4. Transformation

The third stage uses pneumatic actuation through the balloon skin to trigger the general morphological transformation of Tent. Through expansion and contraction, the combination of individual tetrahedral modules forming the elastic skeleton performs complicated morphing behaviour that can be envisaged at full scale. This design investigation—the responsive Tent—mimics a simple living organism that responds to proximity.

As discussed in Section 4.1, since the elastic tetrahedral module is fabricated with hollow plastic tubes and elastic strings, it is capable of certain form transformations when force is applied. It returns to its original shape if the force is released. This transformative behaviour of the tetrahedral module allows a series of form configurations, especially when joining two or more modules to form a transformable space frame as an elastic skeleton (Figure 4.11). Figure 4.11 shows a diagram of five selected transformable tetrahedral modular systems for possible configurations, ranging from one to six joined modules. First, there is a single elastic tetrahedral module that can change its size in a reversible manner. Second, adding another tetrahedral module doubles the size of the first module and enables a more comprehensive system to take shape. When three tetrahedral modules are joined, they form a linear system that allows more configurations and sizes. The fourth and fifth tetrahedral systems add an extra three modules from the mirror part of the third modular system in a vertical and horizontal manner. These five transformable tetrahedral modular systems are an early digital simulation to test the possible constraint transformability of the elastic skeleton of Tent.

Figure 4.11: Diagram of five selected transformable tetrahedral modular systems of elastic space frames, as the skeleton structure of Tent. Source: Author.

Figure 4.12: Elastic tetrahedral module formed by elastic string and straw-like plastic hollow tubes, chosen for their lightweight and flexible properties. Source: Author.
The digital simulation of the five selected modular systems eventually provides constructive information, and is used as a testing platform prior to the fabrication of the physical transformable tetrahedral modules. The transformation of these physical modules is triggered by applied active and passive forces. While the active force causes the deformation, the reversible elastic nature of the tetrahedral module provides a passive force that causes it to return to its original form (Figure 4.12). A physical elastic transformable skeleton is formed by composing a series of tetrahedral modules to further investigate larger possible configurations. Figure 4.13 shows sequential frames of the transformation of the elastic skeleton in terms of horizontal expansion and contraction. The purpose of this primary test is to examine transformability at the global scale, even by changing a small portion of length of a tensional cable prior to integrating the balloon skin that links most of the tetrahedral modules (Figure 4.13).

Figure 4.13: Experiment to test the transformability of the modular tetrahedral elastic skeleton in various configurations by changing the length of the tensional cable. Source: Author.

The subsequent step involves the balloon skin actuators developed previously in Section 4.3, which pierce the hanging elastic skeleton to test the informal transformations for the ‘closed’ and ‘opened’ state of Tent. An electric air pump is used to supply compressed air as a compressional element that changes the elastic outer layer skin of the linear balloon skin actuators, making it contract or expand. By controlling the volume and speed of the compressed air supply, several non-linear transformations of the elastic skeleton occur to provide a platform for further exploration that integrates the responsive capability of the overall structure (Figure 4.14). The next section explores the possible responsiveness of this transformable elastic material system by adding sensing and controlling devices. It intends to complete a set-up for Tent that senses and responds to external stimuli by focusing on proximity.

Figure 4.14: A series of transformations to demonstrate the opened and closed states of the hanging Tent actuated by the balloon skin. Source: Author.
4.5. Responsiveness

The fourth stage of the RKMS initiates a responsiveness test of Tent to assess its response to proximity. I conduct this test using a series of digital and physical devices to activate the pneumatic linear ‘balloons’ that actuate the flexible contraction and expansion of the surface of Tent. These devices include open-source parametric software, sensors, physical output components and a microcontroller. Integrating all these physical and digital devices forms a completed set-up that ‘communicates’ to enable the responsiveness of Tent.

![Diagram of the overall set-up for the responsiveness of Tent. Source: Author.](image)

4.5.1. Responsive system

Figure 4.15 shows a diagram that summarises the relationship between the different devices and their individual roles. This diagram provides an initial guide to conducting several early tests and experiments for the responsive system of Tent. First, a code uploaded to the Arduino microcontroller through Arduino software is used for light sensing. The Arduino protocol used in this test is written in Java and Processing open-source software that facilitates interaction between the physical and digital environment. It provides a simple platform for writing code and uploading it to the Arduino microcontroller.

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169 The original code is adopted from work by the OOMLOUT design company, which focuses on open source products. Please refer to Appendix D for the complete code, or download it from http://ardx.org/CODE09.
170 For further detail about this open-source software, see “Arduino,” Arduino, accessed August 15, 2011, arduino.cc/en/.
functioning as a light sensor, I use it as a ‘pseudo-proximity’ sensor because it produces high value if an object is near (less light incidence) and low value while the object is away from the resistor. A torchlight is located to project light onto the photoresistor, thereby creating a consistently lit environment. While an object moves within the boundary of this lit environment, the constant value of the lighting begins to change to cause a different value reading for the photosresistor. I consider this responsive behaviour created by the overall set-up to be a proximity-sensing capability (Figure 4.17). The photosresistor is able to read the real-time high or low value as input data to the Arduino microcontroller to analyse and process eventually as output data to control the activation of the electric air pump. In the last test, the electric air pump produces compressed air that pumps into the balloon skin to actuate the elastic skeleton of Tent to enable global transformation that responds to external environment stimuli.

Second, I modified the code originally used for light sensing in order for the Arduino microcontroller to control the electric air pump. Eventually, Tent responded to the analogue data of proximity through a photoresistor (Figure 4.16). The serial monitor of the Arduino software displays real-time streaming data from the photoresistor. It produces a low value while it is well lit, but produces a high value if there is no light. Third, instead of

Figure 4.16: Arduino code is uploaded to the Arduino microcontroller. Source: Author.

Figure 4.17: Left: Arduino microcontroller for controlling and data processing. Middle: Initial set-up for the responsiveness of Tent. Right: Light source of the overall set-up. Source: Author.

After the initial experiment of connecting all the physical and digital devices with Arduino software and code, I began to construct a
developed version of the circuit that eventually served as the final responsive system for Tent. Figure 4.18 shows a simple schematic diagram of the overall connectivity and relationship of the responsive set-up of Tent. This schematic circuit is composed of an Arduino microcontroller, a photoresistor, a 10k ohm resistor, a 330 ohm resistor, a diode, a transistor, two relays, an external power supply and an electric air pump (Figure 4.18). This schematic was finally developed after several failures of testing and experimenting to connect all the devices physically.\(^{171}\) It is a simple pilot schematic for the entire material system of Tent that makes responsiveness possible.

\(^{171}\) For further information of schematic diagram, please refer to Appendix E.

Figure 4.18: Diagram showing the circuit for the overall responsive set-up of Tent. Source: Author.

There are several input and output pins on the Arduino microcontroller used in this schematic circuit. Pin five is chosen to receive the analogue input data from the photoresistor, while pin three outputs the data processed by the Arduino microcontroller to activate the electric air pump through a transistor and two relays. The transistor is used to amplify the small electrical current provided by the Arduino microcontroller into a much larger current. This larger current is provided to the two relays that are the electrically controlled mechanical switch that turns the air pump, connected to an external power supply (nine volts, three amps), on or off.
This schematic responsive set-up controls the process to drive change between the various states of the balloon skins while compressed air is supplied, and returns the surface to its original state if the air is released. This minimises the energy that would otherwise be needed for local actuation. It develops an economic technological approach to creating performance structures that possess adaptive and evolutionary personalities related to environmental stimuli, by using the IPO process discussed in Chapter 3.

Figure 4.19: Left: The set-up of overall Tent. Right: The devices for responsiveness of Tent, including the Arduino microcontroller, solid-state relay, electrical air pump, photoresistor and torchlight, controlled by a laptop computer. Source: Author.

4.5.2. The complete set-up

The final complete set-up is built based on the digital and physical schematic developed for the early responsiveness test of Tent. It is composed of several components, including a 900 mm x 600 mm x 600 mm frame as an explicit hosting structure in which to hang the skeletal skins of Tent. As aforementioned, these components also include devices such as the Arduino microcontroller with uploaded code, breadboard, solid-state relays, electrical air pump, photoresistor and light source (torchlight). This overall set-up is controlled by Arduino protocol with a laptop computer (Figure 4.19). The first responsive operation of Tent is a primitive actuation process of deflating and inflating the elastic balloon skins through the air pump controlled by the relays (Figure 4.20). This operation triggers the global and local transformation of the tetrahedral modular skeleton that allows expansion and contraction to occur. Through this transformation, closed and opened states of Tent are available, and the process is reversible by controlling the amount of compressed air pumped into the balloon skins (Figure 4.21).

Figure 4.20: Left: The deflated balloon skin integrated with modular tetrahedral elastic skeleton. Right: The inflated balloon skin allows the modular tetrahedral elastic skeleton of Tent to contract and expand. Source: Author.
When equipped with responsive capabilities, which is the goal of this section, Tent performs creature-like and organic kinetic movements when an object in motion is detected. As explained previously, this responsive capability reacts to the proximity of a moving object. If more objects are detected within range, Tent expands its skeleton and skin and turns them into an opened state that represents and mimics an architectural soft structural membrane to create a configurable space that accommodates the increasing number of objects (Figure 4.22). When the number of objects decreases, the closed state is restored. This is controlled by the Arduino microcontroller by releasing compressed air from inside the balloon skins. This is a passively reversible actuation process that takes advantage of the elastic forces of the tensional balloon skins. Although this responsive opening and closing process is performed as a simple and controlled feedback loop, every individual process is generated by a unique state of the transformation pattern, almost none of which is repeatable. This observation suggests that an interesting non-linear soft transformable space is possible. When embedded with lighting effects, it even creates a potential elastic wall or partition that constantly changes its surface appearance, with unlimited configurations.

4.6. Design implications

Tent is an inaugural design investigation that is a first approach to exploring the physical possibilities of designing responsive reconfigurable architectural skins with elastic materials. The design implications of the elastic, state-changing surface of Tent suggest an architectural membrane or skin that transforms or deforms in response to various conditions and needs. When embedded with an illumination and lighting system, it can potentially be used as a reciprocal ‘luminous space divider’ to reconfigure existing dark space in response to changing populations and the activities of users. It is also a possible expandable architectural envelope for altering the atmospheric conditions of different existing environments.
A design complication of Tent is that the property of the elastic material makes it problematic as a self-supporting structure. The introduction of an embedded pneumatic air-muscle skin as a stretchable actuator in the tetrahedral modular system causes it to stiffen and thus supplies a certain level of structural integrity. This design strategy led to creation of the lightweight structural system that allows a soft elastic architectural skin or membrane to transform from thresholds to enclosures. Further development of contemporary applicable soft architectural materials, such as ethylene tetrafluoroethylene (ETFE), embedded with photovoltaic cells and shape memory polymers (SMP), equipped with responsive capabilities to adapt to various environmental stimuli, could provide design opportunities for large-scale elastic and soft architectural components that can morph and respond.

4.7. Summary

Tent is the primary design investigation that creates the opportunity to further develop reconfigurable elastic architectural membranes and envelope designs. Its responsive capacity to adapt to uncertainty and changing environmental stimuli is further investigated in the subsequent project works. This elastic and responsive skeletal skin addresses the focus area of elasticity. In addition, upon reflection, the outcome of a working prototype also generates results to establish the research area of Tensegrity, which is explored through the design investigation in the next chapter.

Through further observations and evaluations, I discover the pneumatic balloon skin structure, which is also considered a Tensegrity structure. Upon reflection, this discovery unveils the possibility of implementing larger-scale flexible structures that adopt similar principles (tensional and compressional components) to those used in Tent. It provides a platform for the next stage of the research, to focus the investigation on dynamic skeletal structural designs without movable joints and connections. The linkage between elasticity and Tensegrity is discussed in detail in Chapter 5, prior to the development of the subsequent project work. The results of this design investigation initiate the beginning of the subsequent project, Curtain, which serves as a continuing and evolving morphology of Tent, but focuses on a different research area in terms of its goals and implementation.
Design investigation 2: Curtain

The previous design investigation, Tent, demonstrated the design possibilities of morphing architectural skin through the organic kinetic behaviour of a modular elastic tetrahedral structural and skin system. It established the integration of the actuator and skin, thereby engendering a new idea, of implementing them as one entity. This outcome of Tent led experimental design investigation two, Curtain, to further investigate the design potential of elasticity, particularly in the relationship between kinetic structure and actuator.

This chapter reflects on works that investigate how architectural skins can change shape and morph while minimising the use of intricate mechanical components. This design investigation demonstrates early physical and digital modular experiments focused on actuated Tensegrity skeletal structures and surface prototypes. Curtain is a bottom-up design investigation of the integration of skin and structure as a vertical visual brise-soleil, in the form of a second skin intended to improve the interior spatial conditions of an existing building. In contrast to the conventional top-down approach, a rigorous design method as the strategy of investigation is followed, based on the four stages of a responsive kinetic material system (RKMS), as discussed in Chapter 3. Prior to further discussing these stages of the RKMS, the next section is a brief review of why Tensegrity is relevant. It also presents a focused research area in this design investigation, particularly in terms of the dynamic and flexible structures implemented in morphing architectural design.

5.1. Tensegrity

When designing the dynamic responsiveness of architectural structures and surfaces, most designers and researchers focusing on building skin designs that reconfigure themselves in changing conditions have used mechanical systems. These flexible structural systems often involve intricate and high-tech mechanical joints, hinges, actuators and controls. The movable joints connect each structural component and inevitably create constant frictions that make this dynamic mechanical structural system vulnerable and maintenance-heavy. In my research I seek to discover whether there is an alternative to designing a flexible and dynamic surface structure, beyond using mechanical joints.

The elastic balloon skin actuator developed in the previous chapter provided early inspiration for the mechanical principle of the Tensegrity system. Based on this, in this chapter I continue to investigate the soft actuated and kinetic system by adopting the Tensegrity principle. Tensegrity, which was coined by Buckminster Fuller during the early 1950s, was described as follows by Anthony Pugh in 1976:
A Tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space.\textsuperscript{172}

According to Pugh, Fuller showed the similarity of the Tensegrity system to balloons and inflatable structures. Pugh further explains the Tensegrity principle by using the balloon analogy. He states that the air inside a balloon has a higher pressure than the surrounding air. It is pushing outwards against the inwards-pulling elastic skin. This is similar to the Tensegrity system, in which the compressional struts or bars push outwards like the air inside a balloon, and the tensional cables or tendons pull inwards like the elastic skin of a balloon.\textsuperscript{173} This balloon analogy was further developed by Rene Motro in 2003. He describes how a balloon can be considered a Tensegrity system because it is a stable self-balancing system that consists of two fundamental components, the internal air as the compressed component, and the external membrane is a tensional component.\textsuperscript{174}

This is a potentially novel kinetic system that, when controlling the air (compression) pressure inside the balloon, allows various deformations or transformations of the elastic balloon skin (tension) to occur. Similarly, the Tensegrity system changes forces in individual local tensional or compressional components to create different strength capacities that allow kinetic and transformable operations to occur within the system.

Both Pugh’s and Motro’s balloon analogies reflect a similar approach to that used in the previous Tent investigation, which involved elastic balloon skin actuation for structural deformation and actuation. Since there are few precedents to explore this analogy for dynamic structural skins, particularly in architectural skin design, this became another motivation for me to further explore the focus area of a flexible structural system derived from the elastic balloon skin actuator that was developed from previous work inspired by the idea of Tensegrity in a structural context. Tensegrity is stable, yet flexible. The compressed parts do not touch one another—they are connected by tensional cables or tendons. It has the potential to enable a full-scale skeletal type of structure to be implemented within an morphing architectural skin (MAS) system.

Prior to the discovery of the Tensegrity system, a Russian constructivist artist, Karl Ioganson, invented the concept of tensile integrity in his 1921 sculpture \textit{Study in Balance}. This introduced the original idea that a structure composed of metal pipes and wire to support its own weight in equilibrium can sway fluidly when forces are applied that disrupt the balance of the structure.\textsuperscript{175} Although many argue that Ioganson’s sculpture is not a true Tensegrity structure, it is

\begin{flushleft}
\textsuperscript{172} Anthony Pugh, \textit{An Introduction to Tensegrity} (Berkeley: University of California Press, 1976), 3.
\textsuperscript{173} Ibid.
\end{flushleft}
considered a pioneer resembling Tensegrity, which inspired the subsequent development of Tensegrity systems. Since Ioganson’s discovery, after three decades, two uses of the term ‘Tensegrity’ have been developed. First, as Buckminster Fuller described it, it refers to a structural system specific to architecture, comprised of rigid struts that can bear tension and compression. Second, sculptor Kenneth Snelson coins the term ‘floating compression’ in Tensegrity structures that achieve mechanical stability through tensional pre-stress components, including struts (compression) and cables (tension). Fuller’s Tensegrity vision focuses on achieving high strength in a structure with minimal materials, as demonstrated by his geodesic domes, which are widely recognisable in architecture and engineering. However, the work of Snelson provides more insightful knowledge for designing kinetic structural systems in responsive architecture. In contrast to Fuller’s architectural vision for Tensegrity, as an artist, Snelson had no interest in applying his floating compression idea in any actual applications. However, I interpret Snelson’s work in a similar way to Donald E. Ingber’s view of Tensegrity. Snelson’s work demonstrates the flexibility exhibited by a floating compression Tensegrity structure, and offers potential advantages that allow structures to take on different shapes and forms if forces are applied.

It is important to question how Tensegrity is relevant to designing architectural skins that are capable of morphing. Developing morphing with Tensegrity structures is not a new approach in aeronautical engineering research, due to the capability of shape-changing for improving flight, mission control, aerodynamics and energy efficiency, specifically in morphing wing design. In this context, the flexible nature of the tensional and compressional members in a Tensegrity structure is advantageous, because forces within it are purely axial and constantly in tension. This means that a slight change to this force equilibrium triggers large-scale transformation. While applying this structural system in MAS design, changing the length of one tensional component (normally a strong material in tension in cable form) of this structure, and, for example, replacing it with a small material actuator, such as a shape memory alloy wire or spring, will transform the overall structure into variable geometric configurations. It also provides the advantage of achieving a lightweight transformable structure while exploiting hard and soft material efficiencies. When integrating elasticity, as discussed in the

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178 In a letter written to the editor of International Journal of Space Structures, Kenneth Snelson clearly states that there is no other purpose for a floating compression structure than to reveal the exquisite beauty of the structure itself. For further detail, see Kenneth Snelson, “From Kenneth Snelson to R. Motro,” International Journal of Space Structures Nov (1990).

179 The primary research of Donald E. Ingber, the Founding Director of the Wyss Institute for Biologically Inspired Engineering at Harvard University, included the discovery of Tensegrity architecture in the way that molecules are structured in a living cell. For further detail, see Ingber, “The Architecture of Life,” 57.

180 Matthew D. Stubbs, “Kinematic Design and Analysis of a Morphing Wing” (MSc diss., Virginia Polytechnic Institute and State University, 2003).

181 William Brooks Whittier, “Kinematic Analysis of Tensegrity Structures” (MSc diss., Virginia Polytechnic Institute and State University, 2002).
previous chapter, the reserved passive energy in the elastic tensional component within a Tensegrity structure will potentially perform self-contraction or self-expansion. The behaviour of the elastic skins serves this purpose well and demonstrates that the skins have this kind of ability, which can be used as part of the tensional components for designing MASs.

Despite the vast potential of the Tensegrity structural principle to be applied to responsive architecture, reviewing the literature I found very few situations in which this approach has been used to design kinetic architectural skins, particularly in transformable architectural systems. This underexplored research area thus becomes the core investigation for the Curtain project, in terms of flexible skeletons, permeability of skins and actuation for transformation. A flexible Tensegrity skeleton, particularly, serves as one of the crucial components throughout the design process of Curtain, and in the subsequent projects.

I formulated a Tensegrity-oriented investigation for designing Curtain, involving soft (tension) and hard (compression) components in order to allow for flexibility in the overall exoskeleton, with fixed connections, yet flexibility, in the overall structure. This Tensegrity approach reduces the friction between mechanical joints and achieves a lightweight structure. Tensegrity structures are particularly interesting when considering the development of responsive kinetic architectural systems. They have microscopic mechanisms and exhibit microscopic deformation and transformation when subjected to external force. Furthermore, due to the interdependent nature of all the elements within the Tensegrity structures, a slight change in any of their parameters can result in a significant form transformation. Thus, this structural implementation becomes part of the soft responsive kinetic system due to its flexibility and lightweight components.

The assembly of Curtain includes a series of modular tetrahedral components that form the overall design framework. In general, following the same rigorous method with the RKMS that was used in the previous project work, the design investigation framework of Curtain consists of four stages, as listed in Section 3.2. These stages are further discussed in the following sections.

5.2. Skeleton

Prior to the fabrication of the final morphing skeleton of Curtain, by using the Tensegrity principle I tested and experimented with the elastic tetrahedral space frame developed in Tent. This led to further exploration of a full-scale flexible and dynamic exoskeleton composed of an inverted medium-density fibreboard (MDF) tetrahedral modular system. This early experiment to develop the skeleton of Curtain created an optimised version of the tetrahedral module, inspired by Anthony Pugh’s four-strut tetrahedron, proposed in 1976. This sought to minimise weight by reducing

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182 Omer Orki, “A Model of Caterpillar Locomotion based on Assur Tensegrity Structures” (MSc diss., Tel Aviv University, 2012).
183 Frumar and Zhou, “Kinetic Tensegrity Grids.”
184 For further detail, see Pugh, Introduction to Tensegrity, 8.
components from six to four struts in each module (Figure 5.1). There is also an optimised profile for the shape of this inverted module, intended to achieve material efficiencies while also achieving maximum structural strength and rigidity.

Figure 5.1: Left: Optimised profile for the two laser-cut MDF elements. Right: Simple inverted tetrahedral module that forms the basic backbone for the early study of the skeleton of Curtain. Source: Author.

Figure 5.2: Early digital study for the formations of the first stage inverted modular tetrahedral cluster. Source: Author.

5.2.1. Early modular cluster design

There are four early design stages in the form of modular clusters that create a flexible and elastic skeleton by composing tetrahedral modules with flexible joints to test their possibilities and feasibilities in various configurations (Figure 5.2). First, the exploration includes a configurable modular cluster that resembles six inverted tetrahedral modules for possible spatial transformations in order to achieve various configurations of the skeleton structure (Figure 5.3).

Figure 5.3: Six inverted tetrahedral modules form the first-stage modular system by performing various transformable configurations. Source: Author.

The second-stage modular system is composed of the three first modular clusters to form a linear spine-like flexible structure that
further advances its transformability and generates more possible configurations (Figure 5.4). This linear modular cluster demonstrates the potential to form a planar surface that can become the overall skeleton of Curtain.

The third-stage modular cluster includes nine first-stage clusters as a planar surface structure that creates Curtain’s initial structural system. This flexible, yet constrained, transformable modular structure performs bending and twisting facilitated by flexible joints. Its singular planar configuration is an interesting rectangular structure that establishes an early prototypical skeleton for Curtain.

The subsequent stage is the final test for the early experiment of the flexible skeleton fabrication. This rectangular skeleton structure consists of nine first-stage tetrahedral modular clusters. It is capable of contraction and expansion deformations in order to enable
morphological operations of the overall structure (Figure 5.5). This test indicates the initial possibilities for morphing behaviour with the constrained transformable modular clusters systematically allowing subsequent design experiments to occur to eventually develop the full-scale Tensegrity skeleton of Curtain. Figure 5.6 shows the permeable elastic foam skins embedded in the structure as the early experiment tests the feasibilities of the integrated flexible skeleton and skins to initiate the pre-structural framework of Curtain.

Figure 5.6: The sequential transformation of a rectangular modular cluster skeleton tested with integrated foam skins. Source: Author.
5.2.2. Modular Tensegrity skeleton

After experimenting with several prototypical working models, as discussed above, for the early stage flexible skeleton design, through observation, I discovered an inevitable disadvantage to these physical prototypes. The dynamic movement of these skeletons creates too much friction between modular clusters through their flexible joints. This is almost contradictory to my original idea to develop a non-frictional flexible skeleton with morphing ability through the Tensegrity principle. Upon reflection, based on the original four-strut tetrahedral module, I adopt an alternative approach by using the same tetrahedral modules. However, I modify the connection between them to enable a new modular formation to occur.

Figure 5.7: Physical tetrahedral modules form the basic Tensegrity space frame as the skeleton of Curtain, actuated by form-changing material (SMA spring) through electric stimuli. Source: Author.

Instead of flexible joints, in this further development, I use fixed joints with non-elastic high-strength polymer cables to connect each tetrahedral module by shifting the connection point to the middle of the two original connection points (Figure 5.7). This shifting and rearranging of the tetrahedral modules immediately creates a fixed, yet flexible, skeleton structure that takes advantage of the Tensegrity principle. Although this Tensegrity skeleton is composed of hard and soft components, such as non-elastic polymer cable, rigid MDF board and fixed joints, this integrated material system ironically creates elasticity in the overall structure that allows transformation through passive energy. After testing passive actuation based on the skeleton’s own elastic nature, I embed two SMA springs between

Figure 5.8: Top: SMA springs embedded within the Tensegrity skeleton, heated by electric current to actuate the overall structure. Bottom: Contractions of embedded SMA springs allow local transformation of the skeleton. Source: Author.
two tetrahedral modules in an early experiment to test its active actuation capability (Figure 5.8).

Since the main structural intention of Curtain is to fabricate a simple, flexible and lightweight skeleton, it is necessary to eliminate and minimise complicated and heavy mechanisms, such as joints and actuators, in order to produce a highly flexible structure. Thirty-six tetrahedral modules form the Tensegrity space frame of Curtain. The integration of lightweight components, such as MDF board and high-strength fishing string, ensure that the physical model is easy to construct and flexible enough to perform expansion and contraction (Figure 5.9).

Figure 5.9: The sequential expansion and contraction of the lightweight Tensegrity skeleton of Curtain, actuated by two SMA springs. Source: Author.

5.3. Skin

The characteristics of human skin have previously been used as a reference to design a morphing architectural surface as a ‘second skin’ in an existing building. This becomes one of the core areas of investigation in this section. This skin metaphor is not new; however, this approach still holds great potential for developing responsive architectural skins, especially in terms of lightweight and elastic design implementation integrated with Tensegrity skeletons.

Figure 5.10: The initial digital simulation for the ‘eye-like’ soft opening of the Curtain surface. Source: Author.

The vertical skin of Curtain explores responsiveness to the porosity performance of the existing building fabric by using elastic lightweight material. The primitive elastic material used for this experiment is foam, which forms the basic membrane non-load-bearing surface for the architectural skin intervention. The initial geometry of the membrane porosity is inspired by the performance of the eye and tested in an early digital simulation (Figure 5.10). This ‘eye-like’ permeable louvre functions as a skin muscle mechanism in the eye and allows various porosity patterns (Figure 5.11).
The eye-like louvres in the geometry are determined by their relative curvature on the responsive undulating surfaces, and actuated by active form-changing material (SMA wire).\textsuperscript{185} This approach is considered the ‘local’ application of Tensegrity, composed of tensional (skin) and compressional (SMA wire) elements for the opened and closed states of the eye-like louvres (Figure 5.12).

The subsequent physical test of the global deformation by using a material similar to the foam skin is illustrated in Figure 5.13. This test seeks to demonstrate and explore the foam skin’s behaviour when actuated by the Tensegrity skeleton with embedded SMA springs (Figure 5.13). This global transformable ability of the overall elastic foam skin potentially allows the organic movements to manipulate various shading configurations.

\textbf{5.4. Transformation}

Curtain includes an early study of the dynamic properties of the form-changing materials used to introduce a simple type of physical material transformation: expansion and contraction. This transformation allows actuation to occur in any three-axis configuration, thereby resulting in a complicated morphing performance of the transformable Tensegrity skeleton and skin. The constraints on the movement and change of this continuous morphing skin contribute possibilities and limitations to the morphological transformation. The global surface curvature of Curtain is modifiable. It allows contraction and expansion while maintaining the continuous topology of any undulating or flat surface. It potentially responds to various functional drivers to manipulate daylight shading and shadow casting.

\textsuperscript{185} The active form-changing material SMA as actuator will be discussed in detail and implemented in Chapter 6, focusing on kinetic materiality. The use of this material in this chapter served as an early test of its capability and applicability. Section 5.4 will briefly discuss the application of this material for transformation purposes.
I consider the continuous topology of the skin as a constraint and limitation that serves as a motivation to develop the skin surface transformation of Curtain in three different rigorous forms:

- **Morphological transformation**: the global surface curvature of Curtain is modifiable. It allows contraction and expansion while maintaining the continuous topology of any undulating or flat surface. It can respond to various functional drivers (Figure 5.14).

  ![Figure 5.14: Four selected transformable configurations of elastic space frame as skeleton structure of Curtain. Source: Author.](image)

- **Patterned transformation**: the changing form of the soft and elastic opening on the surface facilitates change between multiple possible visual patterns. This real-time analogue media effect can manipulate the various appearances of the skin. Therefore, the existing building surface is in constant flux as part of a dialogue with which the environment and users can interact (Figure 5.15).

  ![Figure 5.15: Top: Patterned transformation of local cluster skin (six eye-like openings). Bottom: Selected patterned transformations through the opened and closed states of eye-like openings of the skin in the global surface. Source: Author.](image)

- **Porosity transformation**: the transparency of the surface is generated by the individual elastic eye-like openings that respond to sunlight penetration and shadow. This local transformation changes the spatial conditions of the interior and exterior spaces through dynamic communication between the two (Figure 5.16).

  ![Figure 5.16: Selected porosity 'hot-spots' allow light penetration and cast various shadow configurations. Source: Author.](image)
5.5. Responsiveness

The initial step is to test the responsiveness of Curtain with parametric software and physical computing devices used as design tools to fabricate a full-scale responsive digital simulation (Figure 5.17).\textsuperscript{186} In the digital simulation, the prototype system is applied to an existing building as the second skin that creates a morphing surface for visual and lighting manipulation. The IPO process embedded in the RKMS, modelled with sensors and actuators, generates phenomenal responsive capacities.

First, Grasshopper and Firefly parametric software, together with the Arduino microcontroller, photoresistors and potentiometers, are used as design tools with the IPO process engaged with the simulation process in global and local transformations (Figure 5.18). The simulation of global transformation provides information as an initial test of the responsiveness and transformable behaviour of Curtain to interact with external real-time data in its overall global undulating surface (Figure 5.19). The local transformation of Curtain is also tested with a digital simulation that interacts with external lighting stimuli to form various pattern formations through the opened and closed states of the eye-like apertures (Figure 5.20). Both simulations serve as informative previews that assist in the fabricating process for construction of the final physical prototype.

\textsuperscript{186} For further information on this schematic diagram, please refer to Appendix E.
Figure 5.19: The IPO system process set-up of global transformation for the digital simulation of Curtain responds to external real-time stimuli, such as different light intensities and directions. Source: Author.

Figure 5.20: Digital simulation of local transformation with IPO process for local eye-like aperture openings that respond to external analogue lighting stimuli. Source: Author.

Second, a physical working prototype is constructed, based on the digital simulations, for comparison of results. This final physical prototype of Curtain is fabricated through the developed skeleton and skin components, including tetrahedral Tensegrity skeletons, elastic foam skins and SMA springs. These are integrated with the sensors controlled by the Arduino microcontroller. The shape memory alloy (SMA) springs particularly serve as material actuators for the global (structure) and local (opening) transformations of Curtain (Figure 5.21). The next section further explores the design implications and potential of this prototype in terms of its climatic and cosmetic aspects.

Figure 5.21: Top: Digital simulation of morphological transformation: Bending and twisting in IPO system process. Bottom: Physical implementation of the Tensegrity modular skeletons integrated with elastic foam skin to test the responsiveness of Curtain to the direction of light. Source: Author.

5.6. Design implications

There are two potential design implications of Curtain as a second skin. The first implication is its response to specific aspects of environmental stimuli, such as altered daylight and shading, to respond to changing light conditions. Curtain serves as a lighting regulator between the exterior and interior environment by integrating digital and analogue sensing devices. The second implication suggests Curtain as an analogue media skin for visual manipulation, which can also be responsive to ambient conditions or live data streaming. These two potential design implications are termed ‘climatic’ and ‘cosmetic’.

5.6.1. Climatic

Curtain supports the climatic design implication by using the kinetic undulating surface to regulate shading and shadow control to improve the ambient level of existing spatial conditions. This
function embeds a data input schema and IPO system process set-up that also tests one of the potential applications of the RKMS.

The global transformation of the overall surface benefits from the tetrahedral Tensegrity skeleton that responds to the direction of the sunlight. The morphing operation consists of intentional bending and twisting transformation of the vertical surface of Curtain to achieve maximum natural light penetration during winter and minimum heat gain during summer for optimal comfort conditions within the existing space. Instead of testing this potential implication through digital simulation, this process is embodied in a hypothetical experiment. The climatic aspect is tested using a photoresistor and torchlight to mimic the path of sunlight towards the digital and physical responsive surface model in various morphological states for optimal performance (Figure 5.22).

Another part of the climatic implication is improvement of the spatial condition of an existing, improperly designed building. For instance, by creating a transition space between the second skin and the existing façade, a new private usable area can formed. The spatial quality for the occupants of this new between-space is manipulated by the transformable second skin, which modifies ventilation and light penetration.

5.6.2. Cosmetic

The other potential design implication of Curtain is that it serves as an analogue media skin on which to display binary images and motion graphics by using the perforation process of the soft surface composed by the eye-like permeable louvres, as discussed in Section 5.3. This cosmetic intervention creates a new layer of appearance for visual manipulation between the existing building skin and the surrounding urban fabric. It occurs as the constant changeable porosity of Curtain’s surface responds to real-time data input of the changing environmental conditions during the day and night (Figure 5.23).

The shadows cast into the existing interior space through this process provide a morphing atmosphere that suggests a continued relationship between the exterior and interior (Figure 5.24). This is an alternative approach to the conventional digital media screen, which does not have an effect on interior conditions, especially as a result of porosity and permeability.
5.7. Summary

From the early sections discussing the various stages of the RKMS (skeleton, skin, transformation and responsiveness), to the final assembly of the prototype of Curtain, potential is evident for full-scale application of Tensegrity in responsive architectural skin design, with flexible skeleton implications. This suggests an unconventional direction for future design development, in terms of the reciprocal relationship in retrofitting, between the existing building fabric and new architectural intervention.

The results of the Curtain investigation also reveal design possibilities for further implementing the soft kinetic concept in physically responsive architectural interventions. This is investigated in the project works presented in the following two chapters. The outcomes of this chapter provide an important platform for a shift from hard to soft kinetic material system approaches in responsive morphing architectural design. Instead of inventing new materials, I move to explore existing accessible and economical materials that have been applied in other disciplines, yet are new in the context of this architectural vision.

As discussed in previous sections, the vertically morphing second skin embodied in Curtain serves as a reciprocal intervention for existing buildings. It exploits new design possibilities to integrate the focused areas of elasticity and Tensegrity. The design of this soft responsive morphing skin challenges the traditional hard approach—such as that of using mechanical responsive building skins that are
often fabricated with steel and glass. Responsive building skins constructed from soft and elastic materials seem paradoxical because architecture is built to last, whereas soft and elastic materials, such as Tensegrity systems, appear to lack structural integrity. However, advances in soft and lightweight material technology—such as carbon fibres, shape memory alloys (SMAs), acrylonitrile butadiene styrene (ABS), polypropylene and silicone synthetic rubber—reveal their relevance to architectural design, particularly in structural textile technology. Textile structures have become more popular as design alternatives in contemporary architecture. Examples of these structures are inflatable membranes, braided cables and metal mesh.

This soft textile structural system offers potential for the further development of responsive kinetic architectural skins and envelopes that offer climatic and visual control. Flexible and lightweight systems that have fewer or no mechanical components for actuation also reduce energy consumption. Based on reflection of the outcomes of this chapter, the textile structural approach is applied to the design investigation in the next chapter, Blind. This examines the MAS as a form of canopy, as an intervention above an existing courtyard space. This design investigation in Chapter 6 focuses on exploring kinetic materiality for active and passive actuation to perform spatial transformations integrated with Tensegrity skeletons and elastic skins in the form of a responsive media canopy.
6

Design investigation 3: Blind

The early success of implementing the Tensegrity and elasticity principles in the previous two design investigations led to a critical reflection that forms the basis of further investigation in the research area of kinetic materiality. In this area, I explore the potential of deformable materials for passive and active actuation purposes, as well as their potential to respond to external stimuli in morphing architectural skin (MAS) designs. This research area seeks to achieve a viable architectural skin surface that performs seamless physical deformation and responds to changing environmental stimuli. By exploring this new research area, a third design investigation, Blind, is initiated to further anticipate the MAS investigation through visual communication and patterns in the architectural context. As an alternative design for a vertical architectural media skin, Blind is a horizontal media canopy that goes beyond being a digital display. It explores the kinetic and responsive properties of the materials it employs, to achieve analogue media effects.

The rising popularity of designing media façades using LED, fluorescent lighting and projection technology in contemporary architecture is attributed to the increasing accessibility of such technologies. The BIX façade in the Kunsthaus Graz in Austria is a significant precedent for these approaches.187 The GreenPix B screen in Beijing, designed by Simone Giostra & Partners with Arup, is another example that involves the use of conventional LED displays for communication and social interaction.188 However, there are no existing media façades that have also been used as a fenestration device. The permeable properties of architectural skins that allow moderation between interior and exterior conditions can be used as a key consideration for designing a media skin. This investigation questions whether a media skin with permeability features can perform similar visual effects to conventional media screens.

As briefly discussed in Chapter 2, the ETFE skin façade of the Media-ICT building in Barcelona is a soft architectural skin that uses flexible materials and a pneumatic system as part of its visual display. Although this soft ETFE façade is not intended for dynamic visual display, it can manipulate sunlight and shadow in an analogue manner. The original purpose of this layer of ETFE skin is to protect the interior by regulating indoor temperature through direct sunlight. This pneumatic shading device is an early inspiration for the present design investigation, which further investigates light fenestration and shadow-casting for possible analogue media skins. Another precedent is the project ShapeShift, which uses an assembly of

kinetic membranes that use EAPs to prototype robotically fabricated room dividers. However, this prototype needs extremely high energy for transformation and has no design intention to present any media content.

The third design investigation, presented in this chapter, explores the morphing aspect of the soft kinetic architectural skin through form-changing material properties. It is used to perform visual communication effects as an alternative to using an LED digital display. In the field of engineering, the term ‘morphing’ is used to refer to continuous shape change. For instance, no discrete parts move relative to each other; instead, one entity deforms upon actuation. The term is embodied within the focused research area of this chapter, kinetic materiality, to describe the use of form-changing materials to perform kinetic actuations on responsive skins with minimal mechanical components. This contrasts to other kinetic or media façade projects. This focused area led to the development of Blind, based on reflections on the previous two project works. This further investigates new possibilities for incorporating elasticity and Tensegrity in a form-changing material system that applies to an architectural skin. It also responds to environmental stimuli and acts as a communicative display. Passive and active form-changing materials, such as silicone rubber and SMAs, are used to test these new possibilities. The simple, thin and lightweight design of the MAS provides an analogue alternative to the conventional digital media surface by adding inherent potential functions that regulate daylight and shadow display.

Blind, as the third design investigation of MAS through RKMS, intends to expand the repertoire of current responsive digital media skin design. By integrating form-changing materials with physical computation during the design process, Blind becomes a responsive analogue media canopy that manipulates light and shadow for the existing building environment. This approach provides an alternative design method for responsive architectural media skins, focusing on kinetic materiality. It exploits the passive and active transformability of material properties to integrate parametric design tools and contemporary sensing devices. The following section discusses this research area in detail and reveals its relevance to morphing skin design through exploring the form-changing capacity of materials for actuation and transformation.

6.1. Kinetic materiality

Think, for instance, of the dimensional changes of materials due to changes in environmental conditions, such as thermal expansion. This was seen as undesirable, problematic and to be avoided at all costs. Does this amount to the biggest missed opportunity in the history of architecture as material practice? Yes, actually.—Hensel, Sunguroğlu and Menges

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189 Kretzer, “Towards a New Softness.”
The outcome of the critical review in Section 2.3 suggested that deformable or form-changing materials now play an important role in small-scale movements that anticipate the flexible transformation of larger surfaces, particularly in responsive architectural skin designs. This novel design approach is further investigated in this chapter by using various active and passive form-changing materials to test the possibilities for morphing architectural surfaces with seamless movements and transformations.

<table>
<thead>
<tr>
<th>Form-changing materials</th>
<th>Commercial</th>
<th>Electrical stimuli</th>
<th>Actuation</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape memory alloy (SMA)</td>
<td>Yes</td>
<td>Yes</td>
<td>Strong</td>
<td>Large</td>
</tr>
<tr>
<td>Shape memory polymer</td>
<td>No</td>
<td>Yes</td>
<td>Weak</td>
<td>Large</td>
</tr>
<tr>
<td>Elastic polymer</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
<td>Large</td>
</tr>
<tr>
<td>Piezoelectric crystals</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
<td>Small</td>
</tr>
<tr>
<td>Dielectric electro active polymer</td>
<td>No</td>
<td>Yes</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Ionic electro active polymer</td>
<td>No</td>
<td>Yes</td>
<td>Strong</td>
<td>Large</td>
</tr>
<tr>
<td>Paraffin wax (liquid)</td>
<td>No</td>
<td>No</td>
<td>Strong</td>
<td>Large</td>
</tr>
</tbody>
</table>

Table 6.1: Comparison of selected form-changing materials. Source: Author.

As discussed in Chapter 2, form-changing materials can potentially serve as actuators, as well as structural components, for responsive kinetic architectural designs. Table 6.1 lists several selected form-changing materials that can be applied as actuators, and studies their individual properties. Based on this comparison, it can be seen that most materials with the potential for architectural applications are either not commercially available or are not strong enough for actuation purposes (Table 6.1). These shortcomings are obvious disadvantages in architectural-scale transformation. I find that shape memory alloy (SMA) is one of the most appropriate active form-changing materials to apply to the design investigation of this chapter because of its accessibility and durability. As reviewed in Section 2.5, although potential electroactive polymers (EAPs) have been used widely in robotic research, EAP-based actuators still exhibit force below their efficiency limits, are not robust and are not available as commercial materials for practical application in this type of experiment. Furthermore, they require a high activation field (> 150 V/μm) close to breakdown level and are considered a danger to users if operated inappropriately.

Since the 1960s, shape memory alloys (SMAs) have been the most accessible form-changing materials in the present market, and they have many applications in the aerospace and automobile sector. An SMA is a unique metal with two novel properties that have interchangeable phase capacity at its molecular level: martensite and austenite. Martensite is a soft phase that is deformable with applied force in the normal temperature condition (< 30°C). Austenite is a strong and ‘memorised’ phase that occurs when heating (> 50°C) takes place. These two interchangeable phase-change capacities of

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SMAs at the microscopic scale provide a potential platform for an iterative cycle of actuation with applied forces and temperature changing processes (Figure 6.1).

At the macroscopic scale, SMAs are commonly used in a wire or spring form that contracts in length when heat is applied. This heating can be undertaken directly via electricity to give electrical actuation. SMAs expand by as much eight per cent when heated and cooled. The typical expansion of SMAs in relation to temperature is graphed in Figure 6.2. When the SMA is below the transform temperature (60°C), the material takes on an elongated and neutral form. If heated, it contracts and returns to the memorised form. This process creates a dynamic range in the way that the SMA wire expands and contracts for various state changes (Figure 6.2).

Ordinary metal alloys have an internal structure that is not altered by small temperature or electric current changes. Electrical stimuli create heat, causing the atoms of the metal to vibrate faster. This makes it easier to bend when an external force is applied. The molecular form of the metal is not normally altered by heating. However, form-changing materials such as SMAs are naturally dynamic, and deformation occurs under electrical stimulus. This experiment uses five volts for a three-amp current (Figure 6.3). There are two stable crystalline states in the SMAs’ structures. When a temperature change occurs, this triggers a change from one crystalline form to the other. I selected SMAs to be implemented in my research and developed further because of their accessibility, reliability and low electric current usage. This form-changing process
produces expansion and contraction, which can be harnessed for actuation of the whole kinetic system.

Figure 6.3: Left: ‘Stretched’ SMA wire in room temperature. Right: Deformation of SMA wire occurs when heated by electric stimulus. Source: Author.

Figure 6.4 shows four potential profiles for material actuation based on the process of expansion and contraction in specific parts of the SMA wire. While profiles one and two show the potential for the pull and push actuation, profiles three and four function as a spring system that can actuate greater distance and force. They demonstrate that an alternative actuation system can be embedded in the overall Tensegrity structure—as discussed in Chapter 5—for various transformation purposes. Profiles one and four are selected to use their form of actuation in Blind, in terms of transformation, for their robustness and stronger pulling force (Figure 6.5).

Figure 6.4: Four potential profiles for material actuations of SMA wire. Source: Author.

Figure 6.5: Early test of the expansion and contraction of SMA spring (profile four) responding to light via photoresistor for transformation of the overall Tensegrity skeletal structure. Source: Author.

One of the identified shortcomings of SMA actuation (through one-way memory effect) is that it requires external force to return the SMA to its original state. When integrated with silicone rubber, the silicone rubber’s passive elastic capacity compensates for this shortcoming of the SMA, thereby allowing the reversible performance of contraction and expansion to take place, especially in
the form of skin and surface. By exploiting the advantages of both passive (silicone rubber) and active (SMA) form-changing materials, the positive result generated through the early experiments described above conveys a further design investigation embodied in Blind. Identically to the previous two investigations, Blind is conducted through the rigorous method of the RKMS, with four distinct stages. These stages are discussed in the following sections.

6.2. Skeleton

The skeleton element of Blind is further developed based on the flexible Tensegrity structural approach presented in Chapter 5. This reduces the friction between mechanical joints and achieves a lightweight and flexible skeletal structure. This structural principle is based on the use of isolated components in compression inside a net of continuous tension. This use is made in such way that the compressed members do not touch each other and the pre-stressed tensioned members delineate the system’s spatiality. This further development of the optimised version of a Tensegrity structure provides the lightweight and simple skeletal material system of Blind.

The materials used to assemble the skeleton of Blind include easily accessible acrylonitrile butadiene styrene (ABS) as a primary lightweight and strong explicit material. This creates an optimised version by reducing the struts of the tetrahedron, developed from the previous version explored in Curtain. This three-strut tetrahedron is integrated with stainless steel wires as tension components to fabricate the Tensegrity tetrahedral modules with reduced components and a modified profile. These modules are used for the exoskeleton structure (Figure 6.6). The Tensegrity lattice is one of the crucial components in the fabrication of Blind, in terms of transformation, as well as providing flexible structural support. While integrated with SMA springs and an elastic silicone rubber skin, it serves as the overall backbone that allows active and passive deformation to occur (Figure 6.7).

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196 Gomez-Jauregui, Tensegrity Structures and their Application to Architecture, 296.
Figure 6.7: Early design of Blind’s layers, ‘exploded’ to individual components and functions. Source: Author.

6.3. Skin

Based on critical evaluation of and knowledge learnt from Chapter 4 regarding the issue of elasticity, the skin element of Blind continues to further exploit and develop elasticity to produce flexible kinetic architectural skins. As in the results and findings of Chapter 4, elastic materials deform when force is applied and the deformation is reversed once the force is removed, returning the materials to their original state. The potential energy stored within the material itself can be harnessed to activate the deformation process back to its original state. This offers a potential new form of flexibility, adaptability and deformation by using the memory effect in responsive architectural skin designs. The elastic material used for the skin element of Blind is silicone rubber, chosen for its durability, heat resistance and elastic capacity. The heat-tolerant material property is another advantage that makes silicone rubber a suitable material to embed with active form-changing materials, such as SMAs, to form a responsive morphing skin that addresses elasticity and actuation (Figure 6.8).

Figure 6.8: Early experiment for elastic silicone rubber skin embedded with linear SMA wires set as the passive elastic component, as well as an active actuator operated by electric stimuli. Source: Author.

Silicone rubber generally offers good resistance to extreme temperatures from −55°C to 300°C. Under these extreme temperatures, its properties in terms of elongation, compression, tear and tensile strength are far superior to conventional soft and elastic materials. Conventional organic rubber has a carbon-to-carbon backbone that can make it susceptible to ultraviolet, heat, ozone and other ageing factors that silicone rubber can withstand even in extreme environments. This property of high heat resistance makes silicone rubber a suitable material to integrate with SMAs to form a morphing skin, addressing elasticity and actuation. In addition, the

skin itself serves as part of the passive actuation, as well as the structural component, of the overall modular Tensegrity system.

With the proposal for the multilayer skin of Blind, I initially explore the possibilities of the porosity performance in a rectangular skin surface through digital and analogue fabrication processes (Figure 6.9). When integrated with the lightweight Tensegrity skeleton developed in the previous section, the silicone rubber is used as an elastic skin to form the basic non-load-bearing membrane surface of Blind, with the eye-like apertures allowing porosity to occur (Figure 6.10). The opened and closed states of these eye-like apertures are actuated by the embedded tensional SMA wires. When heated by electric stimuli, the SMA wires contract (austenite phase) in order to open the apertures. The apertures close once the temperature of the SMA wires returns to its original condition (martensite phase), taking advantage of the passive actuation of the elastic silicone rubber skin.

![Figure 6.9: Left: First test for silicone rubber in the mould. Middle: Laser-cutting the openings of eye-like apertures with embedded SMA wires. Right: Rectangular-shaped silicone skin for early testing and experiments in terms of elasticity and durability. Source: Author.](image)

![Figure 6.10: Left: First experiment for the integration of Tensegrity tetrahedral modules and silicone rubber skin. Right: Outer side of the silicone skin with eye apertures. Source: Author.](image)

### 6.4. Transformation

This section discusses the transformability of Blind by introducing the integration of the Tensegrity tetrahedral skeletons, SMAs and silicone skins. Blind is a multilayer morphing architectural skin (MAS) composed of two types of triangulated modular skins that are developed from the rectangular experiment in silicone skin discussed in Section 6.3 (Figure 6.11). They manipulate daylight by bending and twisting the undulating surface. This malleable fenestration, modulated through the input of real-time data, constantly casts controlled shadows over the surface under its semi-ellipsoid canopy (Figure 6.12). The shadow is cast onto the existing surface below via 32 type-1 and 36 type-2 triangulated modular skins, whose individual eye-like apertures provide a morphing atmosphere that suggests a continued relationship between exterior and interior spaces (Figure 6.13). Conventional digital media screens, in comparison, lack
consideration of their effect on the interior condition behind or beneath their surfaces.

Figure 6.11: Two typical types of triangulated modular skin embedded with Tensegrity tetrahedral modules. Source: Author.

Figure 6.12: Blind in the form of a semi-ellipsoid canopy performing morphological transformation for optimal daylight manipulation through bending and twisting. Source: Author.

Figure 6.13: Unfolded overall surface skin of Blind, composed of 32 type-1 and 36 type-2 triangulated modular skins. Source: Author.
Blind can perform two types of transformation, morphological and patterned, which enable the production of adaptive visual effects and media communications. Morphological transformation is a global morphing process of the entire undulating skin structure to control shadow casting and lighting manipulation for various visual effects in the space under Blind. This global transformation process is actuated by a series of SMA springs integrated within the Tensegrity skeleton (Figure 6.14). Patterned transformation involves local individual openings that are opened and closed to serve simultaneously as analogue pixels and apertures. They function as daylight and shadow manipulators to project morphing shadow patterns beneath the surface of Blind (Figure 6.15). To complement the digital simulation and generative process, the responsive capacities of these two types of transformation are tested through actual material engagements and parametric and physical computing tools. The next section focuses on investigating the issue of responsiveness in the transformable capabilities of Blind, and involves several rigorous systematic steps of investigation to generate feasible outcomes and results.

6.5. Responsiveness

While the previous section introduced the two transformable capacities of Blind, this section further discusses the responsiveness of these capacities through exploitation of passive and active form-changing materials with parametric design tools and physical
computing devices. I investigated this aspect of the responsiveness of Blind for two forms of transformation, as described in the previous section. These focus on the responsiveness of morphological and patterned transformation. Investigation of the first responsiveness explores the applicability of SMA springs that can respond to external stimuli to actuate the overall global transformation of Blind. Investigation of the second responsiveness involves physical implementation of the eye-like apertures on the skin that are controlled by the contraction and expansion of embedded SMA wires to perform locally patterned transformation.

6.5.1. Responsiveness of morphological transformation

Morphological transformation explores the possibility of the global surface curvature of Blind to be modifiable while maintaining the continuous topology of the undulating or flat surface. Blind responds to various functional drivers to manipulate lighting effects on a global scale. This morphological transformation demonstrates an alternative actuation system using SMA springs integrated with the overall Tensegrity structure, as discussed in Chapter 3. Global actuation takes place between the tetrahedral skeletons and skins and is triggered by the contraction and expansion of the SMA springs through heating by electrical stimulus.

Figure 6.16: The Arduino environment. The Arduino protocol is based on a script-processing platform. Source: Author.

Figure 6.17: Left: Firefly physical computing schema in the Grasshopper environment, including processing the external input values to regulate electrical power output that controls heating of the SMA springs. Source: Author.

An early schematic diagram is proposed for control of the SMA spring operations, allowing them to respond to external data stimuli. This schematic is created with a series of parametric and generative design tools, including Grasshopper, Firefly, the Arduino protocol
and Arduino microcontroller, to form an integrated responsive material system for Blind. The responsiveness of this material system is achieved through a step-by-step process. First, an open-source Arduino communicative protocol, called Firefly Firmata, is uploaded to the Arduino microcontroller to enable real-time communication between the microcontroller and the parametric plug-in, Grasshopper for Rhinoceros (Figure 6.16). Second, Firefly is used as a communicative software tool to bridge the digital Grasshopper and physical Arduino microcontroller to allow real-time external data stimuli to flow between them (Figure 6.17). Third, pin one and pin five of the Arduino microcontroller are selected to serve as analogue input pins connected to individual photoresistors to read real-time values (from zero to 1,023) and send them to be processed in the Firefly environment. These processed values (re-mapped from zero to 255) are then sent to the individual transistor to regulate the external power source for the heating process of the SMA springs that perform contractions and expansions through the digital output pin five and pin six (Figure 6.18). As discussed in Section 6.1, SMA springs contract (austenite phase) when heated by electric current. This final step allows various real-time values sensed by photoresistors to directly control the form-changing process of SMA springs. These real-time values regulate the variable electrical power outputs through the Arduino microcontroller to heat the SMA springs. This process creates contracting and expanding actuations that cause the morphological transformation of Blind (Figure 6.19).

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198 For further detail of the schematic diagram, please refer to Appendix D.
Responsiveness in the morphological transformation process of Blind is represented in a prototype composed of type-1 and type-2 triangulated modular skins integrated with a Tensegrity tetrahedral skeleton. By using a photoresistor as a light sensor and torchlight to mimic the path of sunlight, the prototype embodies the initial global transformation of the physically responsive triangulated modular skin. It responds with various morphological states for optimal visual performance, as a direct sunlight modulator that creates multiple lighting effects (Figure 6.20). This global morphing process constantly redefines the face or image of the existing building environment in order to materialise Blind as a media brise-soleil, as well as a responsive intervention to the existing site context. This process also allows Blind to serve as a new, transformable visual barrier between the interior and exterior spaces that have been overlooked in conventional digital media façades.

Figure 6.20: Morphological transformation of the composed type-1 and type-2 physical triangulated modules, in response to a direct light source, for optimal shading and visual performance. Source: Author.

6.5.2. Responsiveness of patterned transformation

The other focused transformation Blind is capable of is patterned transformation. The changing form of the soft openings or eye-like apertures on the surface of the silicone rubber facilitates change between multiple possible visual patterns (Figure 6.21). This real-time analogue media effect controls the appearance of the skin surface. The new horizontal building envelope is in constant flux as part of a dialogue with the environment and occupants with which it interacts. This effect, which is applied to provide fenestration of the surface, is generated by the individual porous openings that respond to sunlight penetration and shadows. This transformation improves the spatial conditions of interior and exterior spaces through dynamic communication between the two.

Figure 6.21: The opened and closed states of an individual eye-like aperture module, actuated by SMA wire through a DC electric power supply regulator (arrows indicate). Source: Author.

6.6. Design implications

Architectural skins are the interface between buildings and their urban surroundings. They are becoming crucial components for architecture in terms of climate control and visual appearance. In contemporary architectural practice, these architectural components often serve as building ‘billboards’, which normally perform as one-way information communicators. The digital screens of these billboards—more commonly referred to as ‘media screens’ and ‘façades’—often neglect consideration of the interaction between
interior and exterior conditions, especially in terms of moderating visual effects and lighting penetration to the space beneath or behind their surfaces.

While further developing the focused areas of elasticity and Tensegrity developed in the previous two chapters, Blind acts as a viable progression of alternative analogue media skin design through active and passive design strategies for form-changing materials integrated with elastic and Tensegrity structural components. It demonstrates an alternative design strategy that uses less energy and simpler actuation to control and regulate the behaviour of responsive morphing skins in terms of light and shadow for animated visual pattern purposes. The form-changing and deformable materials that operate inside the Tensegrity system become the integrated component of the overall skeletal structure. It actuates the elastic component that is actively exposed to the ambient environment to be functionally adaptable. This novel approach for actuation can create multiple states of stability in terms of transformation and deformation for architectural skins. It has potential, is more economical in energy usage, and is more silent than using conventional mechanical components, because kinetic operation occurs within its microscopic material properties instead of in-between macroscopic elements.

These new possibilities have been tested through the digital and physical conceptual prototypes of Blind to provide architects and designers with a novel design strategy—a mix of form-changing materials and physical computing devices as new tools for design investigation in the research area of responsive kinetic architectural design. Although the conceptual prototypes of Blind focus on the early stage of design and are evaluated through the criteria of visual lighting and shadow-casting capacities, they demonstrate the potential and the challenges for full-scale architectural implementation in two design areas: visual communication and pattern.

6.6.1. Visual communication

Visual communication through the permeability of Blind is afforded by treating the individual domestic soft apertures as analogue pixels projecting light spots in response to sunlight penetration. This transformation manipulates the spatial conditions of the interior and exterior spaces through the dynamic patterns of the skin surface. The initial geometry of the membrane aperture is inspired by the performance of the eye. The eye-like apertures in the geometry are determined by their relative curvature on the responsive undulating silicone rubber surfaces, and are actuated by SMA wires and springs. This analogy of an eye-like permeable aperture functions as a skin muscle mechanism in the eye that allows various changing porous patterns in binary form represented on the skin (Figure 6.22). This perforation process creates a potential application for the surface of Blind as an analogue media brise-soleil displaying binary images or even motion graphics.
The local transformation process of Blind’s horizontal surface adds a new layer of aesthetics for visual communication between the existing space and the external surrounding environment. This visual intervention is demonstrated in a digital simulation to create a new analogue media skin for communication between the existing space and the surrounding environment through its constant changeable porosity activated by real-time data input. The exterior skin of Blind allows light to penetrate the eye apertures to form numerals from light spots projected on the surface underneath Blind. Other textual visual patterns include numeric and alphabetic symbols that are also formed by light spots penetrating the eye apertures (Figure 6.23).

6.6.2. Visual pattern

The fenestration of patterned transformation can also display motion graphics as pattern representations in an analogue manner. The actuation of the eye apertures of Blind occurs in two states: opened and closed. This produces an animated shadow play that is an appearance of still and animated images caused by the illumination of Blind under sunlight (Figure 6.24). This real-time shadow play potentially creates a 3D volumetric analogue cinematic interior environment that responds to changeable events. The patterned transformation allows Blind to become a projective device by controlling direct sunlight and artificial light penetration by using real-time input data with shadow castings. This process extends the
cinematic ability of conventional shadow play, but in an architectural media context.

![Figure 6.24: Real-time animated shadow play patterns projected beneath the canopy of Blind through various light spots generated by the opened and closed states of eye-like apertures. Source: Author.](image)

I investigated this alternative potential of responsive architectural media skins with the initial idea of achieving visual communication without digital display by using soft active and passive form-changing materials integrated with a Tensegrity skeletal structure. This approach demonstrates a novel method of extending the design of architectural media skins with urban environmental design considerations, particularly for moderating light and shadow in existing built environments. The design investigation of architectural morphing media skins reveals a new territory of responsiveness, moving from mechanical component operation towards a solid-state kinetic material for actuation and transformation. This solid-state approach further advances a possible design paradigm of elastic, thermal, magnetic and sensing properties of form-changing and kinetic matter, embedded with digital and physical computational processes for morphing architectural designs.

### 6.7. Summary

Broadly speaking, the materials used to construct and fabricate architectural skins are commonly glass, steel and concrete. This has not changed for a century. As discussed in the introduction of this chapter, I consider these materials to be hard materials. Their hardness is literal in terms of both system and materials. The current advancement of material technology provides alternatives to these materials—most notably those that are soft textiles or form-changing, such as Aramid and ETFE. These become increasingly relevant to architecture and responsive kinetic architectural designs due to their lightweight, flexible and versatile characteristics. The kinetic materiality study provided in this chapter moved the design investigation in this direction by using active and passive soft form-changing materials, complemented with digital simulation and physical computing processes, to produce conceptual physical prototypes that capture the full potential of this new design paradigm.

The outcomes and findings generated through the design investigation suggest a novel approach for the design investigation of responsive kinetic architecture with a textile quality through
engagement with new form-changing materials, sensing devices and physical computing tools. The area focused on in this chapter, of kinetic materiality, is tested in the design investigation as the project work Blind, which demonstrates the possibility of achieving the early-stage design of morphing architecture. This design investigation of responsive deformable materials in morphing architectural design is further developed in the next chapter through the fourth and final project work, Blanket. This moves towards a focus area of investigating the embedded sensitivity and illumination capacities of soft and form-changing materials for morphing architectural design.
Design investigation 4: Blanket

In this chapter, I use the positive results generated through the three previous design investigations, which focused on elasticity, Tensegrity and kinetic materiality, to further investigate responsive morphing architectural design. This investigation is focused on sensitivity—a research area that emphasises exploring the potential for designing responsive morphing architectural skins (MASs) with form-changing materials that have integrated sensing and luminous capacities. Instead of embedding individual discrete components, this fourth design investigation intends to integrate sensing devices and building skins as one single entity. This design investigation is continuously conducted through a project work based on the rigorous method of the responsive kinetic material system (RKMS), consisting of the four stages—skeleton, skin, transformation and responsiveness—that have been implemented in the three previous chapters. This project work is Blanket. It provides an evolving approach derived from the outcomes of the previous project works to achieve a lightweight, multifunctional and economical sensory architectural skin design that responds to proximity and lighting stimuli.

In an early exploration, I integrate the sensing devices and architectural skin as one entity, eliminating the need to embed discrete components in a vulnerable system. This approach leads to the development of a new material, Lumina, to apply as a responsive luminous skin of Blanket. This material exploration engages with several responsive materials, including silicone rubber, glow pigments, shape memory alloys (SMAs) and Nichrome wires. It is controlled using parametric and physical computing design processes that respond to external stimuli. Prior to further discussing this research exploration, the next section provides an overview of the research area, focusing on sensitivity in terms of the relevant context and background for the design investigation of Blanket.

7.1. Sensitivity

Skin is the largest sensor of the human body, registering warmth, cold, pain, pressure and other tactile senses. Recent research has produced skin-like sensors to process distributed tactile information across textiles. This technology, which is inspired by various disciplines, such as biology, materials science and architecture, enables new and relevant avenues of enquiry through soft mechanisms and pliant sensing whose behaviour is comparable to

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systems found in nature. This section questions what would happen if this technology were applied to building skins, thereby giving them the ability to perform like human skin. Contemporary architects can exploit these analogies and technologies to design building skins that respond to inputs from the environment and users. This generates new possibilities for simple, ecologically embedded architectural skins that are in constant feedback and interaction with their surrounding environment.

7.1.1. Sensory architectural skins

In responsive architecture, the idea of responsive building skins is often explored through individual sensing devices and mechanical systems that are considered ‘hard’ technology. The label ‘hard’ literally refers to the context of mechanical systems and their discrete individual sensing components. This architectural approach is not new and has been explored since the 1960s. As discussed in Chapter 2, the responsive brise-soleil of the Los Angeles County Hall of Records, designed by Richard Neutra in 1962, is one of the first significant examples of responsive architectural skins. Complex mechanical systems for kinetic movement with sensing facilities tend to break; they fail in terms of longevity and reliability. The Institut du Monde Arabe building in Paris, created by Jean Nouvel in 1987, sets the precedent for this approach. These structures and systems engage complicated discrete elements and physical divisions. They use a series of external sensors to achieve the adaptability of the systems. Both the Neutra and the Nouvel building skin systems hindered the mainstream adoption of responsive façades because of their expensive sensing system and brittle mechanical components. Seeking alternatives to these led this design investigation to investigate responsive architectural skins with fewer mechanical and sensing devices. Technological advancement in material science provides the opportunity to use passive and active form-changing materials, such as elastic silicone polymers and glow pigments, to design kinetic, responsive architectural skins. These soft and form-changing materials can be integrated with other sensing materials. This provides an alternative approach to address the issue of brittleness in the operation of mechanical and sensing systems.

Several recent projects have attempted to integrate sensors and actuators with soft responsive architectural skins. As mentioned in Section 2.2.2, one of these is the Living Glass project by David Benjamin and Soo-in Yang. This project uses silicone polymer actuated by Nitinol wire and carbon dioxide sensing devices to design a responsive kinetic membrane that serves as an air-movement regulator. Another earlier project by Nancy Diniz et al. also explores SMA wire as an actuator to develop a prototype interface.
Although both projects discussed above integrate SMA wire as an actuator into the architectural membrane for deformation purposes, there is an opportunity to further explore the full potential of SMA actuators to be embedded within the flexible skeleton of the architectural membrane or skin in order to achieve larger-scale structural transformation.

On a larger scale, the recently completed façade of the Media-ICT building, designed by Cloud 9 Architects in Barcelona, demonstrates the energy efficiency and implementation of the soft approach to kinetic architectural skin design. This façade is made of ETFE, and uses embedded sensors and multiple Arduino microcontrollers to respond to users and environmental conditions. The ETFE skin protects the interior from direct sunlight, and, when light is needed, it opens itself to allow daylight to enter. This responsive and pneumatic shading device is considered an early implementation of the soft approach; however, there is unexplored potential for lighting control and shadow casting. The Hylozoic series by Philip Beesley is another precedent fitted with arrays of sensors and kinetic devices to explore kinetic architectural membranes through responsive material and mechanical systems. Beesley’s work provides insightful knowledge for designing soft architectural membranes that sense and respond to changing environmental conditions. All the precedents mentioned above explore the initial possibilities of material actuation and external sensing ability. They remain an opportunity to investigate form-changing materials that respond and sense within an integrated materials system.

7.1.2. Sensing and luminous material systems

By reflecting on the results and outcomes of the three previous design investigations, in this fourth episode of the Design Tetralogy investigation, I initially consider how to design a soft responsive architectural morphing material system that integrates sensory and luminous capacities within its system and material properties. It explores a focused research area: sensitivity for integrating form-changing, sensory and phosphorescent materials through a physical computing process. This approach establishes an initial platform for the early design exploration. In this chapter I investigate new possibilities for sensing, illuminating and form-changing materials in relation to an architectural skin that can sense and respond as a single entity to external environmental stimuli. The materials used in this investigation are conductive paints, photoresist elements, Nichrome wires, glowing pigments, silicone rubbers and SMAs. These materials are the main ingredients to fabricate Blanket. Blanket is a prototype sensory morphing skin that serves as a responsive intervention to revitalise an underused passageway at RMIT University, Melbourne. The development of Blanket involves

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207 Ruiz-Geli, Media-ICT.
combining responsive material systems with computational design processes. These material system explorations are an initial step towards investigating the possibility of designing a MAS that integrates materials and computation.

Figure 7.1: Left: A lack of social activities and interactions in the narrow and underused ‘threshold’ is this space’s first shortcoming. Right: A digital lux meter is used to gather light-level data to demonstrate the second shortcoming of the site. Source: Author.

Blanket is a cylindrical envelope that serves as a morphing ‘lantern’. It is soft in its properties, and performs responsive kinetic movements based on its responsive morphing system. This design investigation intends to evoke alternative design possibilities for building-skin sensing ability. The site chosen to test this design investigation is a passageway that is currently underused because it is dark and narrow.

There are currently two shortcomings of this particular site. First, the dark and narrow passageway serves as a threshold between two public plazas, but lacks interactive social activities. Second, although it is considered an outdoor space, due to its narrow configuration and its being surrounded by two 10-storey buildings, there is no direct sunlight penetration during the day and the lighting level of the site is no more than 50 lux (Figure 7.1).

Figure 7.2: Top: Graph of movements and activities data recorded onsite within a 24-hour period. Bottom: Graph showing the collected data of light lux level from day to night. Source: Author.

Figure 7.2 shows two graphs that indicate two sets of recorded data for pedestrian movements and light levels on-site within a 24-hour period on a weekday. During the peak hour of 1.00 pm, the first graph indicates that no more than 50 pedestrians occupy the space each day. This recorded data suggests there is potential to improve the area by increasing pedestrian traffic and social activities at the site. The second graph indicates that the average light level of the site is no more than 50 lux during the day and less than 20 lux at night. This collected data demonstrates another shortcoming of the chosen site. Based on this primary data collection, I see potential for designing a responsive architectural intervention as a reciprocal retrofit to revitalise the existing dull and dark conditions of the site. In contrast to the previous three design investigations, which are
form-undulating planar surface designs, Blanket functions as an independent architectural design feature in the form of a ‘lantern’ envelope skin. It serves as a reciprocal intervention that is designed to overcome the existing shortcomings of specific site conditions through its responsive morphing and luminous capacities (Figure 7.3).

Figure 7.3: The morphing luminous skin of Blanket absorbs light energy and provides lighting effects to revitalise the dark condition of the passageway. Source: Author.

Blanket responds to two stimuli of the site: pedestrian movement and light. Via its responsive morphing and illuminating capacities, Blanket attracts increased pedestrian movement, thus potentially rejuvenating the existing dark and quiet site conditions to encourage more social activities and interactions (Figure 7.4). The skin of Blanket also absorbs passive light energy during the day and performs morphing operations for tracking daylight through integrated responsive kinetic skeletons.

Figure 7.4: Right: Blanket in a static, non-illuminated state. Middle: Blanket responds to proximity of pedestrians and social interaction. Right: Global transformation of Blanket takes place in response to light tracking of the area, delivering a higher lux level. Source: Author.

The following four sections discuss the detailed design investigation based on RKMS with four stages of design investigation, identical to the rigorous method applied to the previous three project works, but focusing on the research area of sensitivity. These four stages remain the crucial step-by-step process that systematically investigates the sensing and luminous capacities of Blanket, eventually leading to appropriate design implications for sensory morphing architecture.

7.2. Skeleton

The kinetic skeleton of Blanket serves as the Tensegrity lattice, as well as the actuator, that performs kinetic movement for the overall system. This is actuated by the SMA springs that are derived from the previous project work, Blind, to provide a more durable and lightweight flexible structure. The nature of this Tensegrity lattice enables minimum actuation to achieve maximum transformation. This flexible skeleton achieves various transformations without moving hinges and parts. It uses the idea of leverage to maximise transformation in the form of bending and twisting through form-
changing SMA springs that can expand and contract to five times their original length. This form-changing process operates through electrical heating of SMA springs controlled by an Arduino microcontroller.

Similar to the structural system of Blind, the Tensegrity skeleton system of Blanket is composed of six rows of skeletal strips. Each row consists of 72 tetrahedral modules fabricated of compressional aluminium tetrahedrons with a thickness of 1.2 mm, and 216 tensional polypropylene ‘tendon’ strips that form the overall cylinder shape of Blanket (Figure 7.5). This approach creates an optimised Tensegrity structure to achieve a lightweight and strengthened skeletal system for global transformation purposes (Figure 7.6). The global transformation process of this skeletal system is actuated by four SMA springs per row embedded in the overall skeleton. These respond to the external data from the individual sensing skin of Blanket.
Since there is a repetitive structural system for every two rows of skeletal strips, in the final construction of the physical skeletal structure of Blanket, I only fabricate two rows of skeletal strips instead of six, as originally proposed, to represent the complete version of Blanket (Figure 7.7). The complete version of this fabrication includes the sensory skin of Blanket as the envelope, integrated with this Tensegrity skeletal structure. This is revealed and further discussed in subsequent sections (Figure 7.8).

Figure 7.7: Top: Two rows of unfolded skeletal strips. Bottom: Complete physical fabrication of unfolded Tensegrity skeleton of Blanket. Source: Author.

Figure 7.8: Left: Triangulated Lumina skins integrated with the Tensegrity skeletal structure of Blanket. Right: Close-up of the 'bended' skeleton with detailed connections of compressional aluminium tetrahedral modules and tensional polypropylene tendon strips. Source: Author.

7.3. Skin

Recent robotic research has included investigation into active property changes in responding materials. However, there are few precedents for applying these materials in the context of architecture, especially in responsive building skin design. There is a need to test the potential of these materials for full-scale architectural applications, especially in responsive kinetic architectural skins. In addition, current research of newer technologies for lighting in urban environments explores materials that provide passive lighting to reduce the demand for delivered electrical energy.\footnote{Sascha Bohnenberger et al., “A Model for Transdisciplinary Design in Passive Illumination” (paper presented at the PLEA2011—27th Conference on Passive and Low Energy Architecture, Louvain-la-Neuve, July 13–15, 2011).} I propose an integrated lighting system that integrates the lighting function in the material itself. This is seen as a potential alternative to contemporary light-emitting diodes (LEDs) and organic LEDs (OLEDs). In this
section, I explore the potential for materials that combine sensing, passive and active lighting, and kinetic response, for application in responsive architectural skin design.

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Sensing capacity</th>
<th>Form-changing capacity</th>
<th>Luminous capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Conductive paints</td>
<td>Shape memory alloys</td>
<td>Nichrome wires</td>
</tr>
<tr>
<td>Passive</td>
<td>Phosphorescent pigments</td>
<td>Silicone rubbers</td>
<td>Phosphorescent pigments</td>
</tr>
</tbody>
</table>

Table 7.1: Sensing, form-changing and luminous materials with active and passive sensitivity, for use in the development of Lumina applied to the skin of Blanket. Source: Author.

I initiate the integration of materials with physical computing to create both active and passive sensibility and luminosity. This integration includes materials such as Nichrome wires, SMA wires, phosphorescent glowing pigments (strontium oxide aluminate) and translucent silicone rubber (containing “poly methyl vinyl”, “poly methyl hydrogen siloxanes” and “poly methyl vinyl siloxane”). Table 7.1 illustrates the aforementioned responsive materials’s passive and active responsive capacities in the focused area of sensitivity, for use in developing a hybrid material system that can sense and respond to changing environmental conditions. This material system focuses on sensing, form-changing and luminous capacities to investigate new design possibilities for a synthetic sensory skin (Table 7.1). This skin is developed through a synthetic material, Lumina, that is lightweight and performs simple sensory, kinetic and illumination functions simultaneously. The following three subsections describe the active and passive responsive capacities of Lumina, focusing on the research area of sensitivity, as the sensing and luminous material applied to fabricate the skin of Blanket.

7.3.1. Sensing capacity

I begin with an early investigation of Lumina to test the possibility of integrating various materials and physical computation to develop a novel sensing skin with fewer discrete components and better energy usage. This initial experiment integrates conductive paints with silicone rubber to test the potential for responsiveness. This process uses conductive paint synthesised with silicone rubber as the initial sensing element that performs capacitive sensing. When voltage is applied to this synthetic soft conductive material, it creates a uniform electric field that causes positive and negative charges to collect on its surface and on the proximal object (my hand). While the distance between these two conductive objects (skin surface and hand) is changing, this process creates an alternating current that sends the variable values to the digital platform (computer) through the Arduino microcontroller.

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210 Capacitive sensing originally measures the changes in an electrical property called ‘capacitance’. It is determined by how the distance between two conductive objects responds to different electrical currents. In the context of my experiment, the two conductive objects are represented by my hand and a conductive synthetic silicone rubber to test the capacitive sensing of the Lumina skin. For more information about capacitive sensing, see “Capacitive Sensor Operation and Optimization,” Lion Precision, accessed November 2, 2012, http://www.lionprecision.com/tech-library/technotes/cap-0020-sensor-theory.html.
Figure 7.9: Left: Early-stage physical experiment with Lumina integrated with conductive paint and silicone rubber. Right: Graph showing variable data received by Lumina skin through its active capacitive sensing the proximity of my hand. This is the first exploration to investigate a soft architectural skin sensing external data without a discrete sensor. Source: Author.

Figure 7.10: Passive sensing capacity of Lumina that senses daylight and absorbs light energy to glow in the dark without external power. Source: Author.

This active sensing process is controlled via a digital platform that includes Grasshopper for Rhinoceros and Firefly with a physical Arduino microcontroller (Figure 7.9). The positive outcome of this early sensing material experiment leads to initiating the development of the sensory Lumina skin, which is flexible and elastic and has passive luminous capacity (Figure 7.10). The development and fabrication process of Lumina, with regard to its luminous capacity, is further discussed in Section 7.3.3.

7.3.2. Form-changing capacity

The initial testing for the form-changing capacity of the skin is explored through silicone rubber embedded with SMA wires and springs, identical to the processes of fabrication in the previous two chapters. Their integration allows the state change of the SMAs to activate the soft silicone rubber as the kinetic element. When equipped with the sensing capacity developed in a previous subsection, this synthetic elastic silicone rubber skin becomes the kinematic performer as well as the capacitive sensor in the soft approach, without any external discrete mechanical components (Figure 7.11).

Figure 7.11: Initial experiment with Lumina skin, testing the active and passive process of its form-changing capacity. SMA springs integrated within the Tensegrity skeleton actively actuate the overall global transformation (arrows indicate), while the elasticity of the skin provides passive force to help it return to its original state. Source: Author.

This form-changing skin is eventually fabricated as a triangulated modular system that is used as part of the design process of Blanket
and considered for large-scale architectural applications. This system uses a composite approach to integrate SMA wires and silicone rubbers. The advantage of this synthetic morphing skin module is not only its lightweight and silent kinetic operation—like its predecessors in the previous investigations, the surface of this form-changing skin also allows individual eye-like apertures to open and close for various lighting pattern effects through shadow casting (Figure 7.12).

Figure 7.12: Left: Eye-like apertures are passively closed by the elasticity of the skin. Right: Eye-like apertures for porosity are actively opened by SMA wires embedded in the skin. Source: Author.

7.3.3. Luminous capacity

The development of a responsive luminous material, Lumina, is part of an investigation into responsive materials to evoke new possibilities for building skins to sense and respond, particularly for illumination purposes. Lumina is composed of translucent silicone rubber and phosphorescent glowing pigments, with a mixture proportion ratio of 5:1 (Figure 7.13). Table 7.2 illustrates a detailed recipe for the three main ingredients, with their appropriate proportions in individual volume, for moulding the synthetic Lumina as a modular triangulated skin (Table 7.2). It is also embedded with SMA wires for actuation and sensing purposes with conductive paint to form an individual triangulated module with an area of 0.07 m² as the main component for fabricating the overall luminous skin of Blanket (Figure 7.14).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone rubber 1 - translucent</td>
<td>100 mL</td>
</tr>
<tr>
<td>(polymethylhydrosiloxanes)</td>
<td></td>
</tr>
<tr>
<td>Silicone rubber 2 - translucent</td>
<td>10 mL</td>
</tr>
<tr>
<td>(polymethylhydrosiloxanes)</td>
<td></td>
</tr>
<tr>
<td>Phosphorescence glow pigment</td>
<td>25 mL</td>
</tr>
<tr>
<td>(strontium oxide aluminate)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: The three main ingredients and their appropriate proportions in individual volume, as used to form the triangulated Lumina skin. Source: Author.

Figure 7.13: Left: Glowing pigment. Middle: Translucent silicone rubber. Right: Lumina in liquid form. Source: Author.

Figure 7.14: Left: Moulding of triangulated Lumina skin module with an area of 0.07 m² each, embedded with SMA wire. Middle: Laser cutting for the triangulated shape skin. Right: Outcome of the skin-fabrication process. Source: Author.
Fabrication of Lumina involves integrating silicone rubber and glowing pigment to develop a passive and active luminous material that glows in the dark, to be applied in the form of skin. The passive luminous capacity of Lumina is to absorb light energy during the day and discharge the light energy after dark to produce a glowing effect (Figure 7.15). When absorbing external heat energy, Lumina can actively produce brightness beyond its passive luminous capacity. I conduct an initial test to observe this active luminous capacity by allowing Lumina skin to absorb heat energy in 100°C boiling water. Through qualitative observation, the Lumina skin obviously glows with extra brightness than its passive illumination (Figure 7.16).

Figure 7.15: Left: Lumina skin within a mould absorbing daylight energy. Right: Passive illumination of Lumina skin in the dark without external power source. Source: Author.

Figure 7.16: Left: Lumina skin absorbing heat energy from boiling water. Right: Extra brightness for luminous Lumina skin. Source: Author.

7.3.4. Three types of Lumina skin panels

Based on the positive results derived from the early experiments with Lumina and its various responsive capacities in the three previous subsections, I further develop three types of triangulated Lumina skin panels to form the whole cylinder surface of Blanket: Type P, Type L and Type G (Figure 7.17). The Type P (proximity) panel is a luminous skin that passively absorbs daylight energy and is embedded with SMA wires for capacitive sensing and actuation purposes (Figure 7.18). The Type L (light sensing) panel is embedded with linear photoresist wires that can sense light, as well as with eye-like apertures as individual openings actuated by embedded SMA wires. The Type G (glow) panel is integrated with triangulated spiral Nichrome wires that serve as heating elements to actively heat the luminous skin in order to achieve extra, brighter illumination. These three skin panels serve their individual functions and respond to each other by being controlled through a simple setting, including a physical computing system, as is discussed in Section 7.5.
Figure 7.17: Top: Three different types of triangulated responsive Lumina skin panels designed for active and passive sensing, actuation and luminous purposes. Bottom: The physical overall responsive skin system of Blanket, composed of three individual types of triangulated Lumina panels. Source: Author.

Type P is fabricated with silicone rubber, phosphorescent pigments and SMA wires to form a modular triangulated skin. It senses the external analogue data through capacitive sensing. In addition to the local actuation purposes of controlling the open and closed states of the eye-like apertures, the integrated conductive SMA wires also serve as capacitive sensors to detect the proximity of objects (Figure 7.19). Based on the positive result generated by the conductive paint used as the proximity sensing element in the early experiment, the
two linear embedded SMA wires are the replacement of the conductive paint. This is a more accurate capacitive sensor that focuses on specific areas on the surface of Type P panel. The advantage of this simple sensing technology is that it produces a lightweight and skin-like proximity sensing system within the flexible surface of Blanket. This exploits the potential and possibility for a mono-functional material to play a multifunctional role while exploring novel research approaches and methods.

In contrast, the Type L panel has light sensing capacity and is embedded with a linear photoresist sensor in wire form to receive various lighting data and perform passive illumination (Figure 7.20). When a Type L triangulated skin panel senses that the surrounding lighting level is below 10 lux on its surface, the integrated light sensing ability of its Lumina skin triggers the embedded Nichrome wires of Type G to heat the skin for extra glowing effect to the recommended illumination level (Figure 7.21). In addition to being equipped with the passive luminous capacity of the other types of panel, Type G is a Lumina skin composites with phosphorescent glow pigments and silicone rubbers for performing glowing lighting effects when absorbing heat energy from the Nichrome wire embedded within (Figure 7.22). This active lighting interaction between pedestrians and Blanket transforms the dark and underused passageway into a vibrant and bright interactive social space during the day and night.
7.4. Transformation

The application of the morphing idea for this transformation stage of the RKMS in Blanket is partially inspired by the Hylozoic Ground project by Philip Beesley, mentioned in the introduction. His work inspired the idea that sensing, actuation and illumination could be integrated into a single responsive material system. This integrated approach focuses the responsive material properties that are embedded with computation processes to be applied in the form of MASs. Like the previous three design investigations, the IPO process embedded within the RKMS is included in this stage for transformation with enhanced parametric design tools, such as Grasshopper for Rhinoceros, Firefly and Arduino software.\textsuperscript{211} The sensing and actuation of this system is controlled by the Arduino microcontroller, which performs data analysis and processing in order for the transformation of Blanket to occur.

This transformation stage of Blanket is operated with three components: sensing, analysis and actuation parts. These communicate through the Arduino microcontroller, with the Firefly software driving a responsive loop. This system is discussed in the following two subsections, which explore Blanket’s ability to perform two fundamental transformable capabilities: global and local.

\textsuperscript{211} I do not review this process detail in this section because it was extensively discussed in Chapter 3. The RKMS is a rigorous method with iterative processes that is applied to every design investigation in Chapters 4 to 7.

7.4.1. Global transformation

The global transformation capability of Blanket provides a proposed light-tracking ability through deformation of its overall Tensegrity skeletal structure towards an environment or light source with a higher lux level. This tentative design intention and ability to track light in order to maximise light energy absorption is derived from the shortcoming of conditions at the site, which has no direct sunlight penetration during the day (Figure 7.23).

![Figure 7.23: Preliminary digital simulation demonstrates the light tracking process of the responsive global transformation capability of the Tensegrity skeletons and skins. Source: Author.](image)

By embedding only four SMA spring actuators in each row of the triangulated Tensegrity skeleton, the flexible and elastic nature of this structural system is made able to perform a greater deformation process, which allows the Lumina skin surface of Blanket to orient itself to the direction with a higher lux level during the day (Figure 7.24).
The overall Lumina skin surface then releases the light energy absorbed during the day to illuminate the darker area of the site through the global transformation process. This process takes advantage of the passive and active responsive capacities of the overall material system of Blanket, which is concerned with minimum energy usage to achieve maximum actuating and luminous performance. Although only two rows of triangulated skins and tetrahedral skeletal structures of Blanket are physically constructed to test its responsive global transformation capability, it represents and demonstrates the full potential of the completed cylinder shape of Blanket. This transformation capability is also complemented by the digital simulation, discussed earlier in this subsection, which shows how the continuous transformable undulating skin surface of Blanket is responsive to various lighting conditions (Figure 7.25).

7.4.2. Local transformation

The ability of the skin of Blanket to perform local transformation for the skin of Blanket is the result of continuous investigation of the previous project works, including Curtain and Blind. This subsection focuses on the transformation of porosity, as well as the lighting pattern triggered by the SMA wires. The SMA wires used in this operation serve two purposes in local transformation. The first is to actuate the eye-like apertures to manipulate light spot penetration, and the second is to heat the skins to achieve possible pattern illumination effects.
The initial purpose is represented through a real-time digital simulation that demonstrates the way the overall eye-like apertures are actuated by SMA wires to create changing shadow-play patterns by allowing variable light spot penetration (Figure 7.26). In addition to actuation, the SMA wires embedded in the physical skin panels of Type P and Type L serve as linear heaters. When heated by electric stimuli, they contract and heat the Lumina material to create linear luminous lines that form the skin’s transformable illuminated patterning (Figure 7.27).

### 7.5. Responsiveness

Blanket is equipped with two fundamental sensing capacities: proximity sensing and light sensing; and two responsive capacities: movement and illumination. Proximity is sensed through capacitive sensing, and Blanket responds through shape memory alloy (SMA) wires embedded in the material for kinematic actuation. Light sensing detects the lux level of its surrounding environment and constantly sends lux data to the Arduino microcontroller through Grasshopper and Firefly to trigger the appropriate response—either activating active light stimulation or not (Figure 7.28).
The responsive movement capacity of Blanket includes actuation by SMA coil springs and wires embedded in its skeletal structure (global) and triangulated skin (local). As discussed in Sections 7.4.1 and 7.4.2, respectively, Blanket has global and local movement capacities, and these capacities respond to various external stimulus data by transforming their shapes and states to adapt to the demands of changing conditions. Illumination is a passive and active capacity of Blanket’s Lumina skin, which can store light energy absorbed during the day and glow when the surrounding environment becomes dark (Figure 7.29). It can also respond to heat activation by passing an electric current through the material.

To implement the two sensing and responsive capacities of Blanket, inspired by the previous design investigations, I further develop a schematic for these capacities using 10 analogue input pins (sensing) and 10 pulse-width modulation (PWM) analogue output pins (responding) of the Arduino Mega microcontroller. This is based on the responsiveness stage of the responsive kinetic material system (RKMS), using the input-process-output (IPO) process developed in Chapter 3 (Figure 7.30). The first initial four analogue input pins (zero, one, two and three) receive light data from the linear

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212 PWM is a technique embedded within the Arduino microcontroller to attain the analogue results via digital means. For further detail regarding this technique, see “PWM,” Arduino, accessed February 17, 2012, http://www.arduino.cc/en/Tutorial/PWM.
photoresist wire embedded in the triangulated Lumina skin. After being analysed by the Arduino microcontroller through the embedded Arduino protocol, the processed data is sent to four respective PWM pins (two, three, four and five) to control the responsive global transformation for light tracking. As demonstrated in subsection 6.5.1, this is done by regulating the external electric current (12V, 3A) through a series of transistors to heat the SMA coil springs that allow actuation (for the lower row surface of Blanket) to occur. The subsequent analogue input pins four and five receive proximity data of pedestrians’ movements to trigger the upper row surface transformation through another two SMA coil springs via PWM output pins six and seven. Analogue input pins six and seven also receive proximity data, and these data are used to control local transformation via output pins eight and nine. This is done to regulate the opened and closed state of the eye-like apertures of the triangulated surface panels through the embedded SMA wires. The final two analogue input pins, eight and nine, sense the lux level of the surrounding lighting individually to allow the two output pins 10 and 11 to regulate the heating process of the triangulated spiral Nichrome wires embedded in the Lumina skin panels to achieve active illumination. This complete physical schematic set-up provides certain flexibilities in increasing or decreasing the sensing and responsive ‘point’ of the individual triangulated skin panel, adjusting according to various environmental and site conditions (Figure 7.31).  

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For full detail of Arduino protocol, please refer to Appendix D.

For further information on the schematic diagram, please refer to Appendix E.
The overall physical set-up for the schematic of the sensing and responsive system of Blanket performs two fundamental sensing capacities as introduced at the beginning of this section: proximity and light sensing. Although each of these has a different sensing purpose, they respond in an identical manner—via morphological transformation through actuation of the SMA springs embedded in the Tensegrity skeleton of Blanket.

7.5.1. Proximity sensing

Blanket’s proximity sensing is controlled through its Type P modular skin panel, which performs active capacitive sensing. As described in Section 7.3.4, the Type P panel is fabricated with SMA wires, silicone rubber and phosphorescent pigment as one composite entity. When conducting an electric current, the two tensional SMA wires embedded in the silicone skin serve as probe sensors that use changes in capacitance to sense changes in distance to an object. Once they sense proximity of a moving object in the surrounding environment, the skin surface of Blanket leans towards the object. This sensing and responsive process is achieved through contraction and expansion of the SMA springs embedded in the Tensegrity skeleton to allow various transformable surface configurations (Figure 7.32).

The luminous skin of Blanket not only performs seamless proximity sensing—by responding to the proximate object, it illuminates and glows in the adjacent dark atmosphere (Figure 7.33). This capability is further discussed in Section 7.6 regarding the light tracking and luminous patterning capabilities of Blanket, represented in digital simulation.
7.5.2. Light sensing

Instead of the typical approach of using responsive sun shading devices or brise-soleil for building façades, the skins of Blanket provide an alternative that allows the skin itself to glow, thereby providing illumination for the surrounding environment. The newly developed synthetic phosphorescent material, Lumina, as discussed in Section 7.3, is used as the skin of Blanket to absorb light energy during the daytime and discharge the light energy when dark.

The sensing skins of Blanket detect areas with higher lux levels, and the kinetic skeleton responds and morphs towards this area to absorb maximum light energy during the day. When the light level of the area is lower than 20 lux, Lumina illuminates the surrounding area without an external power source. When Type L panels sense that the lighting effect of the surroundings is lower than 10 lux, the active luminosity of Blanket is instantly activated by Type G panels with their embedded Nichrome wires, which heat the Lumina material to increase the glowing effect to the surrounding environment (Figure 7.34). Lumina, with its composite of glow pigments and silicone rubbers, performs a glowing lighting effect powered by the heat energy (at 70°C to 80°C) from the Nichrome wire embedded within. This process uses minimal energy (3.75 W [2.5 V, 1.5 A])—equivalent to one LED globe—to activate the illumination of a 150 mm x 150 mm sample of the material when passive illumination is not bright enough.

When the local light level is lower than 20 lux, Blanket illuminates the surrounding area, without an external power source. When Type L panels sense that the lighting effect of the surroundings is lower than 10 lux, the active luminosity of Blanket is instantly activated by Type G panels with their embedded Nichrome wires, which heat the Lumina material to increase the glowing effect to the surrounding environment (Figure 7.34). Lumina, with its composite of glow pigments and silicone rubbers, performs a glowing lighting effect powered by the heat energy (at 70°C to 80°C) from the Nichrome wire embedded within. This process uses minimal energy (3.75 W [2.5 V, 1.5 A])—equivalent to one LED globe—to activate the illumination of a 150 mm x 150 mm sample of the material when passive illumination is not bright enough.

The active luminous lighting effects of Blanket, created by the Type G triangulated panels, provide potential luminous visual patterns that
alter the atmosphere of the surrounding dark environment. Lighting patterns are also performed through the opened and closed individual luminous eye-like apertures actuated by embedded tensional and linear SMA wires. The atmosphere of the chosen site is revitalised through the performed lighting effects of Blanket, transforming the existing environment into a dynamic place for social interaction.

7.6. Design implications

There is a tentative onsite design evaluation of the effects of Blanket as a reciprocal intervention for the chosen passageway. The two shortcomings of the selected site, as briefly discussed earlier, are the lack of social activities and poor lighting conditions. Blanket was installed on the selected site for a 24-hour period to test its effects on these shortcomings and collect useful data for later evaluation. The graphs in Figure 7.35 reveal the data collected before and after the installation of Blanket. This data presents the numbers of pedestrian movement or motion recorded onsite to represent social interactions and activities (Figure 7.35). I record this data through a motion-detecting infrared camera, with and without Blanket installed, to compare the number of pedestrian movements onsite. The graphs in Figure 7.35 indicate that after the installation of Blanket, there is an obvious increase in movement in the underused passageway, showing it encourages increased social interactions and activities.

Although I had little intention of designing Blanket to serve as a lighting device for this dark passageway, its passive and active illumination creates luminous effects that trigger the curiosity of pedestrians and slows their walking speed, thereby achieving increased social interaction. Instead of using a conventional lighting system, such as incandescent and fluorescent lights, to illuminate the passageway, Blanket creates a luminous landscape and saturated space between the environment and itself to attract increased social activities during the night. It also provides design potential for self-illuminated architectural elements and devices with minimal energy usage. One of the main purposes of developing the Lumina skin of Blanket was to minimise the use of energy for architectural illumination. Figure 7.36 shows the passive illumination level of the Lumina skin using a lux measurement meter. This demonstrates a positive result. The combined passive and active illumination of the
Lumina skin is, on average, five lux, and the energy used is no more than 3.75 watts for this 1.5 mm thick responsive material. Although the illumination capacity of Blanket still does not fully achieve the recommended illumination level of conventional artificial lighting, this prototypical luminous material introduces an alternative design paradigm for future responsive architectural illumination and design.

Figure 7.36: Left: The average lighting level of the passageway environment is no more than 50 lux from day to night. Right: Lux measurement meter indicating 0.1 lux for passive illumination and five lux for active illumination of the Lumina skin. The data of the graph show that there is not much improvement after Blanket is installed, in terms of lighting. However, it creates a luminous landscape that attracts increased social activity. Source: Author.

7.6.1. Digital simulation of responsive capacities

In addition, the early proposed responsive capacities of Blanket, global light tracking and local luminous patterning, become potential design implications, augmented by Blanket’s light-sensing capacity and responsive transformable structural system. These are represented in the digital simulation that visualises the skin of Blanket responding to changing lighting conditions and performing morphing illuminated patterns. The light-tracking ability enables the morphing skin of Blanket to absorb and store maximum light energy during the day and passively release that stored light energy to illuminate the dark environment (Figure 7.37). When this active illumination is complemented by heating the Lumina skin with embedded SMA wires, the skin surface of Blanket presents luminous patterning that creates a malleable architectural lighting performance, as well as providing passive and active illumination in the dark atmosphere (Figure 7.38). Both simulations project the design possibilities of physical realisation and implementation for the responsive capacities of Blanket. This provides room for future research to investigate the full potential of Blanket in terms of designing reciprocal architectural illumination and media skins with a responsive material system.

Figure 7.37: The sequential images demonstrate that the morphing undulating skin of Blanket responds to the light source and performs light tracking to absorb maximum lighting energy. Source: Author.
Figure 7.38: The morphing illuminated patterns performed by the Lumina skin of Blanket. Source: Author.

The possible future design implications generated through Blanket focus on the integration of Lumina with other bio-inspired materials, such as self-healing and energy-harvesting materials, to further the applications for responsive morphing architectural design. These possibilities also suggest a solid-state sensorial polymer skin synthesised with actuators and piezoelectric sensors for responsive kinetic architectural design. This design paradigm eventually seeks to achieve a multifunctional material system to perform various tasks with fewer discrete parts.

7.7. Summary

Current technological advancements in material development provide new opportunities for architects and designers to create architectural devices and components never anticipated before. The design investigation in this chapter takes an initial small step towards exploiting this opportunity and developing a synthetic material for responsive kinetic architectural design that uses novel methods and tools. Instead of providing an ultimate answer, Blanket and the newly developed material, Lumina, not only demonstrate a promising design paradigm, but also offer alternative solutions to problems of responsive kinetic architectural design and illumination. They serve as a trajectory for future research in the field of responsive materials and systems for morphing architectural designs.

For decades, architects and design researchers have investigated the idea of architecture that responds to users and has a certain intelligence. These investigations have led to countless design outcomes and produced some very intriguing potential architectural designs. Responsive architectural skin is one of many applications among these design explorations, and perhaps the most common. The outcome of the project work in this chapter is an approach—in conjunction with the collective results of the previous investigations—to develop a design strategy through novel materials and tools, thereby developing a conceptual prototype with sensory morphing material systems for responsive architectural skin design. This approach of integrating form-changing, sensing and luminous materials with physical computational processes applied to real-time data of external stimuli signifies the beginning of a different design paradigm in which responsive kinetic architecture can go beyond mechanical components and discrete sensing devices.

The outcome and material developments of the design investigation of Blanket are proofs of concept. They provide a platform for future researchers and designers to investigate the new possibilities in the research area of sensitivity, involving sensory material systems for
responsive kinetic architectural design through the exploration of form-changing and sensing materials. Far from suggesting an ultimate solution, this final design investigation of the Design Tetralogy series reveals positive outcomes that serve as a stepping-stone for further research and innovation towards the realisation of morphing architecture.
Discussion

My research has generated appropriate insight and knowledge in the areas of kinetic architecture, physical computing and responsive material systems. This knowledge was accumulated and learnt through the project-based design investigations, leading to the development of strategies and proposed methods to investigate the potential early-stage design of morphing architecture. This approach employs an imperative to integrate both responsive materials and novel computational design tools. In this chapter, I discuss this learnt knowledge in terms of the techniques and skills gained through this approach, by reflecting on the overall research outcomes and results generated through the series of project works in Chapters 4 to 7, in conjunction with Chapters 2 and 3. This reveals the possibilities of their potential implementation and applications in architecture. These reflections enable me to reach a conclusion in the next chapter. This chapter is divided into three sections:

1. Section 8.1 reflects on this research journey through reviewing my project-based research approach and its systematic means of enquiry to produce legitimate research outcomes and results.

2. Section 8.2 discusses the individual results of the applied research of design investigations, conducted through four projects. These results reveal the practical design implications in five areas—architectural design, materiality, technology, environment and lighting aesthetic—to apply to a potential design agenda for morphing architecture in order to test my initial research hypothesis.

3. Section 8.3 outlines several limitations of the outcomes of this research in terms of its technological and practical factors. These factors include issues related to the durability, energy efficiency and scalability of the results generated through the design investigations.

In these sections I discuss the findings and results generated by the four design investigations as a new exposition within the current context of responsive kinetic architecture. In addition, they indicate the shortcomings and limitations of the outcomes of this research in order to provide a platform and opportunity for future research to occur.
8.1. Overview of research

[A] designer’s sensibility towards the animated is perhaps an
instinct that has always been there, only to have been
challenged by the limitations of the constructional and
representational repertoire before the digital age.²¹⁵

—Mark Burry

My research began with several enquiries into alternative design
possibilities regarding architecture that can morph and respond to its
surrounding environment. This form of architecture is often
represented either digitally or via mechanical components. These
enquiries prompted investigation of possible novel design strategies
and physical implications of morphing architecture, explored through
new material systems and tools integrated with physical
computational processes to create sensing and responsive capacities.
All the chapters in this exegesis are discussed within the overall
framework of this aim to directly and indirectly provide individual
summaries as supporting arguments to reflect on the outcomes of the
responsive material systems as alternative paradigms for designing
morphing architecture.

Chapter 1 introduced briefly the background of the inspiration for my
research study, and proposed its general theoretical framework. This
framework included the research motivation, aim, question,
methodology and exegesis structure.

Chapter 2 based the related literature and precedents in five fields:
kinetics in responsive architecture, responsive kinetic skins,
responsive materiality, physical computation in architectural design
and the inspiration of morphing technology. This was done to ground
the reader within the scope of this research. The summary of this
review allowed the concept of ‘soft kinetics’ to be conceived, and
eventually served as a guiding principle to develop a pilot system as
method that was applied to every design investigation.

While Chapter 2 presented a summary and overview of literature in
various disciplines, Chapter 3 discussed the development of the pilot
system, the responsive kinetic material system (RKMS). This is a
method based on the concept of soft kinetics. It was implemented in
the subsequent individual design investigations in Chapters 4 to 7, in
conjunction with the critical review and reflection of Chapter 2.

Chapters 4 to 7 consisted of four experimental design investigations,
each reported on in an individual chapter, as the technique of enquiry
that focused on specific research areas established in Chapter 3. The
outcomes of these experimental design investigations acted as
evolving critical reflections on each other during the design research
process. The first investigation developed a modular prototype using
current accessible industrial elastic materials and components to
design a responsive structural skin. In the second investigation, this
prototype was further developed to become a working material

²¹⁵ Mark Burry, Scripting Cultures: Architectural Design and Programming (West
Sussex: John Wiley & Sons Ltd, 2011), 226.
system, fulfilling its implementation as a responsive morphing architectural skin (MAS). The initial two investigations (Chapters 4 and 5), Tent and Curtain, were dedicated to the design enquiry of existing technologies in terms of elasticity and Tensegrity. These were two of the focused research areas addressed in Chapter 3. The last two investigations (Chapters 6 and 7) discussed the use of external variables for manipulating the environmental and visual conditions of the skin for existing buildings. The third design investigation, Blind, was developed to implement a working prototype system that explored the ability to adaptively create visual patterns and communication with kinetic materiality. The subsequent fourth design investigation, Blanket, served as the final project work, focused on sensitivity in conjunction with the reflective outcomes of the previous three design investigations. This evoked new design possibilities involving building skin sensing and adaptive ability.

As demonstrated in the previous four chapters, each design investigation, except for the inaugural project work, was an evolution based on reflections of the previous project work, through further design developments such as the skeleton and skin systems. The outcomes of the four design investigations function within the final research argument to interrogate the original ideas, test the hypothesis and address the research question. These design investigations serve as evidence or proof of concept to support the research argument and embody knowledge more efficiently and appropriately than through text alone. In addition, the design investigations serve two specific functions within the research process by acquiring primary results and developing appropriate outcomes.

The final sections of this exegesis, this chapter and Chapter 9, present a concise discussion and conclusion, respectively, to discuss the outcomes of this research that respond to the original aim and address the research question. This chapter includes an evaluation and discussion of the research outcomes in five specific areas: architectural design, materiality, technology, environment and lighting aesthetics. Chapter 9 is the final chapter of this exegesis. It presents a conclusion and suggests a platform to further these research findings and envision the beginning of a different design paradigm that will allow future morphing architecture to be developed.

8.2. Research findings and implications

Designers and researchers are both concerned with improving current situations and circumstances. Both also share a common goal to generate, communicate, and extend human ideas and experiences. Furthermore, designing and researching both draw heavily upon investigative techniques, and both are forms of educative enquiry.216 —Pedgley and Wormald

In general terms, although designing and researching seem contradictory because of their different objects, methods and

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purposes, the quotation above argues that there are similarities. This argument initiated and inspired the early intentions of this research’s methodological approach. This approach allowed this project-based research, through four design investigations, to produce outcomes that include real-time responsive digital and physical conceptual prototypes, and develop composite materials and novel fabrication techniques.

Based on this approach, this section discusses the research findings and results generated through the four design investigations to explore how they are different and how they are relevant to the contemporary responsive architectural discourse and design implications. As briefly introduced at the beginning of this chapter, I evaluate these in terms of five aspects of the current architectural context: architectural design investigation, materiality, technology, environment and light aesthetics. These proposed aspects establish evaluation platforms to determine the legitimacy of the knowledge produced through the research outcomes in my series of project-based design investigations.

8.2.1. Architectural design investigation

Architects rarely have the privilege of working directly with the object of their imagination. While other artists work immediately with their materials, architects work abstractly. —Thomas Schropfer

The speculative outcomes of the design investigations in Chapters 4 and 7 produced various scales of digital and physical design prototypes. These were fabricated and manufactured during the research process to suggest several design implications that affect the contemporary responsive architectural discourse. These architectural design implications were introduced in individual, evolving investigations that were empirical and evidence-based. Although some of them remain speculative, they demonstrate some promise, especially for designing MASs. As the editors of the International Journal of Architectural Computing, Christiane M. Herr and Stanislav Roudavski, comment in one of my published refereed journal papers, co-authored with Flora Dily Salim and Jane Burry:

Designing involves a leap of faith into the unknown. The same applies to research, where the initial of most inquiries are curiosity and initiative, built on the trust that new and relevant answers can be found.

For me, this comment reaffirms that design speculation is a crucial part of design research, and the trajectory of adopting the design investigation approach in my research. However, speculation in

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designing requires rigour to justify outcomes formally. Rigour in this research context does not adhere to or replicate a conventional research approach. Rather, it provides choices for the design outcomes to be accountable to achieve new knowledge through rigorous research enquiries.

The evolution of a rigorous design process across the design investigations was conducted with a step-by-step method that allowed design developments to occur through subsequent projects. No subsequent project was conceived without reflection on the previous project’s outcomes. Although every project was individually conducted through an iterative methodological process and focused on a specific research area, each project-based design investigation produced a design development that evolved from its predecessor, moving towards the overall individual goal of embodying the responsive MAS. Each design advancement included exploration of larger-scale prototypical components, more comprehensive skin and skeleton designs, new composite material developments and greater embedded sensing ability in the material systems.

The possibilities of an alternative design paradigm for responsive morphing architecture were tested and discussed in the previous four chapters. These embodied four exploratory design investigations, metaphorically named Tent, Curtain, Blind and Blanket. These served as the design prologues of morphing architecture in the form of architectural skins that challenge the norm of the current responsive kinetic architectural design approaches that are fully dependent on mechanistic component devices. Instead of being finite design products or artefacts, these prologues were generated by design investigations that constantly served as a model to potentially inspire alternative and different responsive architectural design outputs using a rigorous method in conjunction with novel material explorations.

As briefly discussed in Chapter 2, Goulthorpe’s Aegis Hyposurface and Nouvel’s responsive façade of the Institut du Monde Arabe in Paris are two prominent examples that represent mechanically operated responsive architectural skins. Each of the works generated through the four design investigations focused on a different approach by using material sensing and actuating responsive skins. These demonstrate the positive outcomes set as the design alternative to the two aforementioned prominent examples. These research outcomes serve as early architectural design prototypes and reveal promising potential for future research and design of emerging architecture, in which morphing architecture is becoming a priority.

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221 Ibid.
222 This rigorous design investigation generating positive outcomes has influenced the design works of an architectural firm, KG/MG Architects, being identified as a public recommendation. For further information, please refer to Appendix C.
223 This approach is further explored in an international design competition: the eVolo 2011 Skyscraper Competition. For further information, please refer to Appendix F.
Although inventing or developing a new type of responsive materials to investigate responsive morphing architecture was not part of the original goal of my research, through new learnt techniques and technological knowledge of material gained during the reflective design investigation, certain novel responsive materials were developed. In the later stage of my research, I published some findings in a journal paper entitled, ‘Lumina: A Responsive Luminous Material for Architectural Skins Design’. This was published in the journal *Advanced Materials Research* to report on the results of my newly developed material, generated to complete my fourth design investigation, Blanket. This particular material, Lumina—as discussed and reported on in the detailed development process in Chapter 7—is a responsive composite material with sensing, kinetic and luminous capacity, suitable for application in the design of responsive MASs.

Lumina is an early-stage synthetic material with responsive capacities that can perform sensing, actuation and illumination. The initial intention to develop this material pushed design boundaries to investigate the potential for its application to architectural sensing and illumination with minimum energy usage. The responsive capacities of this material suggest a promising, transferable application to practical architectural design, particularly due to its passive and active luminous capacity.

The materiality aspect of the results generated through the four design investigations is significantly embodied in the series of developed responsive synthetic materials, particularly in Lumina. While integrated with the flexible Tensegrity structures, these soft and elastic material systems portray a positive direction towards a different, material-oriented paradigm for designing responsive kinetic architecture, which emphasises the responsiveness and performance of material properties, rather than mechanical components and devices. With direct engagement, attaining a novel way to use materials, and developing and defining material behaviour, architectural design is no longer constrained by methods such as digital representation and physical modelling. Contemporary architects and designers who neglect the significant value of direct material engagement and development during the design process will fail to realise the vast design opportunities offered by current material and technology advancements.

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224 For further information and a full paper reading, please refer to Appendix B.
8.2.3. Technology

The focus is shifting from material properties to material performance. Designers intervene in the technological quality of material and define material behaviour rather than having their decisions determined by it. —Sascha Peters

Instead of being solely driven by fascination with contemporary technology, my project-based design investigations explore different approaches to using existing techniques and technology in a new way. This approach was demonstrated through several intriguing technological developments during the fabrication and manufacturing processes. The exploration and exploitation of existing technology in terms of materials and responsive systems revealed viable results on the basis of which to conduct design investigations with an open-ended platform involving physical and digital experimentation.

During my practical investigation process, I customised and developed a series of new composite material systems integrated with physical computing, actuation and multiple sensing abilities. These had not previously been fully explored in architectural research. The results of these material systems, which make a technical contribution to the fields of architectural computing and material research, are evidenced in several peer-reviewed international conference papers and journals. Several developed technologies of actuation, structure, sensing and illumination were explored in new ways throughout the four design investigations within the scope of four focused research areas: elasticity, Tensegrity, kinetic materiality and sensibility.

The technological aspect in design investigation one, Tent, was developed through a pneumatic air system integrated with an elastic balloon skin, as well as through a tetrahedral modular skeleton for passive and active actuation in conjunction with sensing devices. The Tensegrity approach explored in design investigation two, Curtain, is not new in architectural design, but when applied to the design of a flexible architectural skeleton with a new design interpretation, this structural system offers promising potential, especially for large-scale transformable architectural structures. Using kinetic materials such as shape memory alloys (SMAs) for actuation and form-changing purposes is becoming common, especially in the aerospace and satellite industries. However, while applying these materials in the third design investigation, Blind, this technological approach through the exploitation of form-changing materials was a novel gesture and immediately revealed great potential, particularly for kinetic and morphing architectural design as an alternative to the conventional mechanical approach. Once these kinetic and form-changing materials are equipped with sensing and luminous capacities, as tested and demonstrated in the final design investigation, Blanket, they move a step closer to being state-of-the-art, a ‘holy grail’ in the design of sensory and responsive morphing architecture.

Peters, Material Revolution: Sustainable and Multi-purpose materials for Design and Architecture, 12.

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The exploitation of existing technology was also explored during my design investigations. I argue that, as an alternative to traditional architectural design techniques involving drawings and physical or digital modelling, current technology—such as physical computing, accessible software and physical computing devices (Grasshopper, Firefly and the Arduino microcontroller)—serve as new interactive design tools for architects and designers. This existing technology goes beyond the conventional purpose of representation due to its real-time data processing capability. Digital 3D simulations responding to real-time analogue data were explored through each design investigation as an interactive design technique, prior to physical prototyping, providing instant and constant feedback data. These digital simulations are crucial examples of this novel design technique.

Using this technology would not have been possible in this research without the accessibility and affordability of existing technological tools and open-source software. Their economical and near-disposable nature are advantages that provide an accessible platform for architects and designers to explore alternative architectural design processes, especially in the field of designing responsive and kinetic architecture. Architects and designers no longer need to shy away from novel design methods or techniques, because current inexpensive technologies allow for accountable failures and repeatable experiments, particularly during the early design stage.

8.2.4. Environment

It seems that we are ultimately on a quest for an architecture that has the same degree of responsiveness that organisms manifest with their highly evolved active adaptation to shifts and alterations to both cyclical and unexpectedly sudden changes in their environment.\(^{228}\) —Mark Burry

The idea of responsive and kinetic architecture is not new. Many contemporary architects and design researchers interested in this architectural vision are often fascinated by designing installations and prototypes fabricated with advanced technology and implementing new materials. Few engage with the relationship between the installations and their adjacent or surrounding environments. I took this opportunity to rethink and revisit this interactive relationship through works produced in this research. For instance, the fourth design investigation, Blanket, was selected as the representative project of the other design investigations, to test this relationship on an actual site.

As discussed in Chapter 7, Blanket is a reciprocal intervention installed in an underused and ill-designed passageway for the purpose of revitalising this particular building site. Blanket is distinguished from other contemporary architectural interactive installations that do not consider the relationship with their situated environments. The interaction of Blanket with its surrounding environment occurs between the digital and physical environment, and the entire architectural installation physically responds to

\(^{228}\) Burry, Scripting Cultures, 224.
changing site conditions and direct human interaction. It constantly creates a conversation between the adjacent environment and itself, thereby providing an opportunity to alter and reciprocally improve the existing conditions.

Philip Beesley’s projects, including most of his recent works, take a similar approach that allows Beesley’s responsive installations to interact with participants and their surrounding contexts. However, these works are mostly interior installations in controlled environments that either lack interaction with their exterior environment in terms of real, changing climatic issues, or an aim to improve the existing conditions of the built environment. Beesley’s works inspired and provided the opportunity for Blanket to explore its interactive capabilities in the context of exterior environmental conditions at the selected site in order to revitalise inferior and architecturally hostile spatial conditions. Blanket is a full-scale design investigation physically realised in the form of a responsive morphing ‘lantern’ envelope installed in the chosen site. Its predecessors—Tent, Curtain and Blind—also enabled response to their surrounding controlled environments, though on a considerably smaller scale and with designated responsive capacities in the areas of visual and lighting effects.

8.2.5. Lighting aesthetics

There is a common design aspect in all the design investigations: manipulation of the architectural lighting aesthetic in existing architectural spaces. In this subsection, I enhance the lighting manipulation capacity of the four design investigations to discuss their responsive architectural lighting aesthetic. Although this was not a focus when commencing my research, it was revealed as a significant implication for potential responsive architectural lighting design for aesthetic and illumination purposes after reflection on the results of all the design investigations.

Traditional responsive architectural lighting aesthetics and designs mainly focus on illumination via light-emitting diodes (LEDs) and projection on buildings at night. Few consider design for lighting aesthetics in relation to daylight and shadow manipulation, or perform responsive illumination. The outcomes of my design investigations demonstrate a different kind of lighting aesthetic that involves physical and digital responsive illumination during the day and night. Ranging from Tent, a space lighting manipulator, to Blanket, a reciprocal intervention in the context of existing buildings, these prototypical lighting manipulators add another layer of morphing lighting effects to the existing buildings and environment. The luminous effects created a mutable and malleable architectural lighting aesthetic that transforms the atmosphere of the existing building fabrics, and their responsive illumination and shadow play further rejuvenate internal and external architectural spaces to create more social interactions and a saturated environment. With these light and shadow interventions, the existing space ceases to be ordinary. The ever-changing and evolving lighting effects constantly create new ‘masks’ for the existing space with morphing light and shadow.
The amorphous light and shadow aesthetic introduced by the four design investigations is just a beginning, establishing an alternative kind of architectural illumination beyond conventional dynamic digital displays composed of LEDs and projections. This proposed alternative anticipates a novel luminous architecture, rather than a replacement for existing architectural lighting systems. When endowed with responsive capacities, this luminous architecture creates a new layer of communicative and reciprocal illuminated interfaces between people and their surrounding built environments, especially in the absence of sunlight.

8.3. Limitations of research
During the three-year full-time research period of my PhD study, I came across several limitations and shortcomings regarding my research outcomes and findings. These were evaluated through three identified factors: durability, energy efficiency and scalability. These factors emerged when reflecting on the outcomes of the four design investigations through observation and testing of the physical experiments.

8.3.1. Durability
Although the conceptual prototypes produced through the four design investigations demonstrated repeatable performance in terms of sensing and responsive actuations, most remain tested and evaluated in a controlled environment in terms of lighting ambience and temperature. There are still unknown issues regarding the durability of these prototypes when applied in actual architecture in the external environment for a longer period. I identified this limitation at the completion of my project works. Since it is beyond the scope of my PhD study, I foresee this limitation as an opportunity for my future research to focus on an investigation of durability issues in responsive morphing architecture.

There is also room for future researchers to investigate appropriate durability concerns in terms of the wear and tear of the responsive capacities in these design prototypes when confronted with the external environment. Convenient examples will be to test against hostile weather conditions and human interaction. Further studies could investigate the relationship between controlling and material systems by using less discrete components of connection, integrated with weatherproof elements and more efficient ways of exploiting form-changing materials. In doing so, the durability issues of these responsive material systems could be overcome in the near future.

8.3.2. Energy efficiency
As stated at the beginning of this exegesis, the energy efficiency of the responsive kinetic architectural designs is beyond the scope of this three-year project-based PhD research. However, to a certain degree, all the design investigations conducted in this research adopted the idea of an active and passive design strategy to minimise the energy used, especially for actuation and transformation purposes. The energy efficiency of these design investigations became a factor of concern and remains an opportunity for future
research to investigate the area of sustainable kinetic architectural design.

Instead of being restricted by current technological development, this limitation can be overcome to achieve a self-sustainable and energy-efficient responsive morphing architecture by exploiting the existing technology of solar power in a novel manner, such as by using organic photovoltaic printable solar cells. This newly developed technology potentially creates a new paradigm for solar energy distribution that is seamlessly integrated into ubiquitous formats of walls and roofs. While this technology is integrated in responsive material systems such as Lumina, issues of the sustainability and energy efficiency of such systems can be anticipated and overcome.

8.3.3. Scalability

The conceptual prototypes conceived during the process of the design investigation are full-scale implementations that test the optimum potential for responsive material systems applied to responsive morphing architectural designs. Although these conceptual prototypes demonstrate positive and promising outcomes, these full-scale implementations solely reveal the initial potential for early stage prototypical designs. There are still enormous challenges ahead in terms of practicality and applicability in order for morphing architecture to be fully implemented. One of the greatest challenges is in transferring small-scale material actuators, such as SMAs, to achieve a full-scale architectural deformation and transformation with fewer mechanical components. In his seminal paper, published in 1929, ‘On Being the Right Size’, J. B. S. Haldane concludes that in the context of nature, it is impossible to literally rescale a small animal to become a larger one without considering its change of form and structure. Haldane identifies that the problem and limitation of scalability in nature is applicable to architecture as well—at least in the relationship between material behaviour and structural composition. Based on this limitation, it is often necessary to constantly refine the original architectural element or component in terms of its material selection and structural design, to achieve an appropriate scale.

Instead of being an obstacle, this limitation of scalability is an opportunity for an ongoing investigation of the possibilities of applying responsive material systems for life-size morphing architectural designs. When using form-changing materials to serve as actuators, and exploiting flexible structural systems in various scales, such as the Tensegrity skeletons developed in Curtain, Blind and Blanket, this approach suggests a different design paradigm that exploits the mechanical advantages of leverage to achieve maximum transformation with minimum force. Based on the early success of

229 Printable solar cells are promised with advantages in longevity and efficiency, and in being low-cost and lightweight. These are in the form of a stable liquid that can be potentially printed and painted onto the surfaces of papers and fabrics. For further information about this cutting-edge technology, see Miles C. Barr et al., “Direct Monolithic Integration of Organic Photovoltaic Circuits on Unmodified Paper,” Advanced Materials 23 (2011): 3500.

experiments in my design investigations, this idea of leverage was introduced and applied within the Tensegrity skeleton structure for transformation purposes. It presents an optimistic research direction with the potential to ease the limitations implied by the scalability issue, to anticipate full architectural implementation, even with small-scale material actuators integrated into responsive morphing architecture.
Conclusion

A new breed of ‘smart materials’ is emerging: plastics that change shape, metals that change strength at the right moment or wafer-thin coatings that lend the underlying material certain additional properties. While the properties of so-called switchable materials can be changed externally by sensors or controllers, intelligent materials are able to regulate this process themselves, reacting without outside control. These adaptive materials will in future open up new application areas and make other architectural forms and technical constructions possible. —Schumacher, Schaeffer and Vogt

Responsive architectural design is at a crossroads where it can either embrace the silent revolution in current responsive material technological advancements or continue towards further refinement of existing approaches that use mechanistic components. The former approach, as demonstrated in all the outcomes of the design investigations in my research, suggests a legitimate alternative in pushing the limits of designing responsive morphing architecture.

In this concluding chapter, I reflect on the outcomes generated through the developed methods and techniques used to achieve the alternative design approach, as discussed throughout this research, with two sections: ‘Beyond mechanics’ and ‘The end of the beginning’. Section 9.1 responds to the research question by offering concluding thoughts on how a different methodological approach is embodied in the RKMSs developed in this research. This is done to establish the legitimacy of an approach that goes beyond contemporary mechanical paradigms in responsive kinetic architectural designs. The subsequent and final section of this chapter serves as a final, concise discussion of the emergence of the novel instruments that materialised during the processes of the design investigations. These are arguably new design tools, developed beyond the conventional representational purposes of the drawing and modelling approach. These tools employ an interactive design process with actual material engagement and physical computing devices. This intriguing approach is a viable technique, especially for investigating the alternative design process of morphing architecture, moving towards the dawn of a new design direction for responsive kinetic architecture.

9.1. Beyond mechanics

We seem embarked today into a world where materials themselves are becoming active shapers of dynamic environment. This applies at the literal, mechanical level with the emergences of programmable materials ... and of new techniques, such as the integration of organic molecules and piezoelectric elements or crystals into the deep structure of matter, rendering it sensitive and increasingly responsive and cross-referenced with random fluctuations in its immediate environment. —Sanford Kwinter

Broadly speaking, architecture is a material practice, and contemporary material technological advancements provide substantial opportunities for architects and designers to design architecture never imagined before. In my research, I take an initial step towards exploiting this opportunity with embedded computation to develop new material systems for responsive morphing architecture designs using methods that are novel in architectural design. These material systems, as discussed in the core chapters of the design investigations, were mostly explored through soft and form-changing materials with embedded responsive digital and physical computation. This provides new design possibilities for morphing architecture that adapts and responds to external stimuli in order to potentially revitalise existing built environments. These possibilities were tested through four design investigations as experimental and conceptual prototypes that sought to enable the emergence of new ideas for morphing architectural designs, partly through physical and digital prototyping. One of the fundamental investigations for these prototypes was testing the soft approach of flexible architectural skins and structures to provide an alternative to the conventional kinetic approach that uses mechanical components to achieve responsive morphing architecture.

Although the concept of soft responsive architecture was explored by creating spaces made of soft materials, pneumatic systems, various sensors and electronic feedback circuits in the early 1970s, very little fruitful research has investigated this soft approach that uses soft materials and systems with responsive and kinetic capacities in responsive architectural design, even after four decades. In contrast, hard responsive architecture, which often obtains mechanisms from other disciplines, such as mechanical engineering, has been widely implemented by architects and designers. Through the series of outcomes from my design investigations, I argue that an alternative design approach for responsive morphing architecture is to employ soft, form-changing material systems that focus on exploiting the mechanical properties of materials, rather than purely employing the operations of mechanical components. This approach is demonstrated by the four experimental design investigations, particularly in the areas of actuation and deformation within the concept of soft kinetics. The outcomes and results of these design investigations illustrate the great potential for responsive material systems to fulfil


full-scale architectural implementation in future research on responsive morphing architecture.

In addition, when applying physical computing devices such as Arduino microcontrollers as design tools for the prototypical material systems of these design investigations, multiple analogue external input data flows through the responsive algorithm—such as the input-process-out (IPO) process—activate the soft and form-changing materials. These responsive form-changing material systems serve as actuators and sensors to enable the flexibility, versatility and adaptation of transformable architectural elements such as skins and skeletons. The revelation of this responsive material system illuminates a ‘brave new world’ for future research that proposes novel methods, explores simpler and more robust prototypical morphing architecture, and shifts away from visually driven digital representation towards material practice. With further development and exploration of lightweight, elastic, form-changing responsive material systems, a dynamic and morphing architecture can be fully achieved that embraces functional aspects such as seamless transformation and self-sustaining responsiveness.

Hence, instead of being limited by the kinetic operation of current technological approaches, which often exploit mechanical components, responsive kinetic architectural designs employ a different design notion in which the operations usually completed by mechanics can now instead occur within materials’ properties. The research outcomes of the four design investigations of my research indicate the dawn of this different design notion. This is a notion for a different kind of organic aesthetic using soft mechanics with material properties that perform poetic movement. It goes beyond the overwhelmingly machine-like mechanical aesthetic represented in contemporary responsive kinetic architectural designs.

9.2. The end of the beginning

Moving beyond the mechanical components approach to designing kinetic and morphing architecture is no longer wishful thinking. The physical conceptual prototypes in this research, demonstrated in the Design Tetralogy, consisted of four design investigations as a continuum towards a design that anticipates a possible and promising responsive architectural design approach. They suggest a different design approach that uses responsive materiality for designing actuating and morphing architecture. The morphing nature of these prototypes can accommodate responsive mechanisms with passive elastic memory while minimising the energy and weight required for physical transformation. Instead of choosing between the hard and soft materiality of future responsive and morphing architectural design, the outcomes of my research suggest a potential hybrid material system that achieves its full potential through further exploration towards a morphing architecture as a platform of convergence between transformable architectural elements and responsive space. This hybrid material system is represented in the series of morphing design prototypes developed through the design investigations, specifically focused on the research areas of elasticity,
Tensegrity, kinetic materiality and sensibility, to achieve a morphing architecture that responds to environmental and communication stimuli. They serve as evidence and proof of concept, espousing the potential for future full-scale architectural applicability—for instance, in materially dynamic transformable structures and other responsive architectural applications.

By reflecting on this evidence, a different approach for designing responsive morphing architecture has emerged. It is a new design technique that goes beyond contemporary digital design representation and visualisation. As briefly discussed in the previous chapter, I argue that direct engagement with materials and responsive physical computing devices, such as SMAs and Arduino microcontrollers, as different design tools, provides a viable alternative to conventional design techniques such as drawing or modelling, in the analogue and digital realm. In a normal context, these tools serve as ordinary materials and devices in their original functions or usages. By using a novel approach, they shifted their role to become part of the tools used for the design investigations throughout my entire research. The novel technique of engaging the materials and physical or digital tools has demonstrated the use of these unconventional alternative tools, especially for responsive morphing architectural designs. The findings and outcomes of the design investigations generated through these materials and tools respond to the first part of my key research question: ‘How can soft material systems be used …?’

Based on the different design approach I developed in this research, I further envisage a future morphing architecture engaged with responsive material systems that harvest energy for self-sustainability while reducing their use of mechanical components. This includes technology such as paper-based ‘printed’ photovoltaic cells as a self-sustaining power source. These create new paradigms for solar power distribution to seamlessly integrate with architectural elements, including walls and window shadings. This vision can be achieved when furthering my research outcomes with a practical methodology that conceives responsive material systems to synthesise active and passive morphing architectural design concerned with the feasibility factors of fabrication and construction. These responsive morphing material systems originally serve as reciprocal interventions in the form of architectural skins and envelopes for existing or new buildings. Their current goal is to revitalise and rejuvenate inferior spatial conditions. Their future goal and alternative purpose is to find a range of possible integrations for responsive morphing skins and structures that can eventually be applied to various architectural components, such as façades, walls, ceilings and roofs.

A complete morphing architecture with responsive capabilities is yet to be realised. However, the outcomes of my design investigations demonstrate promise through the elastic skins of Tent, the Tensegrity skeleton of Curtain, the form-changing surfaces of Blind and the sensing luminous envelope of Blanket. These are the embodiment of

a design vanguard in this newly developed morphing architectural design paradigm. The methods I developed also provide a novel and alternative design approach for responsive kinetic architecture through unique techniques with rigorous processes. The positive results of my research contribute to the creation of an intriguing pathway for design researchers and architects to further the design investigation of morphing architecture that exploits contemporary multifunctional materials and novel tools. The research journey of my PhD study is temporarily ended; however, like design, it is not a finite process, but initiates future research to continue another voyage that is just about to begin. The reflective outcomes and results of this research establish the point of departure for this voyage, and become the prologues to morphing architecture, which segue into endeavours towards a new material culture that questions the static nature of architecture.
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DESIGNING ELASTIC TRANSFORMABLE STRUCTURES

Towards Soft Responsive Architecture

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Abstract. This paper discusses the issues of designing and building environment involving spatial conditions that can be physically reconfigured to meet changing needs. To achieve this architectural vision, most current research focuses on the kinetic, mechanical systems and physical control mechanisms for actuation and structural transformation. Instead of the 'hard' mechanical joints and components, there is an unexplored 'soft' approach using lightweight elastic composite materials for designing responsive architectural skins and structures. This paper investigates the new possibilities for the manipulation of various architectural enclosures using 'soft' and elastic transformable structures, in response to environmental, communication and adapting to various contexts. This approach intends to minimise the mechanistic actuations and reduce weight for such operations. Therefore, this research introduces two modules (a tetrahedron and a cube) as responsive spatial models to test the potentials and limitations for the implementation of elastic materials with responsive capability towards reconfigurable architectural enclosure. Despite their individual differences, these experiments identify a trajectory for new possibilities for elastic architectural components that are more appropriate for 'soft' responsive architecture. We argue that this approach can provide an early hypothesis for design responsive architecture with a mix of passive and active design strategies.

Keywords. Elastic; transformable; soft; responsive.

1. Transformable structures for responsive architecture

“Responsive architecture” was coined by Nicholas Negroponte in the mid
seventies (Soft Architecture Machines) when spatial design problems were explored in responsive space (Sterk, 2003). There are precedents for responsive architectural spaces that can be transformed and reconfigured to accommodate different usage. The first precedent: Villa Girasole, the rotating house built by the engineer Angelo Invernizzi in 1929-35 Marcellise, a completely revolutionary idea of a rotating building designed to constantly capture sunlight and the use of eco-compatible energy source. In addition, Gerrit Rietveld used sliding partitions to allow spaces to be responded to different uses in his Schroeder House, 1924 (Butler and Odusten, 1989). Recently, Shigeru Ban’s 9 Square Grids House has a similar approach, a contemporary interpretation of the conventional Japanese house with sliding partitions as large cabinets to store blankets and mattresses during the day and provide privacy at night (Ban, 1998). However, there are several shortcomings to these approaches that have restricted their implementation. In general, there are only limited possible configurations, and while the partitions are produced as lightweight as possible to allow inhabitants to move them manually, making them poor thermal and sound insulators, the process of reconfiguring a space is fairly labor-intensive (Weller and Do, 2007).

In parallel, computationally generated transformable structures have also been a focus of current digital era. When we consider responsive architecture composed by transformable structure, we are forced to confront issues of human power, space control, environmental manipulation, material economy, operational effectiveness, and energy investment (Sanchez-del Valle, 2005, p.137). Furthermore, contemporary responsive architecture in general is built on the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental responsiveness (Fox, 2009, p.381). The integration of these two areas will provide the environment that is capable of reconfiguring itself and automating physical change to respond, react and be adaptive. This metaphor will lead to a purpose that structure can be reduced for space-making through the ability of a singular system to facilitate multi-uses via transformative adaptability.

2. Soft Responsive Space

Recently, the work of DECOI: Aegis Hyposurface has attempted to integrate two facets of architecture: responsiveness and transformable structure, to create and investigate responsive architectural facades and installations using high-tech mechanical solutions. However, this solution involving ‘hard’ mechanical components like multiple pistons to actuate transformation always comes with high energy consumption and complex mechanism. Is there an alternative to this approach? There is a need to further explore a new possibility to address the ‘soft’ elastic architectural components like elastic strings, textile and silicone latexes towards responsive architecture.

Since the ‘soft’ approach of architecture introduced during 60s and 70s, there is not much progress in this experiment and research area of architecture (Negroponte, 1975). However, in order to achieve this architectural vision, further exploration of kinetic mechanism and materiality is needed. Instead of investigation towards the conventional mechanistic approach, this research explores for the use of day-to-day ‘soft’ elastic materials for constructing kinetic and responsive architectural model. The purpose of this investigation takes the position that a more organic versus mechanistic approach to transformable structures, one that capitalises on material properties rather than technologies of connections, provides an opportunity to holistically address both performance and aesthetics in soft responsive architecture (Khan, 2009). Although works by OHL and HRG, such as project Muscle (Oosterhuis, 2003) aimed to demonstrate a soft responsive space, the pneumatic mechanisms are highly power consuming and less consider the potential of elastic memory of the soft structure for passive actuation and surface porosity. On the other hand, the work of Omar Khan: Gravity Screens provide an alternative approach that the surface constructions form results from gravity’s effect on their elastic material patterning. These elastic mutable screens provide possibilities for responsive space that can mutate from circulation corridors to room clusters (Khan, 2009). However, Khan’s work just provides a starting platform for soft responsive architectural idea and it is still unexplored territory to expand this potential of responsive architecture, from ‘hard’, to ‘soft’ approach.

There is a need for low-tech passive design strategies which can generate responsive architectural prototypes without complex mechanical actuators. Thus, this research aims to explore the application of elastic transformable structures, such as exhibited in elastic material systems, for fabricating low-tech and soft responsive spatial modules. The elastic nature of these structures is able to accommodate responsive mechanisms with passive elastic memory while minimising the energy and weight required for actuation. Although the premise of energy and maintenance of this application are concerns in this research, they are not included in the scope of this paper. We argue, as an early hypothesis of this research, that elastic transformable structure can provide designers with a mix of passive and active design strategies for manipulate soft responsive space through the testing of scaled spatial modules. Therefore, this paper will expands the repertoire of responsive architectural design solutions using accessible ‘soft’ component such as elastic materials integrated contemporary digital sensing devices and parametric design tool.
3. Design Process

The purpose of the design process presented in this section is to design elastic transformable structures using the soft approach of manipulating responsive space. The whole process undergoes iterations of physical and digital modeling and fabrication (Figure 1). Through each step of the process, digital data is exchanged between digital and physical models. This process is called form fostering, which bridges the physical and digital through exchanges of digital data (Salim et al., 2011). Parametric models can be associated with real-time data from sensors, which stream data from physical environment, as input to drive the parametric variations in the model (Salim et al., 2011). The parametric model becomes the platform for simulating the behaviours of the elastic transformable structures in the design stage. In general, the design process of elastic transformable structures consists of four factors as listed in subsections 3.1-3.4.

![Diagram](image)

Figure 1. Diagram of design process in four areas towards form fostering.

3.1. MODULES

The first stage of the design requires modular components to be sketched, modeled, and fabricated. They are represented in the form of parametric models as part of experiment process.

3.2. MATERIALITY

It investigates day-to-day, accessible and affordable elastic materials such as rubber band, elastic spring and balloon for physical implementation.

3.3. MECHANISM

Mechanism is looks at the new possibilities of these elastic materials to produce simple mechanisms like joints, actuators and hinges that could become an alternative toolkit compared to conventional mechanical approach.

3.4. ASSEMBLY

The last process is the assembly of the modules in order to achieve transformable structure that displaying elastic properties to respond digital and physical adaptation. The following section discusses form fostering experiments which include two different modules – an Elastic Tetrahedron and adaptive Cube, which are presented to demonstrate some experiments which include the proof of the early concept for elastic transformable structures that are simulated by computational methods for their active and passive modes responding to changes in the environment.

4. Experiments

4.1. THE ELASTIC MODULE

In general, initial idea of the elastic module has the ability to reconfigure itself - to automate physical change to respond, react and adapt. However, this idea needs further exploration especially in terms of energy and weight. When we argue a structure that moves in whole, or in parts, is like a machine. A machine applies energy to do work and energy use is unavoidable. Thus, this section demonstrates two experiments that address this issue by using lightweight orientated and accessible transformable structure with elastic ability to reduce energy and weight that respond to stimuli by changing their form. It aims to test this hypothesis on two modules. The intention of these modules is to propose general directions to be applied to solve the ‘soft’ technical responsive design and energy issues for future works. The Elastic module discussed these issues focus on the new possibilities of elasticity towards soft responsive architecture in the following areas:

- **Elasticity as structure.** The structure of architectural components such as roofs, ceilings and walls can be contracted and expanded to increase flexibility in the use of existing internal or external architectural space.

- **Elasticity as membrane.** A ‘soft’ architectural surface will be explored through harnessing elastomer (elastic polymer) properties for the feasibility of implementation such as passive amorphous building membrane harvesting kinetic energy through wind or sunlight.

- **Elasticity as actuation.** This research and design looks at the new approach of elastic material as actuator for it lightweight and minimising the use of mechanistic joints and piston. For instance, pneumatic air harnessing balloon...
or muscle for global actuation and reduce weight and fiction between part.

4.2. ELASTIC TETRAHEDRON MODULE

4.2.1. Materiality

The module of Elastic Tetrahedron is using accessible elastic string as a primary material and hollow straws fabricate the Elastic Tetrahedron module used as supportive structure.

4.2.2. Mechanism

It is to form an elastic skin for existing building to response proximity through pneumatic air balloons actuation in order to contract and expand parameter to manipulate the interior spatial condition. It is capable of changing various states while force applied and return to the original state if force released (Figure 2). This behaviour provides the opportunities to minimise the energy for local actuation and attempt to develop a low-technological approach to performance structures that possess adaptive and evolutionary personality related to environmental stimuli.

![Figure 2. Elastic Tetrahedron is formed by elastic string and plastic hollow straws for their lightweight and flexible purpose.](image)

4.2.3. Assembly

Furthermore, the combination of individual module will form the Elastic Space-Frame that assembling more complex formation of elastic structures and behaviour in bigger scale. This experiment is mimicking a simple living organism that responds to human interaction to form a responsive Shelter. Therefore, in order to achieve this responsive phenomenon, form fostering techniques composed of sensors and actuators is necessary that roughly simulates the biologic behaviour. Firstly, Grasshopper and Firefly parametric software together with Arduino microcontroller and proximity sensors are used as design tools engaged with this simulation process (Figure 3). Second, the actuation is involved through the use pneumatic air balloon serves as actuator to reduce mechanistic components as mentioned in the section Elasticity as actuation. The goal of this parametric model is to be an elastic skin actively responds to the environment with a series of features like flexibility, unpredictability and non-linear transformation that constitute important facets of what soft responsive architecture should manifest (Figure 4).

![Figure 3. The formation of Elastic Space-Frame (left); The complete module of Shelter (middle); A setup included Arduino microcontroller, relays and breadboard (right).](image)

![Figure 4. The Shelter contracts and expands responds to the proximity of human intervention and population through the pneumatic balloon as elastic actuator.](image)

4.3. ADAPTIVE CUBE MODULE

4.3.1. Materiality

The elastic and adaptation capability of the structure configuration is the initial goal for this Cube module development process. This Cube structure model basically is assembled by two components, a hard hollow aluminium tube and soft elastic string for their lightweight and accessibility, to minimise the energy required for actuation, and be able to be continuously flexed along each joint to connect them together.

4.3.2. Mechanism

Furthermore, the actuation system will be a similar approach to the Elastic
Appendix

Tetrahedron module previously and the pneumatic air balloon is ‘embedded’ in-between two hard and soft materials for actuation in order to adapt various environment conditions. For example, each corner of the Cube structure is embedded a sensor to detect the proximity of object or surface and it extents the length of the structure until it reaches the stable state (Figure 5).

4.3.3. Assembly

The purpose of this experiment is to test the new possibility for assembling automated adaptability in architectural structure for unpredictable calamity events such as earthquakes and floods to minimise damage and provide protection.

In addition, the design of this module opens opportunities to develop of architectural configuration that responds and adapts for uncertainty (Figure 6).

Figure 5. Digital detail of elastic joint that minimise friction (left). Physical Cube structure with sensors and embedded pneumatic air balloon to detect proximity of surface until reaches its stable state (right).

Figure 6. Adaptive Cube structure for unpredictable environment (left). Early stage of physical study of the elasticity (above). Adaptability of the elastic Cube structure (below).

5. Conclusion and future work

The research presented in this paper introduces the new design possibilities of elastic transformable structures that adapt and respond to environment in order to manipulate dynamic reconfigurable space. By using the two elastic modules as experiments to test, the aim of these experiments allow new ideas emerge from performing physical and digital modeling. One of the fundamental investigations for this research is testing the ‘soft’ approach of elastic structures provide alternative to conventional kinetic approach using mechanical components to achieve responsive architecture. We argue that the ‘soft’ and elastic components such as elastic strings, latexes and fabrics demonstrate more appropriate approach for responsive architecture in terms of actuation and deformation as demonstrated in precedent works by ONL and also experiments described in this paper. This approach has been tested by the two responsive parametric models discussed in section 4 and presented the great potential for full-scale implementation in future research. In addition, when applying the computation design tools for the parametric model; the multiple analogue inputs information flows to the responsive algorithm to activate the ‘soft’ elastic actuator for the flexibility, versatility and adaptation in transformable structures. The further development of this research attempts to refine this method and explore the simpler and robust prototypes using elastic, lightweight, form-changing materials as structure in order to achieve the dynamic reconfigurable space for functional environmental aspects. On the other hand, since the property of elastic material makes it problematic as a self-supporting structure, the introduction of embedded pneumatic air muscle as stretchable actuator shown in two modules cause it to stiffen and hence solve certain level of the structural integrity. This design approach is leading to the lightweight structure that allows ‘soft’ elastic architectural skin to transform from thresholds to enclosures. This approach implemented in the process of designing holds significant potential for further exploration towards the form-changing materials as platform of convergence in between transformable structure and responsive space. The form-changing materials such as Ethylene Tetrafluoroethylen (ETFE) embedded with photovoltaic cell, Shape Memory Alloy (SMA) and Electro-Active Polymer (EPA) that respond to environmental and communication stimuli will provide the potential for full scale architectural applicability of elastic transformable structures; and harvesting energy for self-sustainability while reducing mechanistic components. They also enable real time manipulation of elastic capabilities for transformation demonstrated by the two modules that utilise the novel design framework proposed in section 3. This future research is offered a practical methodology for conceiving a responsive architectural envelope system that synthesizes passive design concerns with the feasibility factors of fabrication and construction goals. Thus, in relation to the hypothetical experiment, the purpose is to find a range of possible integration of responsive skins and structures that
can be applied to various architectural components such as facades, walls and roofs in general to complete the actual design solution for the future work. These transformable components will eventually serve as second skins for existing buildings intended to potentially improve the interior and exterior spatial conditions.

References

1 Introduction

In recent approaches, architecture has adopted kinetic motifs as a process of environmental adaptation and responsiveness. We now consider architecture as extendable and changeable in size and shape. This growth is not merely relative to size or location but concerns energy and the transformation of spatial forms and material substances (Boisen 2003). However, this approach often focuses on expensive, intricate kinetic, mechanical, and physical control methodologies for actuation and structural transformation. The reliability and longevity of these systems is the main hurdle to them becoming mainstream in architectural design. The responsive robotic screen of Le Fu’s Mech-21 module in Paris designed by French architect Jean Nouvel in 1987 is a significant precedent of this kind of approach. This paper begins with the question: is there an alternative approach for responsive kinetic architectural skin, which actively and passively responds to environmental stimuli without using complicated mechanical systems? The observation of the behavior and performance of the elastic form-changing material system through the experiments reported in this paper provides the initial idea for this alternative.

‘Kinetic architecture’ was coined by William Sib and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems (Sib and Clark 1973). Two important attributes of kinetic architecture are integrated in the work of Fredrich von Ossowski (1990–2001) and of Christoph Meier (Adler+Centuri Muehr 2011). The two attributes are manipulability and transformability in kinetic building design. These building skins demonstrated the ability to manipulate the interior spatial conditions using a complex mechanical mechanism and a rigid system. However, these solutions involve complex ‘hard’ mechanical components like machine parts to achieve transformation with some heavy metal and high energy consumption. Since this ‘soft’ approach of architecture introduced during the 1930s and 1940s, there has not been much progress in this experiment and research area of architecture (Krepsig 1971). However, in order to achieve this architectural vision, further exploration of kinetic mechanism and materiality is needed.

Instead of investigating towards the conventional mechanical approach, this research explores the use of soft actuators within a robotic material for constructing kinetic and responsive architectural models. This investigation takes the position that a more organic rather than mechanical approach to transformable structures – one that capitalizes on material properties rather than technologies of connection – provides an opportunity to holistically address both performance and aesthetics in soft responsive architecture (Boisen 2003). Since Khos’s ‘Smart Skin’ provides a novel active response in which the surface constructions respond to a load with a significant response in performance and material. These elastic materials provide possibilities for responsive design that can mimic form, work, and perform with the environment.

Khos’s Smart Skin provides a platform for the soft responsive architectural idea and there is still no unexplored territory to expand the potential of responsive architecture, from ‘hard’ to ‘soft’ approach.

Current researchers attempting to address this ‘soft’ approach include Titian of DrimTek and ArchiFabric. While Bahar produced thermographic components actuated by pneumatic muscle to design on space-architecture structures (Drum 2009). Osterlind uses pneumatic muscle as an architectural membrane to respond to various spatial conditions (Osterlind 2011). Their research provided the insightful knowledge of the initial ‘soft’ approach for responsive architecture. However, there is a lack of further research especially in terms of possibility of soft architectural envelopes that respond to environmental and communication inputs.

Building on this success of pneumatic membrane as a responsive kinetic architecture, we argue that there is a need to explore new materials with form-changing ability in current materials science to advance for the concept of ‘soft kinetic’.

2 Soft Kinetic

The concept of ‘soft kinetic’ is a proposal to use the change of elasticity and memory in form-changing materials to affect physical transformation and reshapes in architecture. In contrast to the conventional kinetic systems, ‘soft kinetic’ offers movement and change in response to material properties rather than changes in mechanical components such as actuators and gears. This shift challenges the current notion of kinetic structure relying on external actuation. In ‘soft kinetic’ the transformed surface becomes the actuator itself. This approach, similar to soft mechanical approaches in aerospace engineering but not, as yet, appropriated in architecture. Whereas the transformable skin from heavy structural skin becomes a lightweight structural support and spatial envelope at the same time.

The implementation for the concept of ‘soft kinetic’ prototyping includes 3 areas. Each area sets out to achieve individual goals for the overall design process (Table 1).

<table>
<thead>
<tr>
<th>Areas</th>
<th>Implementation Goal</th>
<th>Material</th>
<th>Flexibility</th>
<th>Transformation</th>
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<tbody>
<tr>
<td>1. Elasticity</td>
<td>Architectural skin</td>
<td>Deformation</td>
<td>Membrane flexibility</td>
<td>Transformation</td>
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<tr>
<td>2. Tension</td>
<td>Structure</td>
<td>Shape memory</td>
<td>Membrane flexibility</td>
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The implementation for the concept of ‘soft kinetic’ prototyping includes includes 3 areas. Each area sets out to achieve individual goals for the overall design process.

2.1 Elasticity

Elasticity relies on the ability to allow a deformableDisabled reference to work or return to its original state. The ability to return ensures that the design is recoverable. Living things achieve very high strength and elastic behaviour with soft and extensible tissues, and are able to carry large and small masses. Soft biological tissues are very strong and achieve flexibility and adaptability with simple fibre membranes, arranged in complicated hierarchies. One possible way of approaching the design and production of the responsive structure is to examine the characteristics of elastic materials and how they work, and the use of chemical bonds between the starchy material on the material of Stein and Allegre (1954).

A critical characteristic of elastic materials is that they deform in a recoverable manner when energy is applied to them. This potential can create a new way of looking at architectural skin in terms of flexibility, adaptability, and deformation. Despite this obvious potential, such material systems have not found widespread application in architecture, and there are many questions of stability and lack of experience element and Menges (2000). Thus, the research presented here further investigates the understanding of the performance, capacities, and behaviour toward the elastic architectural skin within this material framework of ‘soft kinetic’.

2.2 Tension

The tensional structural approach replaces the struts between mechanical joints and achieves a lightweight structure. Tensional structures are particularly interesting when considering the development of responsive systems. Due to the interdependence of all the elements, a slight change in any of these parameters can result in a significant form transformation (Khos and Zhao 2007). Thus, this structural implementation becomes part of the soft responsive kinetic system for its flexibility and lightweight components.

2.3 Form-changing Materials

Ordinary metal alloys have an internal structure which is not altered by small temperature or chemical changes. Electromagnetic fields causing the shape of the metal to deform, and this makes it easier to bend than an external force to apply. The molecular form of the metal is not normally altered by heating. However, from changing materials such as shape memory alloys (SMAs) are able to change shape when heated by electrical current. SMAs expand by as much 10% when heated and cooled (Figure 1). The typical expansion of SMA in a ribbon form is graphed in Figure 2. When SMA is below the transformation temperature (about 60 degrees) thermal strain on an elongated and retracted form, but if heated it contracts and returns to the memorized form. This process causes a dynamic range of movement, in the way that

- **Figure 1**: Illustration of a SMA wire heated to 90°C. The wire expands by 2.5% when heated and cooled. The SMA wire is then cooled to its memorized form, then reheated to 90°C and returns to its memorized form. This process causes a dynamic range of movement, in the way that

- **Figure 2**: Illustration of a SMA wire heated to 90°C. The wire expands by 2.5% when heated and cooled. The SMA wire is then cooled to its memorized form, then reheated to 90°C and returns to its memorized form. This process causes a dynamic range of movement, in the way that

- **Figure 3**: Illustration of a SMA wire heated to 90°C. The wire expands by 2.5% when heated and cooled. The SMA wire is then cooled to its memorized form, then reheated to 90°C and returns to its memorized form. This process causes a dynamic range of movement, in the way that

**Table 1**: Areas of interest to achieve individual goals for the overall design process.

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Appendix

This form-changing process produces expansion and contraction which can be harnessed for actuation of the whole skin system. However, there has been little investigation into the use of these materials as an actuator for structural adaptation and transformation in architectural contexts. While we discuss the responsive structural component of architectural skins, a certain degree of actuation for performance often requires a complex and high-energy consumption mechanical system.

We propose that the form-changing material embedded in the elastic lamellar structural component is an alternative for less energy and simpler actuation to control and regulate the behavior of responsive architectural skins. This material that operates inside the lamellar system becomes a new kind of ‘structure’. It can actuate the elastic component exposed to the ambient environment to be functionally adaptable. This ‘soft’ actuation can create multiple states of stability in terms of pattern for architectural skins and is more economical and simple than conventional mechanical approaches. Figure 3 shows four potential profiles for ‘soft’ actuation based on the process of Depression and Compression in specific parts of the SKIN-wire. While profiles one and two show the potential for the pull and push actuation, profiles three and four function as the spring system that can actuate greater distance and force. (Figure 3). They demonstrate that an alternative actuation system can be embedded in the overall lamellar structure discussed in subsection 2.2 for various transformation purposes.

3 Designing Prototype System Module

This paper reports on work to investigate how the interior and exterior architectural skins can move and interact while maintaining complex morphological components. This investigation will demonstrate a series of early physical and digital prototypes experiments using form-changing materials to control and actuate elastic transformable surface structures and surface modes. This prototype system, ‘Curlet’, is a design module for integration of skin and structure intended to modify the interior spatial conditions of existing buildings to allow us to attain a representation of the concept of ‘soft skins’ discussed in section 2.1.

The assembly of ‘Curlet’ includes a series of modular components that form the overall design framework. In general, the design framework of ‘Curlet’ consists of four factors as listed in subsections 3.1-3.4.

3.1 Skeleton

The main intention of ‘Curlet’ is to fabricate a simple and lightweight skeleton. It is to minimize the complicated and heavy mechanisms such as joints and actuators in order to produce a highly flexible structure. The interlaminated modules form a lamellar space frame (Figure 4). The integration of lightweight components such as MRF, viscoelastic and flexible string makes the physical module easy to construct (Figure 5).

3.2 Skin

Using the characteristics of the human skin towards the design of an architectural surface and envelope such as a building skin or roof, became one of the core research areas of responsive architecture. This research is not new; however, this approach still holds a lot of potential to develop responsive architectural skins especially in terms of lightweight and passive design implementation.

The multi-layer skin of ‘Curlet’ explores the responsiveness to the porosity performance for the existing building facades using elastic, lightweight materials. The elastic material used for this experiment is foam and it forms the basic membrane non-load bearing surface for architectural envelope intervention. The initial geometry of the membrane is inspired by the performance of the skin, which allows various porosity patterns (Figure 6). The eye-like sources in the geometry are determined by their relative curvature on the responsive undulating surfaces and actuated by SKIN-wire discussed in subsection 2.3.

3.3 Transformation

The prototype system includes a study of the dynamic properties of the form-changing materials used to materialize the form ‘soft skins’. This introduces two simple types of physical material transformation: Contraction and Expansion. This soft kinetic transformation allows the action to take place in any three-axis configuration resulting in complicated real-time performance of the transformable skins. However, the homomorphic consistency of the architectural elevation and skin provide the motivations and limitations to develop the skin surface transformation in three different ways:

- Microstructural transformation, the global surface curvature of ‘Curlet’ is modifiable to allow contraction and expansion while maintaining the continuous tessellation of any undulating or flat surfaces. It can respond to various functional drivers (Figure 7).

- Patterned transformation, the changing form of the ‘soft’ opening on the surface facilitates change between multiple possible visual patterns. This mimics the natural visual effect of various appearances of the skin, therefore the existing building envelopes are in constant flux as part of its ‘interaction’ with the environment and occupants interacting with it (Figure 8).

- Pluvial transformation, the transparency of the surface is generated by the individual ‘soft’ opening that responds to sunlight penetration and shadows created. This transformation improves the spatial conditions of interior and exterior spaces through the dynamic communication between the two (Figure 9).

3.4 Responsiveness

A parametric design tool is integrated to construct a full scale responsive digital simulation. The first digital prototype system is applied to an existing building as the

![Figure 1: Initial Prototype Module](image1)

![Figure 2: Final Prototype Module](image2)

![Figure 3: Diagram of 'Curlet' System](image3)

![Figure 4: Diagram of 'Curlet' System](image4)

![Figure 5: Final Prototype Module](image5)

![Figure 6: Final Prototype Module](image6)

![Figure 7: Final Prototype Module](image7)

![Figure 8: Final Prototype Module](image8)

![Figure 9: Final Prototype Module](image9)
Appendix

4 Application

There are currently two applications under investigation. The first application is a response to specific aspects of environmental conditions, such as airflow and shading response to changing light conditions. The second application is as an analogue media skin for visual communication, which can also be responsive to ambient conditions or live data streaming. These two applications are termed Comfort and Cosmetics.

4.1 Comfort

"Comfort" applies the application Comfort using the kinetic undulating surface to regulate shading and airflow control to improve the comfort level of existing spatial conditions. This function embeds a data input scheme and forms fostering set-up to test the potential of the initial responsive kinetic system (Figure 11).

The morphological transformation of the overall surface responds to the direction of the sun to achieve maximum natural light penetration during winter and minimum heat gain during summer for optimal comfort conditions within the existing space. This process embodies in an empirical experiment, the aspect of Comfort using a photoresistor and the sunlight rerouting the path of sunlight towards the digital and physical responsive surface model in various morphological states for optimal performance (Figure 12).

Another intention of the Comfort application is to improve the spatial condition of the existing inoperable designed building. For instance, by creating a "transition" space in between "second skin" and the existing roof structure, a new private solar area is formed. The spatial quality for the occupants of this new roof area is manipulated by the transformation of "second skin" in terms of ventilation and light penetration. This "second skin" also provides shelter and protection in this context.

4.2 Cosmetics

The other application of the "Curtain" serves as the analogue media skin to display binary images and motion graphics using the perforation process of the soft surface composed by the "soft"-labeled permeable surfaces discussed in subsection 3.3. This cosmetic intervention creates a new layer of communication between existing building skin and the surrounding urban fabric.

Figure 8. "Second skin" that creates a chiroptic and visual envelope. Therefore, in order to achieve this responsive phenomenon, a form following technique using sensors and actuators is necessary that roughly simulates the biologic behaviour (Baha, Moller and Bury 2011). First, Grasshopper and FormIt parametric software together with Arduino microcontrollers, light sensors and potentiometers, are used as design tools engaged with this simulation process (Figure 10). Second, the actuator is involved through the use of an SMA spring that serves as an actuator to reduce mechanical components. The goal of the parametric model is to be an elastic tensile skin actively responding to the environment with a series of kinetics like flexibility, unpredictability and non-linear transformation that constitute important facets of what soft responsive architecture should embody.

5 Conclusions and Future Work

From the early experiments of the "Curtain" models, we conclude there is a place for full-scale application of this "soft kinetic" responsive spatial environment, and it has the potential to be developed further in terms of the reciprocal electronic between existing building fabric and new architectural skin intervention.

It also revealed some of the possibilities for implementing the soft responsive kinetic system in physically responsive architectural skins in future research. This system provides a solution for a shift from hard-to-soft material/pattern approaches to the architectural intervention. It also develops an advantageous method for studying soft responsive architectural skins that will improve the quality for our future experiments. Instead of investing money or composite materials, we move to exploiting existing materials that have been applied in other disciplines but are new in the context of this architectural research.

This research investigates new possibilities of the softness and elasticity in terms of changing material systems for building skins that respond to various environmental conditions. The design of the soft responsive skin challenges the traditional "hard" approach of the glass and steel building envelopes. Building envelopes constructed from soft and elastic material seem "parameteric" because architecture is built, whereas soft material appear to be without structural integrity. However, advances in soft material technology such as Diphenyl Tetrafluoromethylene (DPTF), Polyhedral Polyhedral (PDMS), Electro-Achieve Polymer (EAP), and Carbon fibers have revealed their relevance to architecture, especially in structural textile technology. Textile structures have become more popular as alternatives for today’s architecture. Examples are inflatable membranes, braided cables and metal mesh. This soft structural system is full of potential for further development of textile responsive architectural skins and envelopes in terms of climatic and visual control. The textile-like behaviour, with wire, or no mechanical components needed for actuation mean that it reduces energy consumption as well. The textile structural approach then will be part of our future research into experiments for architectural performing skins while existing building contexts. This future research will include the realtime analysis of textile architectural skins in terms of thermal control, solar onology and global geometry with live connections between the physical and the digital model.
Designing Architectural Morphing Skins with Elastic Modular Systems

Chin Koi Khoo, Flora Salim and Jane Burry

References


Designing Architectural Morphing Skins with Elastic Modular Systems
Chen Koi Khoo, Fiona Salim and Jane Berry

Abstract
This paper discusses the issues of designing architectural skins that can be physically morphed to adapt to changing needs. To achieve this architectural vision, designers have focused on developing mechanical joints, components, and systems for actuation and kinetic transformation. However, the unexplored approach of using lightweight elastic form-changing materials provides an opportunity for designing responsive architectural skins and skeletons with fewer mechanical operations. This research aims to develop elastic modular systems that can be applied as a second skin or brise-soleil to existing buildings. The use of the second skin has the potential to allow existing buildings to perform better in various climatic conditions and to provide a visually compelling skin. This approach is evaluated through three design experiments with prototypes, namely Tent, Curtain and Blind, to serve two fundamental purposes: Comfort and Communication. These experimental prototypes explore the use of digital and physical computation embedded in form-changing materials to design architectural morphing skins that manipulate sunlight and act as responsive shading devices.

1. RESPONSIVE KINETIC SKINS
The term “Responsive architecture” was coined by Nicholas Negroponte in the mid-seventies when spatial design problems were beginning to be explored through digital technologies [1]. In recent examples, responsive and kinetic architectural design can primarily be found in building envelopes or skins. These approaches to designing architectural skins comprise the adoption of kinetic mechanisms for environmental adaptation and responsiveness. The term “Kinetic architecture” was introduced by William Zuck and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems [2]. This concept differs from responsive architecture since it investigates a building’s capacity of motion with less consideration of response to environmental conditions. Kinetic architecture often focuses on expensive and complicated kinetic and mechanical systems as well as physical control mechanisms for actuation and structural transformations. The responsive kinetic skin of L’Institut du Monde Arabe in Paris designed by French architect Jean Nouvel in 1987 is a significant precedent, which is known for its mechanical failure. A decade ago, d’Eco attempted to integrate responsiveness and kinetic skins to create and investigate responsive architectural skins and installations such as the Auga HypoSurface [3], by using high-tech mechanical solutions, such as multiple piston components to achieve transformation [4]. However, solutions involving such mechanical components require designers to deal with the high energy costs and complex mechanisms in the Auga HypoSurface, piston components were found to be prone to fatigue failure, causing gasket leakage from the piston [4]. Such a “hard” mechanical approach often produces brittle and vulnerable kinetic systems. Thus, reliability and longevity factors of the system are the main challenges for kinetic architectural skins to become a more widely adopted approach in architectural design. How to design kinetic architectural skins with fewer mechanical operations? New “soft” architectural components like elastic silicone polymer and other active form-changing materials offer new possibilities for designing kinetic, responsive skins. In this paper, we describe a “soft” approach, which integrates digital and physical computation with elastic materials to embed responsive and kinetic morphing abilities into architectural skins. This “soft” approach has the potential to address the brittleness of the hard mechanical components. Although “soft” architecture is a concept introduced during 60s and 70s, there is still limited progress in this domain [5]. In order to pursue this vision, further exploration with kinetic materials is needed. This research explores the use of “soft” elastic form-changing materials for constructing kinetic and responsive architectural envelopes. The purpose of this investigation is to address performance and aesthetics demands in designing soft responsive architectural skins. We propose that a more organic approach with less mechanical operations can harness material properties
to produce transformations on architectural morphing skins. Omar Khan’s Gravity Screens provides a novel active response where surface form results from gravity’s effect on the elastic material patterning. These elastic mutable screens provide possibilities for responsive space that can mutate from circulation corridors to room clusters [6]. However, Khan’s work just provides a starting platform for the soft responsive architectural idea and there is still unexplored territory to expand from the hard to the soft approach.

Current researchers attempting to address this ‘soft’ approach include Tristan d’Esteve Stier and Kees Oosterhuis with the use of pneumatic muscles in their projects. Stier designed a responsive architectural structure by applying tensile (or tensional integrity) components actuated by pneumatic muscles [7]. Oosterhuis used pneumatic muscle as an architectural membrane to respond to various spatial conditions [8]. The members in a tensile structure are segregated into those which carry only compressive and those which carry only tensile forces in a way that obviates the need for direct contact between adjacent compressive members, giving them the appearance of floating in space. The recently completed Media-ICT building designed by Cloud 9 Architects in Barcelona is an example of a highly energy efficient building, achieved through the implementation of the ‘soft’ approach to kinetic architectural skins. The complex façade made of ETFE (Ethylene Tetrafluoroethylene) presents the interior by moderating direct sunlight in a way that is responsive to changing conditions [9]. The project Scope015 is taking another approach using kinetic membranes with EAPs (electro active polymers) and ‘parametric parament’, prototypes of robotically fabricated room-dividers [10]. Beyond the described examples, work that investigates the porosity and permeability of ‘soft’ architectural envelopes that respond to environmental and communication inputs is largely unknown at this stage.

In this study, we are using passive and active design strategies to create kinetic prototypes that meet the need for complex mechanical actuations as the basis of soft kinetic systems. All the experimental models that have been prototyped in smaller scale through this study combine material explorations, digital and physical computing techniques, as discussed in section 3. The main idea behind deploying soft kinetic systems for designing morphing skins is the integration of an exoskeleton structure, and a surface as the actual actuator. Hence, soft kinetic systems do not require mechanical joints, parts, or motors. The kinetic actuation also takes place in the overall modular system with the use of form-changing architectural panels and little use of mechanical components. This concept is inspired by the soft mechanical approaches in aerospace engineering especially morphing wing technology [11]. In the field of engineering, the word morphing is used when referring to continuous shape change i.e. no discrete parts are moved relative to each other but one entity deforms upon actuation [12]. For example, on an aircraft wing this could mean that a hinged flap would be replaced by a structure that could transform its surface area and camber without opening gaps in and between itself and the main wing [13]. This fascinating concept of morphing skin as an emerging aerospace technology has inspired aircraft wing design but it has remained unexplored territory in terms of architectural morphing skins.

The study presented in this paper seeks to develop prototypes of architectural morphing skins, since the elastic nature of these structures is able to accommodate responsive mechanisms with passive elastic memory while minimising the energy use and the cost of maintenance, these are not part of the scope of this paper. We argue, as an early hypothesis, that elastic modular systems can provide designers with a rich of passive and active design strategies to manipulate architectural morphing skins. We test this approach through design experiments with small-scale models. The paper describes and discusses the development of a new repertoire of responsive architectural morphing skins ideas using accessible ‘soft’ components, such as elastic materials integrated with contemporary sensor devices. These ideas are developed using parametric design tools.

2. PROPOSAL: ELASTIC MODULAR SYSTEMS

Modular systems are not uncommon in architectural design. Their use has largely been concerned with reducing cost and the materials needed to construct full-scale architecture. In contrast to existing kinetic systems, for instance, the Argos Hypersurface and L’Institut du Monde Arabe projects. Elastic Modular System (EMS) offers movement and change in response to material properties rather than changes in mechanical components such as actuators motors and gears based on the concept of soft kinetic systems as discussed in section 1. This shift challenges the notion of kinetic structure relying on external actuation. This approach, although similar to soft mechanical approaches in aerospace engineering such as the morphing wing design, has not liberated the transformable skin from the requirements of a sturdy structure [14]. Modular components of the skin act as a lightweight structural support and a spatial envelope at the same time.

The purpose of the development process presented in this section is to design architectural morphing skins using the soft approach in a simple yet efficient way. The design process requires iterations of physical and digital modelling, electronic prototyping and fabrication. Through each stage of the development process, Skeleton, Skin, Transformative and Adaptable the data is exchanged between digital and physical models (Figure 1).

The four stages for the process of designing EMS as discussed in this paper include:

Appendix
1. Skeleton - the first stage of the design requires modular components of skeleton to be sketched, modeled, and fabricated. They are represented in the form of parametric digital and physical tensity modules (tetrahedra) as part of experimentation process.

2. Skin - the second stage investigates accessible elastic and form-changing materials such as silicone rubber, nylon coated stainless steel tension and SMPs (shape memory alloys) for physical implementation.

3. Transformation - the third stage focuses on the new possibilities of the elastic and form-changing materials to emulate simple transformable mechanisms like joints, actuators and hinges that could become an alternative toolkit to conventional mechanical components.

4. Adaptability - the last stage of the system discusses the adaptability of models in order to achieve morphing skins that display elastic properties able to respond to digital and physical stimuli, and facilitate a feedback loop to the system.

The overall design process conforms to a Sensing-Analyse-Actuation (SAA) system diagram that is general to the responsive set-up within the EMS in all three of the design experiments that are discussed in subsections 3.1-3.3.

Firstly, the sensors receive the analogue data that is sent to an Arduino microcontroller with Arduino code for processing. Then, the Finch plug-in embedded in the Grasshopper program reads the processed data and produces the values that activate the form-changing materials for actuation. This contraction and expansion of the actuated form-changing materials produce kinetic movement in the models as they respond to the external stimuli (Figure 2).

Virtual parametric models can be associated with real time data from sensors, which stream data from the physical environment, as input to drive the parametric variations in the model [15]. The Sensing-Analyze-Actuation process is a way of working that has been called form fostering, which enables interpolation and integration of digital, physical modeling and computing through associative design [15]. Form fostering facilitates the parametric model to be the platform for simulating the behaviors of the elastic modular systems in the early design stage.

The process of designing EMS requires research to be performed in three distinct but overlapping areas: elasticity, tenacity, and form-changing materials.

Elasticity refers to the ability of a body that has undergone deformation caused by applying force to return to its original shape once the distorting force is removed [14]. Elasticity is a result of the chemical bonds between the atoms that a material is made of [17]. During deformation, potential energy is stored within the material which activates the acceleration back to its original state. This offers potential new forms of flexibility, adaptability and deformation using the memory effect in architectural skins. Despite this obvious potential, such material systems have not found widespread application as architects have tended to shy away, cowed by questions of liability and lack of precedent [18].

The term tenacity coined by Buckminster Fuller by combining the words tensional and integrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such way that the compressed members do not touch each other and the pre-stressed tensioned members delineate the system spatially [18]. Thus, the tenacity structural approach reduces the friction between mechanical joints and achieves a lightweight structure which is particularly interesting when considering the development of responsive systems. Due to the interdependent nature of all the compressive elements, a slight change in any of their parameters can result in a significant form transformation [19].
For these reasons the tensegrity structure was chosen as part of the EMS and for its flexibility and lightweight components.

There are several form-changing materials, such as those shown in Table 1. However, there has been little investigation into the use of these materials as an actuator for structural adaptation and transformation in the architectural context. In this paper, an experiment with form-changing materials will be presented in subsection 3.3.

<table>
<thead>
<tr>
<th>Form-changing materials</th>
<th>Commercial</th>
<th>Electrical</th>
<th>Actuation</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensegrity strut</td>
<td>Yes</td>
<td>Coil</td>
<td>Strong</td>
<td>Large</td>
</tr>
<tr>
<td>Shape memory polymer</td>
<td>No</td>
<td>Yes</td>
<td>Weak</td>
<td>Large</td>
</tr>
<tr>
<td>Elastic polymer</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Large</td>
</tr>
<tr>
<td>Paraffin wax</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Small</td>
</tr>
<tr>
<td>Electroactive shape</td>
<td>Yes</td>
<td>No</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Bone-electroactive polymer</td>
<td>No</td>
<td>Yes</td>
<td>Strong</td>
<td>Large</td>
</tr>
</tbody>
</table>

The concept of EMS is explored through implementation in three different prototyped design experiments: Tent, Curtain and Bed. These modular design experiments served as the methods of inquiry. They focus on the research areas: elasticity, tensegrity, and form-changing materials. Each experiment is concerned to achieve individual goals for the overall design process as set out in Table 2.

<table>
<thead>
<tr>
<th>Design experiments</th>
<th>Goal</th>
<th>Research areas</th>
<th>Implementation focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tent</td>
<td>Flexibility with memory</td>
<td>Structural, Architectural skin</td>
<td></td>
</tr>
<tr>
<td>Curtain</td>
<td>Transformation</td>
<td>Tensegrity, Structure</td>
<td></td>
</tr>
<tr>
<td>Bed</td>
<td>Actuation</td>
<td>Form-changing materials, Actuator</td>
<td></td>
</tr>
</tbody>
</table>

These design experiments are conceived as analogue proof of concept for the early architectural morphing skins effects already simulated by computational methods. These early concept models explore active and passive modes of response to changes in the environment. They consider both environmental conflict and use of responsive skins for communication.

3. DESIGNING ARCHITECTURAL MORPHING SKINS

This section describes the design process for three design experiments using the Elastic Modular System (EMS). The Sensing-Analysis-Actuation (SAA) process discussed in section 2 is integral to these experiments. Elasticity, Tensegrity, and Form-changing materials in the context of designing responsive morphing skins.

The first experiment explores the area of Elasticity by using an assembly of passive tetrahedral elastic modules to represent the morphing architectural skin. It investigates the performance, capacities and behaviour of this system under external actuation. A second and subsequent experiment develops the elastic modules of the first prototype to minimize the number of components and reduce the weight of the module in the assembly of the Tensegrity exoskeleton of the morphing skin. The third experiment was an implementation of form-changing materials to become the actuator as well as the skeletal structure of the morphing skin. These exploratory design experiments test the hypothesis discussed at the beginning of this paper that elastic modular systems can provide designers with a mix of passive and active design strategies to manipulate architectural morphing skins.

3.1. Design Experiment 1: Elasticity-Tent

Tent is a responsive elastic architectural skin assembled by series of elastic tetrahedral modules. It contracts and expands without mechanical components such as motors or plenums. It is a holistic skin-like skin which changes shape to meet various needs and environmental conditions.

The initial idea of the elastic experiment was to demonstrate the ability of the structure to reconfigure itself to allow physical change to respond and adapt to inputs. However, this idea needs further exploration especially in terms of energy and weight. This section describes how the experiment tests addresses the issues of energy and weight by using lightweight, simple elastically-transformable modules which respond to stimuli by changing their form. It aims to test on one module: elastic tetrahedron; the central hypothesis that elastic modular systems can provide designers with mix of passive and active design strategies to manipulate architectural morphing skins (Figure 3).

The intention of this experiment was to discover general directions to apply to future "soft" solutions to responsive design and weight issues. The elastic experiment focused on the new possibilities of elasticity for architectural morphing skins in the following areas:

- Elasticity as structure: The structural, architectural components for architectural skins that can expand and contract.

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- Elasticity as membrane: A ‘soft’ architectural surface will be explored through harnessing elastic polymer properties. This tests aspects of the feasibility of implementing passive morphing building membranes that respond to external environmental stimuli.
- Elasticity as actuation: The novel application of elastic material as an actuator is seek for its light weight and for the possible substitution for the use of mechanistic joints and passive. An example is pneumatic balloons or muscles for global actuation that reduce weight and friction between parts compared to equivalent mechanical systems.

These were the lines of inquiry for the experiment. First, the assembly skeleton components of tent included using accessible, basic materials such as elastic string as a primary material and hollow spools to fabricate the elastic tetrahedron module used in supportive and expandable structure (Figure 4). Second, the skin of Tents is the inflatable elastic polymer in ‘balloon’ form that serves as actuator and skin simultaneously. The approach created novel effects that mimic ‘organic’ movement and behaviour. The skin itself is elastic and expandable and achieves a high degree of flexibility and adaptability.

The third area used the pneumatic actuation through the skin to trigger the general morphological transformation of the Tent. Through expansion and contraction, the combination of individual tetrahedral modules forming the Elastic Space-Frame as skeleton that performs as contract and expandable skeletons.

3.2. Design Experiment 2: Tensagility-Curtain

Experiment 1 demonstrated the ‘organic’ kinetic behaviour of a modular elastic tetrahedral structure. It also started to integrate the actuator and skin, engendering a new idea for implementing them as one entity. Thus, Design Experiment 2, Curtain was conceived. This section reports on work to investigate how architectural skins can move and morph while minimizing intricate mechanical components. This investigation will demonstrate the
early physical and digital modular experiment focusing on actuated tensile structure. Tensile structure is a design proposal for integration of skin and structure as a skin-on-laid intended to improve the interior spatial conditions of existing buildings and to allow us to attain a representation of the concept of tensile structure discussed in section 2. The assembly of Curtain included a series of modular tetrahedral components that form the overall design framework. In general, the design framework of Curtain consists of four parts as listed in section 2. The main structural intention of Curtain is to fabricate a simple, flexible and lightweight skeleton. It is to eliminate or minimise the complicated and heavy mechanisms such as joints and actuators in order to produce a highly flexible structure. The tetrahedral modules form a tensegrity space frame (Figure 7). The integration of lightweight components such as MDF board and fishing string makes the physical model easy to construct (Figure 8).

![Figure 7: Simple 'inverted' tetrahedral module formed the basic building blocks of the skeleton of the Curtain.]

![Figure 8: Physical tetrahedral modules formed the basic tensegrity space frame as skeleton of the Curtain and actuated by SMA spring through electric stimulator.]

Curtain includes a study of the dynamic properties of the form-changing materials used to materialise the concept (SMA). These materials introduce a simple type of physical material transformation: expansion and contraction. This transformation allows the actuation to take place in any three-dimension configuration resulting in complicated morphing performances of the transformable tensile structure skeleton and skin. The constraints on the movement and change of this continuous morphing skin provides the possibilities and limitations to the morphological transformation. The global surface curvature of Curtain is modifiable. It allows contraction and expansion while it maintains the continuous topology of any undulations or flat surfaces. It can respond to various functional drivers to manipulate sun shading and shadow casting (Figure 9).

![Figure 9: The contraction and expansion of foam skin actuated by the tensile structure and SMA spring.]

![Figure 10: Folds represent movement in morphological transformation bending and twisting in digital simulation process. By mimicking physical implementation of the tensile modules in act Curtain's response to the direction of light.]

A parametric design tool is used to construct a full-scale responsive digital simulation. In the digital simulation, the prototype system is applied to an existing building as the 'Second Skin' that creates a climatic envelope for comfort purposes. The Sensor-Analysis-Actuation (SAA) model with sensors and actuators is used to make the phenomenon responsive. First, Grasshopper and Fleye parametric software together with an Arduino microcontroller, photo resistors and potentiometers, are used as design tools engaged with this simulation process (Figure 11). Second, an SMA spring serves as an actuator. The goal of this parametric model is to be an elastic tensile skin actively responding to the environment with a series of features like flexibility, unpredictability and non-linear transformation that

Appendix
constuct important facets of what architectural morphing skins might ideally manifest.

The morphological transformation of the overall surface responds to the direction of the sun to achieve maximum natural light penetration during winter and minimum heat gain during summer. It serves the goal of optimal comfort conditions within the existing space. The initial empirical experiment used a photoresistor and sunlight to mimic the path of sunlight. This process embodies the essence of Comfort: the digital and physical responsive surface models are stimulated to adopt various morphological states for optimal performance as a sunlight modulator (Figure 12).

3.3 Design Experiment 3: Form-changing materials-Blind

The initial success of implementing the sensitivity skeleton in Design Experiment 2 led to reflection followed by further investigation of kinetic materials for a stable skin surface. In this third design experiment, called Blind, we extend the skin to exhibit Visual Patterns and Communication. As a result of comparing multiple form-changing materials (Table 1), we found that shape memory alloy (SMA) is the most suitable material for designing elastic modular system (EMS). Although EMPs (Electro Active Polymers) have been used widely in robotic research, EAP-based actuators are still exhibiting low force below their efficiency limits, are not robust, and are not available as commercial materials for practical application in this type of experiment [20]. Furthermore, they require a high activation field (150V/cm) close to the breakdown level. Since the 1960s, SMAs have been the most accessible form-changing materials in the present market, and there are many applications in the aerospace and automobile sector [1]. They are commonly used in a wire or spring form that contracts in length when heat is applied, the heating can be done directly via electricity to give electrical actuation. SMAs expand by as much as 8% when heated and cooled. The typical expansion of SMA is in relation to temperature is graphed in Figure 4. When the SMA is below the transform temperature (60 degrees) the material takes on an "alloyed" and neutral form, but if heated it contracts and returns to the "tempered" form. This process creates a dynamic range in the way that the SMA wire expands and contracts for various state changes (Figure 13).

Ordinary metal alloys have an internal structure that is not altered by small temperature or electric current changes. Electrical stimuli create heat, causing the atoms of the metal to vibrate faster and making it easier to bend when an external force is applied. The molecular form of the metal is not normally altered by heating. However, form-changing materials such as SMAs (shape memory alloys) are by nature, dynamic and deformation occurs under electrical stimuli in this experiment using 5V for a 3 amp current (Figure 14). There are two stable crystalline states in their structures. When a temperature change occurs, it triggers from one crystalline form to the other. Thus, SMAs are selected to implement in this research and develop further because of their accessibility, reliability and low electric current usage. This form-changing process produces expansion and contraction which can be harnessed for actuation of the whole kinetic system.
Figure 15 shows four potential profiles for 'soft' actuation based on the process of Expansion and Contraction in specific parts of the SMA wire (Figure 15). While profile one and two show the potential for the pull and push actuation, profile three and four function as the spring system that can actuate greater distance and force. They demonstrate that an alternative actuation system can be embedded in the overall tensegrity structure. Profiles one and four are selected for use to actuate the transformation of Bird. They are chosen for their robustness and stronger pulling force (Figure 16).

The materials used for assembling the skeleton of Bird included ABS (Acrylonitrile Butadiene Styrene) as the primary lightweight, strong material for a 'reduced' version of the tensegrity skeleton. This was integrated with stainless steel wire as the tension component. The tensegrity tetrahedral module was fabricated with reduced components to be assembled as the exoskeleton structure (Figure 17).

With the multilayer skin of Bird, we explored the responsiveness to light through changing porosity (Figure 18). The elastic material used for this experiment is silicone rubber and it forms the basic non-load bearing membrane surface for the architectural envelope. The skin surface of Bird is fabricated using silicone rubber because of its heat resistance and elastic capacity (Figure 19).
In general, silicone rubber offers good resistance to extreme temperatures from -55 to 300 degrees Celsius. Under extreme temperatures, the properties in terms of the elongation, compression, tear and tensile strength are far superior to conventional soft and elastic materials. Conventional organic rubber has a carbon backbone which can make it susceptible to UV heat, ozone and other aging factors that silicone rubber can withstand even in many extreme environments. Thus, this high-heat-resistance material property makes silicone rubber a suitable material to integrate with SMA to form morphing skin, addressing elasticity and actuation respectively (Figure 20). In addition, the skin itself serves as part of the actuation as well as structural component of the overall modular tensegrity system (Figure 21).

The focused transformation of blind is named pneumatic transformation; the changing form of the ‘blind’ opening on the surface facilitates change between multiple possible visual patterns. This real-time analogue media effect controls the appearance of the skin surface. The new building envelope in the form of a dialogic interface with the environment and occupant interacting with it. This effect, applied to provide the transparence of the surface is generated by the individual porous openings that respond to sunlight penetration and shades cast (Figure 22). This transformation is designed to improve the spatial conditions of interior and exterior spaces through the dynamic communication between the two.

The initial geometry of the membrane porosity or openings is inspired by the performance of the eye. This analogy of an ‘eye-like’ permeable aperture functioned as a skin muscle mechanism in the eye which allows various changing porous patterns on the skin (Figure 23). The ‘eye-likes’ apertures in the geometry are determined by their relative curvatures on the responsive undulating silicone rubber surfaces and actuated by SMA wires and springs. The application of the adaptability of blind is in an analogous media screen for visual communication which can also be responsive to ambient conditions or live data streaming. It addresses the application termed Communication.
Since blind serves as the analogue media skin, it performs communicative adaptability to display binary images and motion graphics through the perforation process of the soft surface composed by the 'eyelid' permeable apertures. This visual intervention demonstrated in digital simulation creates a new layer of communication between the existing building skin and the surrounding urban fabric through its constant variable porosity activated by the input of real-time information (Figure 24).

The shadow cast into the existing interior space under the blind screen provides a morphing penetrated atmosphere that suggests a continued relationship between exterior and interior by shadow casting and modulation of the direct sunlight (Figure 25). This is an alternative approach to the conventional digital media screen, the design of which generally lacks the consideration of its effect on the interior condition especially in porosity and permeability.

4. CONCLUSION AND FUTURE WORKS

Architecture is built to last. Hence, the idea of having building envelopes constructed from soft and elastic materials does not seem intuitively to be feasible since soft materials do not generally possess robust structural properties. However, advances in soft, and form-changing materials technology have revealed their relevance to architecture, especially when integrated with other composite materials such as those used in the aerospace industry, for example: Kevlar and carbon fibre. Current technology on aircraft morphing wing design indicates some of the potential of these materials to be implemented in architectural morphing skins. It is timely to investigate how smart materials can now be applied to designing architectural morphing skins.

This research investigates new possibilities for applying 'intensity' in modular systems for architectural skins that respond to various environmental conditions. It does this through a series of design experiments using kinetic models that combine digital and analogue techniques. In this paper, the evaluation of the three design experiments, Tent, Curtain and Blind, reveal the possibility for elastic modular systems to be applied to architectural morphing skins. The design experiments demonstrate the opportunities for a shift from a hard to a soft material and mechanical design approach. They also develop a method to study soft responsive architectural morphing skins from different perspectives in order to improve the quality of future experiments. One of the related technologies presented in this paper is the elastic modular system using the passive and active form-changing materials, silicone rubber and shape memory alloys. Here they are applied in the novel context of architectural morphing skins. These design experiments while in an early stage, extend the current repertoires of kinetic building to introduce alternative design methods. They point to the potential for full-scale architectural applications.

Future work will include further experiments that explore the scalability of the elastic modular system and implement it in an actual site context. This approach aims to develop a novel design method and a feasibility study for designing full-scale responsive architectural morphing skins with current technologies. Further investigation also aims to design volatile form-changing materials in synthetic composites which have kinetic matter embedded and computational process integrated in the architectural morphing skins.
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References

Sensing Material Systems
- Novel Design Strategies
Sascha Bohnenberger, Chin Koi Khoo, Daniel Davis, Mette Ramsgard Thomsen, Ayelet Karmon and Mark Burry

Abstract
The development of new building materials has decisively influenced the progression of architecture through the link between built form and available material systems. The new generation of engineered materials are no exception. However, to fully utilise these materials in the design process, there is a need for designers to understand how these new materials perform. In this paper we propose a method for sensing and representing the response of materials to external stimuli, at the early design stage, to help the designer establish a material awareness. We present a novel approach for embedding capacitive sensors into material models in order to improve material performance of designs. The method was applied and tested during two workshops, both discussed in this paper. The outcome is a method for anticipating engineered material behaviour.
I. INTRODUCTION

After a period of intense digital focus, there is a new era of material awareness. This has been powered by fast technological progressions in digital design tools (such as parametric design, form finding algorithms and emergent systems) and catalysed by the growing range of digital fabrication methods (such as CNC machining, 3D printing and robots). After a period of rapid development in digitally designed tools for architecture, the ability to simulate and model materials are radically changing the realm of material thinking.

1.1 Context

Recently published publications by designers and theoreticians such as Michael Meredith [1], Lisa Swanston [2] and Reiko Ozawa [3] are defining a new era of tectonic architecture with engineered materials as its focus. The physical and direct engagement with matter, driven by a new ecological understanding that is based on performance-driven design decisions is supporting material oriented design thinking. New digital tools, new fabrication methods and the vast range of new commercial construction materials are supporting this material oriented design thinking.

The growing palette of materials and technologies offers a range of new research fields but also raises questions about how designers apply this stream of unfamiliar construction materials and design tools. Our knowledge of commonly used materials - such as steel, glass, concrete and wood - typically comes from centuries of haptic experience and experimentation. But this tacit knowledge has not yet been developed for many new materials. For designers these new materials present a risk, which is often expressed as a marked preference for the familiarity of traditional materials.

The problem still remains, that many designers lack the detailed knowledge of material behaviour necessary to use engineered materials. This is largely to do with the education of architects, which tends to privilege geometry over materiality. However, this education is experiencing a shift, or perhaps an extension, towards a new understanding of materiality. Once again, the ideas of Max van der Rohe, Josef Albers and Linzhi Maho Ngai are returning to the fore, as students are asked to design in the name of the material. Of particular relevance is Josef Albers' notion of materials studies [4], where he proposed an integrated research and design process between material and matter. Albers argued the whole potential of the material could only be achieved through no full understanding. In his course students were taught to reduce the material to its extreme to create an optimized well-balanced design (Figure 1). Recent methodologies in architecture by the ideas of Achen Menges, Michael Heizer [5,6] and others [7] have re-established the ideas of performance and emergent material studies to produce new architectural strategies, which Ursula Schaefer also mentions in 2010 [8].

In this paper we posit that to be able to apply an unfamiliar material to a design, a new level of encountering the material properties is needed. This is especially true if designers want to work with novel engineered materials. In this sense, physical experiments with the material itself are an important way of generating the necessary rules-of-thumb and gut feeling of the material's behaviour. Through material experimentation, material properties can be discovered and described as parameters that can inform digital simulation. The explicit properties of a material system create a solution space with a range of possible outcomes following Albers understanding. There is no one optimal solution there are many different possible solutions [4]. Therefore, physical material experiments can integrate with digital design tools to better express material behaviour and either guide form-finding or assist designing with the new material observations. With the today's technology integration and interfacing of digital and physical material systems seems more reasonable than ever. Bridging the gap between the digital and the physical world is an on-going research interest of academics and design practices (MIT Media Lab, Tangible Media Group, SMART Solutions Team - Burj Happel) [9,10]. This paper aims to contribute to this investigation by articulating a method to sense, test and visualize micro changes of materials for a better material understanding.

Therefore within this paper, we propose a method for sensing and representing the response of materials to external stimuli, at the early design stage, to help the designer establish a material awareness. The presented research reflects upon the spirit of the Bauhaus ideology of material knowledge, the so-called Formelementen [2]. And this spirit is applied to a series of experimental architectural workshops to test the methods proposed within this paper.

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Figure 1: Paper folding experiments by Josef Albers and Students, Black Mountain College, New Haven, 1946.

Photograph by Gernsheim Naylor.

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Sasha Buttenheiro: Chi-Kui Liu, Daniel Davis, Maria Ruengard Thomsen, Anika Kramen and Mark Burry

Appendix

Appendix
2. DESIGN EXPLORATION THROUGH SENSING MATERIAL PERFORMANCE

Parametric design tools are capable simulating real-time physics to visualize material behavior. Environmental measurements, such as measurements of sun exposure, heat, or moisture, can be used as parameters to influence model behavior. Physical measurements of forces can be used to calibrate particle spring simulations. These flexible digital simulation techniques, combined with simplified geometrical models, can lead to a better understanding of new materials, helping inform design decisions at an early stage. When it comes to the understanding of these materials, we need to link the physical properties to a design environment understanding. Robert Ash describes the design process as ‘seeking implied ideas with incomplete information’ and ‘exploring the necessity of a certain balance of sun shaded’ with a well-developed sense of premeditation (11). Usually the collection of material properties is established via time consuming experiments requiring the measurement of forces and strength, as well as other physical and chemical functions. This detailed data set is necessary to define a descriptive function giving the classes real material performance. However in this paper we propose that a fully accurate descriptive function of materials is not needed in the early design stages. Instead we suggest an approximation will suffice. This approximation can be informed by fast, low-tech measurements with rulers, protractors and observation, and the simulation can be conducted in particle spring simulations that give a feel for the reality of using the new material.

Developments in the last century have produced a range of sensors that can be used for recording and sensing small changes in materials. There have been a number of projects investigating the possibilities of engineered materials combined with sensors to create advanced composites that enable ubiquitous and embedded interactivity (12). Leading examples include robots and technical wearables that can sense light, noise and the presence of bodies. The introduction of capacity sensors in particular has progressed the sensing and augmenting of space, which has been exemplified in projects by Mancito Costello (figure 2) (13). Leah Buechley and the Research Team of the High-Low Tech group at the MIT Media Lab (14). The prevalent use of capacitive sensors stems from the fact that this is a technology with a relative high accuracy and ease of integration and a wide array of applications (15). In capacitive sensors conductive materials are used to record changes in the electrical field around them with response to an interference of a conductive object (human body and others). Applications vary from more standard uses in electrical engineering to more speculative prototyping in the case of design proposals. The relative freedom in material application and new open-source environments for interaction design make this technology most appropriate as a way to develop new scenarios for embedded computing for the built environment.

There have been a number of applications of this sensing technology applied in architectural practice, often to produce flexible and responsive textile skins. In Soft House by Kennedy and Violich, the flexible textile membrane (figure 3) is used as infrastructure for natural photo-luminescent pigments, light-emitting diodes (LED) and film-encased photoelectric cells that control and respond to internal and external forces (16).

The use of capacitive sensors is not limited to just sensing changes in the local environment; they can also be used to measure pressure, bending and tension forces within the material. Here, measuring is not directly related to real forces but indicates the degree to which the sensor is being bent or pushed. In our research we have used this data to monitor the material and inform digital representations of the material behavior.

This method can be adapted to provide real-time feedback for calibrating pseudo physical material simulations (figure 4). In the pseudo physical simulations, the designer can explicitly design and specify which geometric properties they want to leave free, which they want to constrain, and how they want to link them. This spring algorithm then expresses approximate material behavior; without precisely measuring the material properties (Pifer, 2011) (17). Modifying the properties of the pseudo physical simulations with sensor data, the sensing itself becomes a design driver for architectural ideas and solution finding strategies based on the investigation.
of material constraints and the interaction between the physical and the digital modelling environment as described in Figure 4.

2.1. Setup of the sensor network

While touch sensors are not a new technology, recent advances in programmable micro-controllers, such as the open-source Arduino, is making capacitive-based touch sensors a viable alternative to other expensive sensing devices. Touch can be sensed as a capacitance-changing system through the interference caused to the electrical field surrounding an electronic conductor. A human body is filled with conductive electrolytes covered by a layer of skin and it is the conductive property of fingers that0 reorients the electrical field making capacitive touch sensing possible [18]. The conductor does not literally need to be touched since the electric field extends past the surface of the conductor; so anything close to the conductor is enough to register the change in current. This technique already has many different applications, such as in touch-screens. In order to apply these techniques to sense material changes we can use the predefined ‘ touch sensor library’ by Paul Badger that turns two or more Arduino pins into a capacitive sensor, which can sense the electrical capacitance of the human body. The ‘touch’ method reports the variable values (in arbitrary units) and this can be then visualized or reused in different ways. The circuits that are needed in order to operate the sensor and to measure the sensed values are very simple and work with low currents. The integration of the capacitive sensor technology into a digital design tool such as parametric software can be achieved by small and easy to build electronic circuits.

We applied capacitive sensors to measure the material performance of two projects: Performing Sails, led by Mette Rasmussen; Thomsen and Ayedet Karman; and Material Behaviour, led by Saskia Bohnenberger, Chin Kie Khiung, and David Davis. In Performing Sails, the conductive foams integrate as part of the structure of a inflated surface, while in Material Behaviour, removable conductive foam sensors are attached to the flexible surfaces of sails as seen in Figure 5.

2.2. Mapping sensor data to graphical representations

The problem for designers working with unfamiliar materials (like sails or fashion textiles) is anticipating how these materials will behave, particularly if the required data gathering has not yet happened. The introduction of simple sensing techniques can help but the data from the sensors needs to be represented in a meaningful way for the designer. The two workshops use Arduino micro-controllers linked with the programming environment Processing to normalise data and provided targeted visual feedback. (Figures 6 and 7)

Or as Robert Aish says: “How can we augment the cognitive processes?” [11]
3. DESIGN EXPLORATION

A model of abstraction as a mediating language drives the two projects. They both use a simplified representation of materials undergoing forces visualized and fed back into the design process. This simplification is necessary in order to understand the intricate relationship between force and material system.

Within the Performing Skins Workshop different yarn types were woven together in a digitally controlled process with a CNC-knitting machine. The three-dimensional knitted structure contained different material properties, which were combined with a control tool allowing the user to re-shape the knitted fabric. The second project examined how pre-fabricated sails woven from flexible material types such as Dacron, Kevlar, and Polyamide could be used to embed sensing as a representational and sense-making tool of the material behaviour. Here the sensor communicated the different material reactions according to the wind forces in three types of sails.

3.1. Performing Skins

Performing Skins was held as part of Smarts Geometry 2011 at the Royal Danish Academy of Art. In the workshop we investigated techniques for embedding sensing in complex composite. Using knitted fabrics as a model for material thinking, we examined how CNC knitting technologies can be directly interfacial with architectural design environments. The workshop relied on techniques developed for the Linerner research probe ([9, 20]) enabling the embedding and interfacing of capacity sensing and steering of fabrication. The aim for the workshop was to build an understanding of how this localized sensory-data can be integrated into the design process using dynamic material representations and be used to develop site and use specific materials.

In the workshop groups were asked to develop their own composite materials working with a range of different yarns with particular performances. By integrating conductors that stretch and extend, polyethylene monofilaments that stiffen, and extensoids alongside natural materials such as cotton, wool, and linen we experimented with the interactions between structure and material behaviour. The complex textile composites were further extended by integrating conductive fibres (Figure 8). These fibres are spun with silver filaments that enable the flow of electricity.

The conductive fibres were used for capacitive sensing. The sensing was used as a way to simulate humidity sensing, as humidity sensors often use capacitance as part of their technology. Simulating environmental changes through human presence became a strategy for design in the workshop itself, to allow the work to be about multiple scales and multiple locations. Not so much as a way to sense human presence in and of itself. By interfacing the fibres to the Arduino micro-controller, readings of humidity changes in the local environment could be taken.

The first prototypes were used to generate a pool of sensed data. The workshop explored methods for integrating the sensed data with the material design process. Learning from the Linerner prototype, base diagrams of material structures were prepared as a means of interfacing the CNC knitting machine. The diagrams were set up in an architectural design environment (Rhino, Grasshopper and Firefly) allowing participants to directly engage and change the geometric information that informs and encodes the go-deck for the CNC knitting machine. The diagrams are abstracted information models that do not directly depict the material form of the finished fabric nor the behaviour of its fibres but instead structure the fabrication data. As visual representations they are intuitive to understand and therefore easier to manipulate that the direct go-deck.
The workshop established an iterative design process in which generations of materials inform one another. As local information is gathered by the embedded sensors they inform and change the following set of material designs. In one exploration led by Sachs Bachmeier and Chin Koi Khoo, the diagram was developed to predict and simulate the material behaviour of the fabric. The diagram was reconstructed as a meshed surface, which was further tuned to produce an accurate representation of the final geometric outcome as visualized in Figure 9. The sensed data gathered from the conductive yarns of the prototypes were implemented as an interface for the diagram and, as a user feedback system, was the most striking element of the workshop. Allowing designers to directly understand the relationship between environmental impact and design change enabled prototyping different physical changes on the parametric model when the material is ‘touched’ before embedding this behaviour in the material of the fabric.

3.2. Material Behaviour Project

In a workshop led by Sachs Bachmeier, Chin Koi Khoo and Daniel Davies as part of the Designing the Dynamic conference at the Royal Melbourne Institute of Technology, we conducted an investigation into forces carried through cables of different materials and reinforcement patterns. The study was inspired by the work of North Sails and their approach to designing composite fabrics that are shaped into optimised forms. The flexible yet resilient composite materials and the aesthetics of these composite materials when combined into continuous surfaces drove the design investigation. This specific material exploration of composite materials is a challenge that architects and researchers like Greg Lynn [21] and Johan Bettum [22] have investigated, although their work tends to abstract the material for design reasons.

The goal of the workshop was to quickly capture the shapes of the sails under load and use this analysis predict a better design outcome. The difficulty of simulating the nuances of resilient bending, stiffness, elasticity and torsion – particularly in composite materials – necessitated the use of physical simulations. The simulation of the sails was a lightweight Mylar, which was then reinforced with various materials like Kevlar, Dacron and Mylar. The location of the reinforcing initially based on internal force flow of the composite traditionally understood in sail making. This understanding was supplemented by our own FEM simulation of the load paths through the sails, which were then rationalised into casting patterns through a parametric model. The fabrication process was a scaled down version of the North Sails 3DL manufacturing process [23]. Two sheets of Mylar were laminated together sandwiching a middle layer of the reinforcing material (cut to shape). The laminating process forced the three layers to behave as one new composite material.

To examine the different performance of the sails we attempted to measure the pressure and bending of the sail in two key locations. It was necessary to make our own sensor for this purpose since all of the commercially available sensors could not be attached to the sails without having a noticeable effect on the shape due to their weight and their stiffness. The solution was to construct a sensor from conductive foam, which when bent or stretched changes its capacitance in a measurable way.

To sense and record the data, the sensors were linked to an Arduino micro-controller, which sent the data via Firefly to Grasshopper. The validation of the data was based on the comparison of the sensor readings.

The setup allowed for three sails at a time to be measured simultaneously, either under real wind conditions or by simulating wind with three commercial fans (Figure 10).

The three sail rig was connected to a visualisation of the low-stream of data (Figure 11). Of the three sails developed, Sail A had the highest mean data value, indicating it was experiencing the most pressure bending force. The standard deviation of these numbers indicates how the sail is catching the wind, since a poorly performing sail will vibrate in the disrupted airflow, causing fluctuations in the sensor values, which increases the standard deviation. Sail B was the worst in this regard. This data tells a very valuable story about the performance of the sails, the stability of which would be lost in a purely digital simulation, while the detail would be invisible to someone inspecting the sails in a purely physical manner. It is only through bridging this gap a better understanding of the original Sail C occurs and can be developed further in regards for better wind drag performance.

Sachs Bachmeier, Chin Koi Khoo, Daniel Davies, Matts Ramberg Thomassen, Ayda Kann and Mark Barry
4. CONCLUSION

The increase in new materials presents a challenge for designers who want to take advantage of the performative gains but lack the familiarity with the materials to confidently design with them. In this paper, we have explored the potential for designing with these materials and the materials to combine early stage prototypes with innovative digital sensors to inform their digital design process. Performing Skin demonstrates how surfaces can be realised based on user interaction. In this case, through sensing the touch of the user and generating a new CNC-routing pattern to engage with this interaction. The sensing of the Sail in the Material Behaviour workshop has a very different outcome. Here, the sensors are used to gather preliminary performance data that would be impossible to gather through data simulation and that was too sensitive to capture without embedded digital sensors. This early stage feedback on material performance necessitates a bidirectional link between digital and analogue models, where sensed changes in material behaviour of either model is feedback into the system to give a more full understanding of the project's early stage performance. Furthermore through the tacit, intuitive engagement with materials and the described way of representing the material performance, a new understanding of the material performance is formed. These types of linkages between the digital and the physical world have the potential to change how designers engage with materials by enabling them to embrace the unfamiliar with the confidence they will be able to tune the system to capture its full benefit.

In architecture this strategy is not only helpful for gaining a better knowledge of novel materials but can also be thought of as an design and control system for adaptive architecture with an embedded feedback system to react to environmental changes.

ACKNOWLEDGEMENTS

We would like to thank the sponsors of the 2011 Smart Geometry Event for providing the ground of testing the performative Skin Project. The Material Behaviour Cluster was part of Designing the Dynamic workshop at the Royal Melbourne Institute of Technology, Australia. Without the sponsorship of BVN, the Australian Research Council and SIAL RMIT – Melbourne this research would not be possible. We would like to thank K. Vivian, A. van der Horst, M. Korecky and Z. Qiu for their assistance.

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Source: Böhmerberger, Chi, K. Koo, D. Divkovic, M. Roepke, Thristen, A., Klassen, and N. Burney.
Lumina: A Responsive Luminous Material for Architectural Skins Design

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Keywords: Responsive; sensing; phosphorescence materials; and architectural skins

Abstract. This research explores the potential for developing responsive composite materials with sensing, kinetic and luminous capacity for application in the design of responsive architectural morphing skins. We integrate sensing devices and building skins as one ‘integrated’ entity, eliminating the need to embed discrete components in a vulnerable system. This investigation develops and explores the properties and performance of a new material, Lumina for application as a lightweight, flexible and economical luminous architectural skin that responds to proximity and lighting stimuli. The design exploration uses silicone rubber, glow pigments, embedded physical computational and shape change material. It is controlled using parametric design processes.

Introduction

Recent research has produced skin-like sensors for processing distributed tactile information across textiles [1]. This technology, inspired by various disciplines from biology and materials science to architecture, enables new and relevant avenues of inquiry through soft mechanisms and plant sensing that is behaviourally comparable to those found in nature [2]. What if this technology was applied to building skins, giving them the ability to perform like our skin? Contemporary architects can exploit these analogies and technologies to design building skins that respond to inputs from environment and users. This opens up new possibilities for simple, ecologically embedded architectural skins in constant feedback and interaction with their surrounding environment [3].

In the responsive architectural context, the idea of responsive building skins is often explored through individual sensing devices and mechanical systems considered as ‘hard’ technology. The label ‘hard’ literally refers to the context of mechanical systems and their discrete individual sensing components. This architectural approach is not new and has been explored since the 1960s. The responsive brise-soleil of LA County Hall of Records designed by Richard Neutra in 1962 is one of the first significant examples addressing the question of responsive architectural skins. Complex mechanical systems for kinetic movement with sensing facility tend to break and to fail in terms of longevity and reliability. The Institut du Monde Arabe building in Paris by Jean Nouvel in 1987 sets the precedent for this approach [4]. These structures and systems engage complicated discrete elements and physical divisions. They use a series of external sensors to achieve the adaptability of the systems. Both the Neutra and the Nouvel building skin systems hindered mainstream adoption of responsive facades because of their heavy maintenance and brittle mechanical components. Looking for alternatives has led to this material investigation into responsive architectural skins with fewer mechanical and sensing devices. Technological advancement in material science provides the opportunity for using passive and active form-changing materials like elastic silicone polymers and glow pigments to design kinetic, responsive architectural skins. These soft and form-changing materials can be integrated with other sensing materials. This provides an alternative approach to addressing the issue of the brittleness in operation of mechanical and sensing systems.

This research develops a responsive phosphorescent material for designing soft responsive architectural skins that integrates a sensory and luminous system within the surface. By exploring the method to integrate the form-changing and luminous materials through physical computing process, it is soft in system control as well as in material properties. This approach sets an initial platform for the early design exploration. This research aims to investigate the new possibilities for sensing, luminous
and form-changing materials applied to architectural skins that can sense and respond to external environment stimuli as a single entity. The potential materials used in this investigation are photoresistant elements, Nichrome wires, glow pigments, silicone rubbers and shape memory alloys (SMAs). This investigation is conducted through a material design exploration, called Luminia, a prototype responsive luminous material used in architectural skin design. The subsequent sections discuss the development this responsive material system and its application. These material system explorations are an initial step in investigating the new possibilities to design an architectural skin that integrates materials and computation.

Responsive and Luminous Materials

Recent robotic research has included investigation into active property change in responding materials. However, there are few precedents for applying these materials in the context of architecture, especially in responsive building skins. There is a need to test the potential of these materials for full-scale architectural application. The initial responsive materials tested in this research are silicone rubber embedded with SMAs. Their integration allows the state change of the SMAs to activate the silicon as the kinetic element. The elastic silicone rubber becomes the kinematic performer in the soft approach without any external discrete mechanical components.

In addition, current research of newer technologies for lighting in urban environments explores the materials that provide passive lighting to reduce the demand for delivered electrical energy [5]. We propose an integrated lighting systems, integrating the lighting function in the material itself. This is seen as a potential alternative to contemporary LEDs and OLEDs (Organic Light Emitting Diodes). This research explores the potential for material combining sensing, passive and active lighting and kinetic response for application in the context of responsive architectural skins design.

The integration of materials with physical computing brings both active and passive 'sensibility' and 'luminosity'. This integration includes materials such as Nichrome wires, SMA (shape memory alloy) wires, glow pigments (strontium oxide aluminates) and translucent silicone rubber (containing polyethylene vinyl, polyethylene hydroxyethylene and polyethylene vinyl chloride). Table 1 illustrates various responsive materials with passive and active responsive capacity to develop a hybrid material system that can sense and respond to changing environmental conditions (Table 1). Using these materials, we investigate the new possibilities for designing a lightweight and simple sensory, kinetic, luminous architectural skin.

<table>
<thead>
<tr>
<th>Responsiveness</th>
<th>Form-changing materials</th>
<th>Luminous materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Shape memory alloys</td>
<td>Nichrome wires</td>
</tr>
<tr>
<td>Passive</td>
<td>Silicone rubbers</td>
<td>Glow pigments</td>
</tr>
</tbody>
</table>

Materials and physical computing. We begin with a basic experiment to test the possibilities to integrate various materials and physical computing to develop a new responsive material system with fewer discrete components and more optimal energy usage. The initial experiment integrates the conductive paint with silicone rubber to test potential for responsiveness. This process uses conductive paint as the initial sensing element that performs capacitive sensing when a voltage is applied to create current. The conductive material constantly sends variable data to the computer through an Arduino microcontroller. The software environment includes Grasshopper for Rhinoceros® and Felt for the Arduino microcontroller (Fig 1). This experiment is the trajectory to the initial development of Luminia.

Luminia is equipped with two fundamental sensing capacities: proximity sensing, light sensing; and two responsive capacities: movement and illumination. Proximity is sensed through capacitive sensing and responds through SMA wires embedded within the material for kinematic actuation. Light sensing detects the luminance level of its surrounding environment and constantly sends the luminal data to the microcontroller to trigger the appropriate response, either activating active light stimulation or not. Illumination is a passive and active capacity of Luminia. It can store the light energy absorbed during the day and glow when the surrounding environment grows dark. It can also respond to heat activation by passing a current through the material.

Proximity sensing. Luminia responds through an active capacitive sensing. The conductive paint blended with the SMA wires and silicone skin serves as a probe surface that uses changes in capacitance to sense changes in distance to an object or person (Fig 4). It senses the proximity of objects in the surrounding environment and responds through transformation of the skin surface.
Actuated by the SMA wire in various configurations. This sensing operation process, through the
Arduino microcontroller and Firefly physical computing software, allows the material to ‘process’
external data and respond to them.

**Light Sensing.** A series of linear phototransistors are embedded in Luminex to detect the level of light in
the surrounding environment. This light sensing facility allows Luminex constantly to detect the light
level and send the data to the microcontroller to process (Fig. 5). The processed light data is a variable
input to activate the heating process of Nichrome wires for active illumination.

**Illumination.** The fabrication of Luminex integrated silicone rubber and glow pigment to develop a
passive and active luminous material that glows in the dark. The passive luminous capacity of Luminex
is to absorb light energy during daytime and discharge the light energy after dark to produce the glow
effect. When the local light level is lower than 20 Lux, Luminex illuminates the surrounding area
without an external power source. When the lighting effect of the surroundings is lower than 10 Lux,
the active luminosity of Luminex is activated by the embedded Nichrome wires which heat the
luminous material to increase the glowing effect to the recommended illumination level. Luminex
material with the composite of glow pigments and silicone rubbers performs a glowing lighting effect
by absorbing the heat energy (at 70-80 degree Celsius) from the Nichrome wire embedded within (Fig
6). This process is using minimal energy (1.75 Watts (2.5V, 1.5Amp)), equivalent to one or more
LED globes, to activate the illumination of a sample of the material of 150mm x 150mm when passive
illuminating is not bright enough.

**Conclusion and Future Work**

Architecture is a material practice and current material technological advancement provides new
opportunities for architects and designers to design novel architectural components never imagined
before. This research takes an initial small step to exploit this opportunity and to develop a new
material for responsive architectural design purposes using methods that are novel in architectural
design. We see Luminex as just a beginning to finding alternative solutions for certain problems of
responsive architectural design and illumination. It serves as a trajectory for future research in
responsive materials for architectural applications.

Future work will focus on the integration of Luminex with other bio-inspired materials such as
self-healing materials to further the applications for architectural skins design. The potential of these
responsive materials and these novel approaches to architectural design will have a significant impact
on the architecture of the future.

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Integration for Intelligent Systems, Seoul, Korea (2008), pp.20-22

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C. Public recommendation

The following interview cites my works as part of the influences to their design projects:

This was clearly demonstrated by the exposition. The projection of a programmed 2D system on the floor of the main hall of the architectural corps of the university. Visually this system consisted of several dynamic patterns changing each other from time to time. These patterns respond to the human rather to his private space described by a meatball.

Based on the physical formula the meatball can be described through its center. In this case the role of a center is played by a human. And the outer limit is formed in accordance to the distance to the neighbor. Thus, each pattern had an individual visual reaction.

This exposition is the first (experimental) step in developing and translation of the idea into reality. In the architectural context the idea is divided into two stages:

1st stage – creating the static transit space.

2nd stage – filling the public space with an array of adaptive elements. It is them that will response to a human creating dynamically changing functional zones.

sP: What or who influenced this project?

KG'MG: We admire the possibilities that are given to us by contemporary scientific researches in developing the computerized tools, cybernetics and materials. Inspiration: Philip Beesley, Chin Koi Khoo.

sP: What were you reading/listening to/watching while developing this project?


sP: Whose work is currently on your radar?

KG'MG: Patrik Schumacher, Daniel Widrig, Kokkugia, Emergent.

D. Arduino protocol

**Tent**: Original Arduino protocol for photoresistor, Source: http://ardx.org/CODE09

```c
// A simple program that will change the intensity of
// an LED based on the amount of light incident on
// the photo resistor.

// Define the pin numbers
const int LightPin = 0; // the analog pin the photoresistor is
// connected to
const int IndirPin = 9; // the pin the LED is connected to

// Function to set the LED to a given value
void setBrightness(int brightness) {
  // Write the brightness value to the LED
  analogWrite(lightlevel, brightness);
}

// Function to change the brightness over time
void changeBrightness() {
  // Decrease the brightness
  setBrightness(lightlevel - 10);
  // Increase the brightness
  setBrightness(lightlevel + 10);
}

// Main function
void setup() {
  // Initialize the LED output pin
  pinMode(LightPin, OUTPUT);
  // Set the initial brightness
  setBrightness(255);
}

// Function to read the brightness level
int readBrightness() {
  // Return the current brightness level
  return lightlevel;
}
```

**Blanket**: Full Arduino protocol of Firefly Firmata uploaded in Arduino microcontroller, Source: http://fireflyexperiments.com/resources/.
E. Schematic diagrams

The series of schematic diagrams for the responsiveness of each design investigation.

Tent
F. Architectural competition panels

Entry panels of eVolo 2011 Skyscraper Competition to test the idea of responsive AMS implemented in high-rise building design. This skyscraper- Morpho-ElastiCity is a self-sustaining vertical university campus that contains sixty multipurpose floor spaces to accommodate various schools and facilities. It focuses on the responsive component – a dynamic elastic membrane that regulates the condition of the semi-interior space in-between exoskeleton façade. It controls air and light penetration and is partially manipulated by prevailing wind passively. This elastic membrane not only serves as the ‘wind catcher’ for passive cooling, shading and ventilation purposes, it is also included the device to harvest the wind kinetic energy. This ecological system makes the energy needed for tower self-sustained and efficient for low maintenance cost in various operations.

G. Visual diary – progress images

Tent – Early experiments
Tent – Early experiments

Appendix
Appendix

Tent – Early experiments

Appendix

Tent – Early experiments
Tent – Early experiments

Appendix
Appendix

**Tent – Transformation**

Appendix
Tent – Responsiveness

Appendix
Appendix

Curtain – Skeleton

Appendix

Curtain – Skeleton
**Curtain – Skin**

[Images of the Curtain experiment focusing on skin material and structure.]

**Curtain – Transformation**

[Images of the Curtain experiment focusing on transformation and movement.]

Appendix
Curtain – Transformation

Appendix
Appendix

Curtain – Transformation

Appendix

Curtain – Transformation
Curtain – Final fabrication

Blind – Skeleton
Appendix

Blind – Skeleton

Appendix

Blind – Skin
Blind – Transformation

Appendix
Blind – Responsiveness

Appendix

Appendix
Blind – Final fabrication

Blanket – Skeleton
Blanket – Responsiveness

Blanket – Final fabrication
Blanket – Final fabrication

Appendix
H. General research timeline

<table>
<thead>
<tr>
<th>Design Investigation 1</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tbody>
<tr>
<td>Elasticity: Tent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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Appendix