Materializing a responsive interior: designing minimum energy structure based on dielectric elastomers

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Biography

Aurélie Mossé is a textile designer and researcher working with responsive materials. Her research is practice-led and sits at the intersection of textile, architecture and smart technologies. She is currently undertaking a PhD at CITA, Centre for IT & Architecture, Royal Danish Academy of Fine Arts, school of Architecture, Copenhagen, in collaboration with Textile Futures Research Centre, Central St Martins, University of the Arts, London. Aurélie trained in textiles at ESAA Duperré, Paris, and at Central St Martins, University of the Arts, London. She is also a founding member of the London-based textile design lab Puff & Flock.

Guggi Kofod received his B.Sc. in Chemistry and Physics and MSc. in Physics from Copenhagen University, Denmark in 1998. Then he worked on dielectric elastomer actuators at Risø National Laboratory Denmark, to obtain the Ph.D. degree in 2001 from the Danish Technical University. Further work has included research at SRI International, USA, Danish Institute of Fundamental Metrology, and Ateneo de Manila University, the Phillipines. In 2006 he received a five-year NanoFutur Post Doc. Group Leader project grant (project title: “KompAkt”) from the German Ministry of Education and Research, to establish and head a group that will develop new materials for dielectric elastomer actuators, based on a nano-composite approach.

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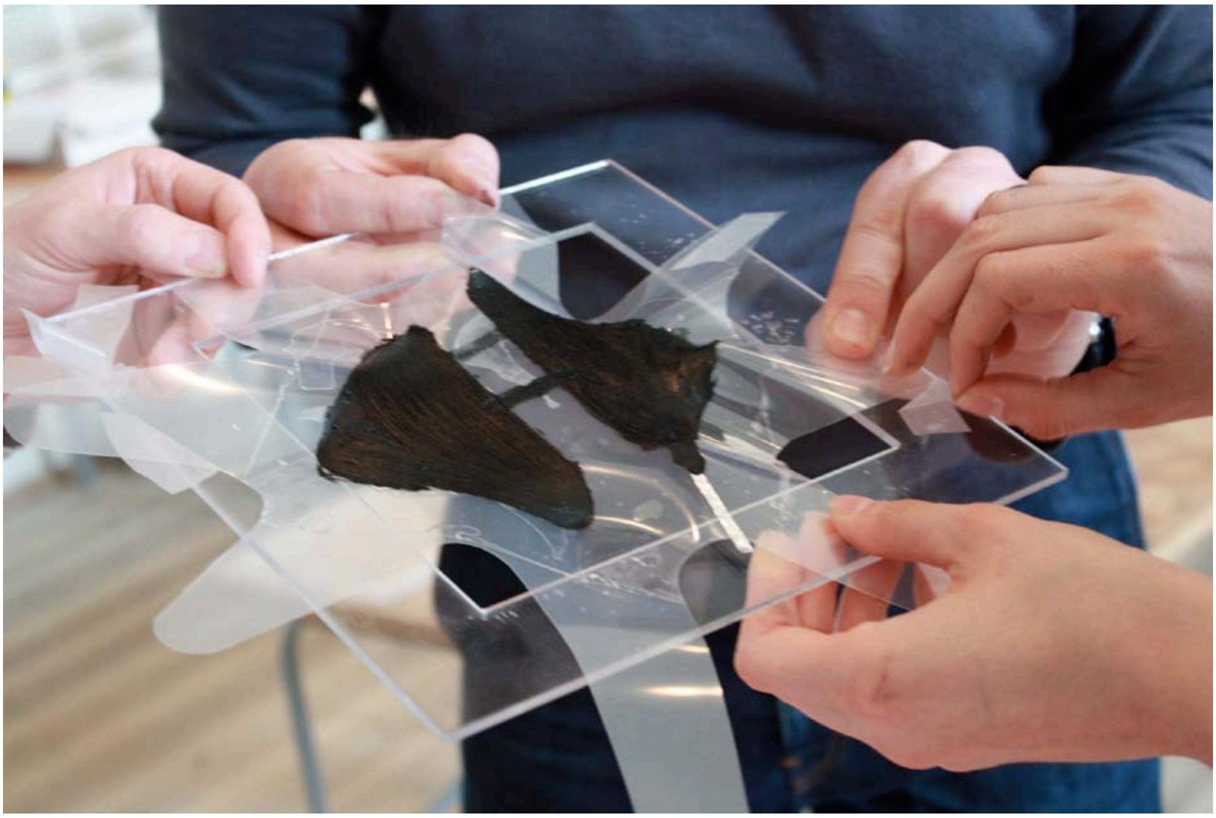


Abstract

This paper discusses a series of design-led experiments investigating future possibilities for architectural materialization relying on minimum energy structures as an example of adaptive structure. The structures have been made as laminates of elastic membrane under high tension with flexible frames possessing arbitrarily shaped holes. The structure is highly amenable to shape changes, which has been demonstrated in the case of electrical actuation of the elastic membrane (Kofod, Wirges et al. 2007), however, other means of actuation are possible, involving stimuli such as temperature (Lendlein, Kelch 2002) or light (van Oosten, Bastiaansen et al. 2009). All in all, this approach could form a whole new design paradigm, in which efficient 2D-manufacturing can lead to highly flexible, low weight and adaptable 3D-structures. This is illustrated by the design and manufacture of electro-active structures based on dielectric-elastomer, where energy-minimization and self-organization principles become central processes for the realization of shape-changing architectural surfaces. In Reef, a concept for self-actuated ceiling surface, we examine the integration of these dynamic structures into an architectural context by questioning how these technologies can be appropriated so as to reconnect the home with natural rhythm and cycles.

Keywords: Electro-active polymers, minimum energy structure, responsive architecture

Introduction

Recent developments in the field of smart polymers are opening new possibilities for architecture to become responsive. However, without technology transfer and appropriation of these new materials by architects and designers, there is little chance for them to reach the architectural realm. Firstly, smart materials are expensive, and can be expected to remain at a high cost factor. Leveraging smart materials with cheap, dumb materials (as demonstrated here in the minimum energy structure) has the potential to make a prohibitively expensive technology more accessible to architects. Then, bridges must be built between the micro and macro scales that still frame the architectural and material science traditions. Indeed, smart materials differ from traditional building materials in that they are dynamic, able to change their properties in response to external signals or changes in ambient surroundings. Their function is inherently tied to scale as their dynamic ability results from mechanisms at the molecular or microscopic level. Consequently, one of the challenges for the field of responsive architecture today is to re-think and adjust the scale of the materials we are using (Addington, Schodek 2005). Beyond the performative, these new materials also pose a series of questions related to aesthetic, conceptual, philosophical, and technical issues (Fox, Kemp 2009). What does it mean when time becomes an integral part of our built environment? How does this challenge the traditional understanding of home as a hermetic shell protecting the individual from the outside world? Can they reacquaint us with the idea of a home interconnected with its natural environment?

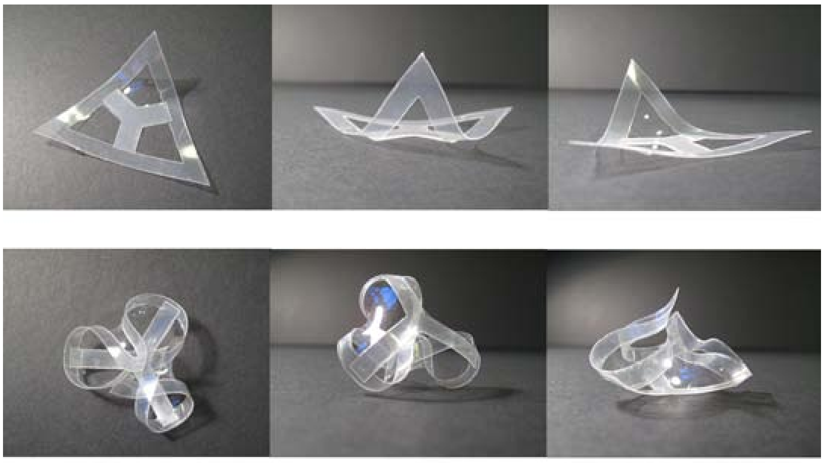
1 Smart actuators: the case of dielectric elastomers

Actuators respond to external stimuli by changing their shape and internal state of stress. This allows the intelligent manipulation of an associated structure, such as in the case of a motorized blind being folded and opened when electricity (the stimulus) as passed through a motor (the actuator). Although electrical motors are simple to operate and are quite energy efficient, they can be impractical due to their size and weight, and can wear out due to internal friction between parts.

Electro-active polymers are actuators that address many of these issues directly: these materials change their shape and structure directly, without any internal sliding motion. They are stimulated directly by electricity, which acts both as the energy source and the control signal. As they are made from polymers, they have comparatively low weights and high actuation strength. Uniquely among actuators and other motion-giving technologies, electro-active polymers are entirely silent.

Actuators made from dielectric elastomers have all these interesting properties. As elastomers are highly stretchable, very compliant structures can be achieved with these actuators as elements. They have comparably high actuation strength, and can themselves stretch at least 5%, and in some cases much further, under the influence of applied voltage. Currently, their major drawback is the high activation voltage, which is still in the range of 1000 V. In some contexts this level is dangerous, though in architecture it can be managed. Since only one manufacturer provides a well-tested material for this purpose, the aspect of ageing is not yet fully investigated.

2 Minimum energy structures as adaptive structures



1 Minimum energy structures: change in geometry affects the morphogenesis

When a soap bubble spans a frame, the shape of the bubble surface will change until the smallest possible surface is found (Hildebrandt, Tromba 1996). From early-tensile based structures to the Munich Olympic Stadium, such surfaces have been part of the architectural tradition, as to provide lightweight thus transportable structures and particularly today as to reduce material and energy consumption in respect to environmental concerns (Beukers, van Hinte 2005). Within this debate, adaptive minimum energy structures (Kofod, Paajanen et al. 2006) are of particular interest as they couple the optimization of material and energetic resources with the capacity of adaptation to changing circumstances. This means that the structure can not only change geometry but also become interactive: it can sense information from the environment and respond to it adequately.

2 Elastomer pre-stretching, frame lamination, conductive coating

In our work, we focus on adaptive structures actuated by integrated dielectric elastomers. These have been employed in a variety of forms and applications: linear actuators, bending rolls, diaphragm pumps, as sensors or power generators (Ashley 2003). The chosen approach relies on self-organization and energy-minimization principles as a means to design complex adaptive 3D structures through a simple planar manufacturing process. The process consists in the pre-stretching of an elastomer onto which a flexible plastic frame (mylar) , a conductive coating (carbon nanotubes) and a pair of electrodes is applied. As it is stretched, the elastomer stores entropic energy in its structure, due to the elongation of its polymer chains. Upon release, the frame undergoes large deformation. This transformation occurs due to the release of entropic energy by the elastomer and the simultaneous harvesting of bending energy by the frame – to allow the whole structure to find a configuration with minimum energy. Only through this self-organisation can the 3D-shapes appear after the 2D manufacturing. When a third energy contribution is applied, the self-organized module will change its configuration, a process which is known as actuation. In the present case, the actuation is induced by the application of an electrical charge on both sides of the elastomer. The attraction of the charges makes the elastomer contract in the direction of the electrical field and expands in the perpendicular direction, thus making the structure move as it is searches for another minimum energy configuration.

The actuation response of these actuators is proportional to the stimulus: the higher the voltage, the larger is the motion; therefore very fluid and biological motion becomes possible. Beyond their astonishing organic character, their dynamic supersede the one of more traditional responsive materials in their scale of actuation - much larger-, in their degree of controllability and reversibility of movement. For instance, where shape memory alloys or shape memory polymers must be ingeniously coupled with materials presenting a different behaviour than their own to come back to their initial state (Berzowska, Mainstone et al. 2007, Lelieveld, Teuffel 2010), dielectric elastomers operate this reversible shape-change intrinsically as the voltage passing through them increases or decreases. Therefore the dynamic of these structures can be determined very precisely, controlling both the pace and the degree of shape-change according to the nature of the electrical flow.

Beyond controllability, this approach presents distinct opportunities responding to the requirement for lightweight constructions methods and the need for more adaptive environments (Koch, Habermann 2004, Kronenburg 2007). Although these materials cannot act as load-bearers, their lightness allows for hitherto unseen adaptive structures while requiring only low levels of energy for their actuation. Further, their cost is low compared to other active structure materials as it primarily relies on cheap materials (polymers) and simple manufacturing processes. Given more developments, (the use of these materials for such purposes is novel) durability could be measured in years and decades. Highly significantly, the performance is unlike any previous materials, in that the material deforms, instead of sliding (like normal window-actuators, for instance), giving rise to a complete new aesthetic of actuation.

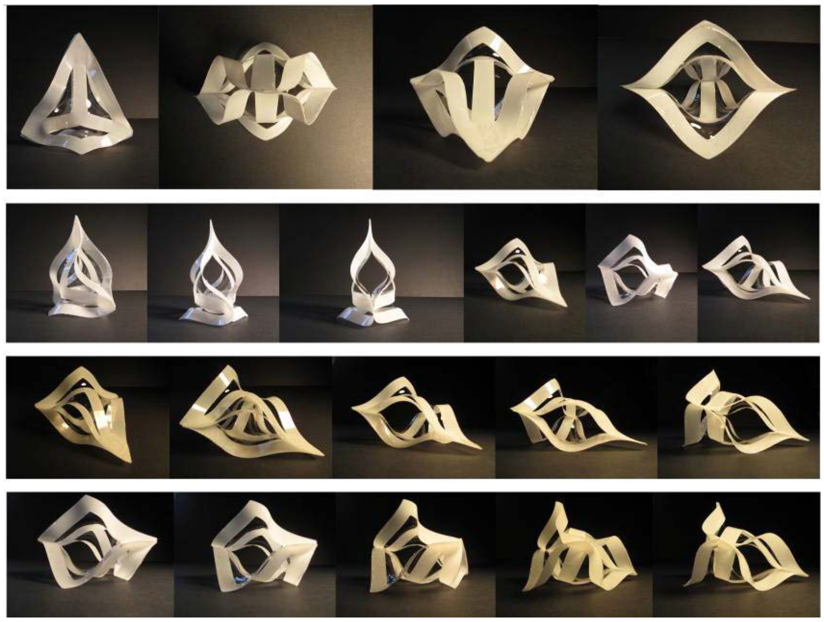
3 Crafting Minimum Energy Structures based on dielectric elastomers

Material behaviour is at the heart of this aesthetic, determined by the nature of their morphogenesis, their temporality and by the specific tools these processes require.

3 Minimum energy structure made from pre-stretched jersey fabric

Morphogenesis

More than with any other structures, the crafting of adaptive minimum energy structures relies on the delicate balance between material, shape and processes. Each time one of these parameters is tuned, even slightly, this deeply affects the shape-formation outcome. Particularly at stake here is the understanding of how to control the erratic behaviour of pre-stretched elastomers, in other words how to design with deformation. This was initially explored by a series of empirical tests examining how the nature of the frame (material thickness and geometry) affects the morphogenesis. Figure 2 shows how the decrease of a few millimetres in the following triangular structure’s width dramatically affects the curvature of the object, revealing the level of detailing required for the design of such structures. The subtle balance of these parameters give rise to an incredible variety of forms while offering opportunities for mass-customization since the alteration of tension in the pre-stretched material is sufficient to give rise to different structures from the same frame. Further investigation into materials focused on the translation of this form-finding process into textiles. The substitution of the elastomer for stretch fabric was driven by an interest in up-scaling and making the technology less fragile. The actuation of textiles according to the dielectric elastomer principle remained impossible due to the porosity of the material, but might be possible through the lamination of the stretch fabric with a regular elastomer sheet. Interestingly, the textile-based experiments illustrate new design methods for form-finding with textiles where no prerequisite pattern cutting is required to obtain three-dimensionality.

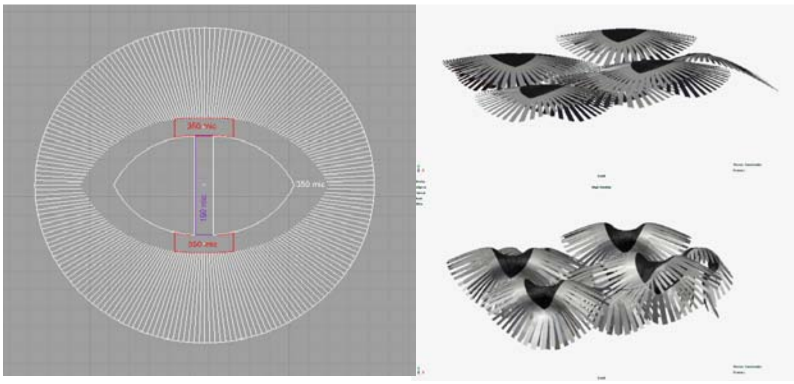


4 Double-skin minimum energy structure

Time as a design component

The field of architecture has a long tradition of conceptualizing materials thus building as fixed in time and space (Addington, Schodek 2005, Kwinter 2002) . What makes these structures so peculiar from traditional building materials is that they are inherently dynamic. Beyond the understanding of their molecular actuation mechanism, designing with such materials requires the understanding of their tangible temporality: how they move in the time-space of our perception. By investigating the design of a vocabulary of electro-active movements, the project has lead to the identification of three types of behaviours or movement's typologies. In the first case, the movement is translated by the extension or stretching of the surface, reminding the behaviour of the lungs, inflating and deflating with air. The second category provides a flutter-like behaviour (fig 3), where the movement is providing the oscillation of a flap, while the third group can be identified as gripper systems, where two parts of the same module tend to move closer to each other.

5 Dielectric elastomer behaviours: Flutter-like movement



6 Reef's modules: digital drawing (Rhino) and 3D simulation (Maya)

A second aspect of their motile qualities relies on their pace of actuation. Depending upon the properties of the materials, the subsequent structures can react very quickly (within a few milliseconds for small structures made from silicone elastomers) or very slowly, within a few seconds. Slow-reacting materials have the advantage of shock-absorption, but would require higher levels of activation energy compared to fast-reacting. Of course, a fast-reacting material could be driven with slow actuation signals only. Here materiality defines pace, but equally determinant is the actuation's modalities. The fact that dielectric elastomers are driven by the amount of voltage passing through them (potentiometer) and not by the binary on/off system of a switch means their motion is adjustable and their tempo alterable, which is quite unique in comparison with more traditional smart materials. Besides, when these single adaptive structures become aggregate, they start to pose the question of their orchestration, addressing another temporal scale.

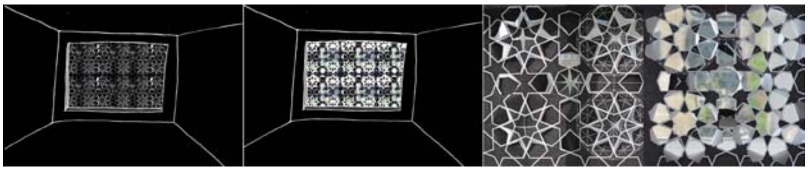
Digital crafting methods Renewing the designer's palette with a whole new set of unexplored expressions, these dynamic qualities are challenging traditional means of representation and prototyping (Addington, Schodek 2005, Kwinter 2002). To apprehend these qualities, digital tools become essential. By reaching an unprecedented level of detailing, computer assisted design-to-fabrication methods allow architecture to operate at the level of precision required by these new materials. Within this project, while geometries were developed through 3D modelling software, laser-cutting manufacturing allowed the precise translation of these structures into materials, before being tested by manual assembly. Besides, material behaviour simulations via the Autodesk *Maya* 3D animation platform were proved being a valuable sketching tool for the design and anticipation of the overall dynamic performance of these materials as a responsive environment (Holden Deleuran, Tamke et al. 2011).

3 Appropriating dielectric elastomers actuators in an architectural context

Rare are the architectural applications involving elastomers as a primary building material (Khan 2009b). This scarcity can be largely explained by architecture's historical affinity for the static (Addington, Schodek 2005, Kwinter 2002) as well as the complexity of apprehending material behaviours such as elasticity. Within this class of materials, dielectric actuators are just starting to emerge as commercial products, which makes explicit why there is so few precedents in an architectural context. Since these materials have not yet reached all the requirements for the built environment standards (Ritter 2006), most of these works have been developed as technological probes or demonstrators, pushing the boundaries of material research toward real world applications. The 'Homeostatic façade system' (Decker Yeadon 2010) or 'ShapeShift' (Kretzer, Rossi et al. 2010) are conceptual and material probes representative of the terms in which these materials are currently embraced in architecture: as scaffolds or performative skins, with a specific emphasize as shading systems.

With *Zephyr* and *Breathe*, two design concepts, we showcase further potential applications for minimum energy structures based on dielectric elastomers actuators taking place in a domestic context.

Zephyr is a three-dimensionally dynamic membrane translating the concept of mashrabiya into a dielectric elastomer materiality. Mashrabiyas are carved wood lattice windows, typical of Arabic architecture, that primarily work as to temper indoor climate by filtering daylight and airflow. In this conceptual probe, traditional Arabic patterns were similarly used to provide the geometric basis for the development of a network of responsive minimum energy structures. Embedded in a rigid frame, they work as a constellation of small active interstices, opening to encourage the cooling of the space by allowing airflow to get in and closing so as to provide shading. Therefore *Zephyr* is not envisioned as a shading-system to augment glass facades but rather as a screen taking part in a larger system of natural air and light management, in these in-between spaces such as patio, corridors or entrance. If dielectric elastomers do not present the same porosity as wood (Hensel 2010), the value resides here in the design of more adaptive and localized system, where each interstice's position can be controlled individually and over time so as to adapt to weather changes.



7 Zephyr: a dielectric elastomer Mashrabiya

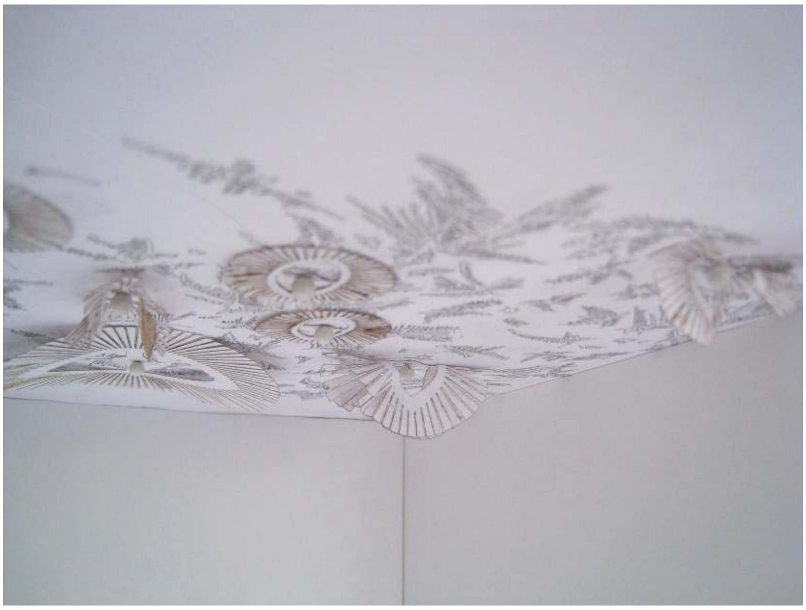
Breathe Thermal insulation is dependant of the capacity of a material to facilitate or prevent heat transfer. The breathing-like behaviour quality of dielectric elastomers suggested the opportunity for a shape-morphing membrane, whose double skin structure inflates and deflates as to regulate the amount of air accumulated between its two inner surfaces. This was tested through the design of *Breathe*: a double-skin component those pace of inhalation and exhalation is regulated by the change of season. The thickness would increase in winter and decrease during summer. The shape-morphing component suggests adaptive solutions for indoor climate management, where the integration of temperature-, moisture- or light-sensitive materials makes itself obvious for direct adaptation.

Actuation and the interior Both *Zephyr* and *Breathe* are inscribed in a re-reading of the history of the interior in its relationship with the concept of actuation. In the home, actuation has traditionally been conceived as the management of the thermal, luminous and acoustic environment through a variety of sensor-actuating systems such as heating, ventilation and air-conditioning. With environmental technologies the home became an environment primarily conditioned by technology, largely contributing to the perception of the interior as a hermetic shell, totally independent from its surroundings (Addington 2009).This spatial separateness from the natural environment has also progressively induced a temporal detachment from nature's own rhythms and cycles. From low quality building -where artificial systems have replaced direct sunlight and fresh air, while promoting phenomena such as sick building syndromes and seasonal affective disorder-, to the increased pace of our ubiquitous society -where anything can be done almost everywhere the 'deterritorialisation of time' is completely achieved. 'Not only can time be praised out of nature's diurnal and seasonal cycles as we travel across time zones within our bodies, it can also be entirely severed from the geographical place and time in which our bodies are physically located. […]We all now exist in several time zones at once, and in the virtual time of no place at all' (Hoffman 2009). However, as we start to understand the building as a zone of exchange rather than a zone of delineation between the inside and the outside, we realize the necessity of thinking the home as a dynamic environment, not only connected, but actually fundamentally interdependent of its surroundings. We explore this issue further with the design of *Reef*.

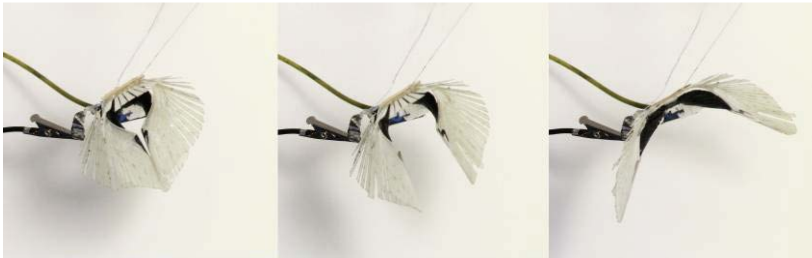
4 Reef: a self-actuated ceiling surface for the home

Reef is a material tale: an embodied scenario for the future where reality and fiction meet as to question and mediate how to appropriate new technology in the everyday. This on-going experiment focuses on the conceptualization and materialization of a responsive interior through the probing of a self-actuated ceiling installation. The architectural exhibition 1:1 will serve as a public venue for the testing of a 1:1 prototype[1]. The objective is to engage dielectric elastomers at the architectural dimension, both in terms of scale of apprehension and production while questioning how adaptive minimum energy structures can contribute to re-establish the home in a synergic relationship with nature.

Composed by an archipelago of electro-active modules, *Reef* constantly re-designs its own landscape as its modules change shape according to wind intensity and direction. In a very straightforward sense, this is achieved by a wind sensor coupled with a micro-controller that in turn induces the actuation of the modules by allowing, via electrical signals, the passing of information between the exterior and the interior. Actuation in this process is used as a mean to materialize the invisible flow of energy that connect the inside and outside.



8 Model for the self-actuated ceiling surface Reef



9 Reef's electro-active module in actuation

Reef combines a hundred of self-organized and energy-minimized modules. Mixing both responsive and non-responsive structures across three different sizes, they rely on an elliptic geometry, optimized with local reinforcements. Decorative fringe serves to visually amplify their motion. The active modules are paired together in three distinct parallel circuits, according to their voltage requirement. Working from a simple set of rules, they are programmed to breathe at the pace of the exterior. They open and close gradually following the pulse of the wind. When wind conditions are light, the modules are slowly opening to reach their full pre-stretched configuration. On the other hand, when wind-speed

[1] Exhibition 1:1, by Institute for Design & Communication, Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen, 11th of March -10th of April 2010

is increasing, their pace of opening is accelerating while the amplitude of motion is decreasing. Similarly to the leaves of a tree in the wind, the coordination in space and time of the modules is also induced by wind direction. Like coral reef, the installation is expecting to calcify over time as the supporting technology is becoming obsolete, giving back actuation in the inhabitant's hand via domestic airstreams.

The choice of wind sensing derives from an interest in exploring how buildings, instead of ignoring natural rhythms and cycles, can encourage us in reconnecting with natural and biological temporality. This goes notably through a renewed sensitivity to natural patterns of time such as day and night cycles, the change of weather or seasons etc. While the apprehension of time through light appears as the obvious (sundial), wind as an integrant part of the architectural vocabulary represents a rarely investigated medium.

Even though its organization may recall the shoals of corals, *Reef* keeps its name from the world of sailing, equally evoking this part of a sail that can be tied or rolled up to make it smaller in a strong wind. Like the sail, *Reef*'s module folds and unfolds as they sense wind. Both are subjects to the unpredictability of its variations. Both work as metaphor of control and actuation. However, while the sail satisfies a specific need: controlling the stability of the ship, *Reef* stands outside of the primacy of the user. Self-actuated, it is actively engaged in the activation of its own environment. In that sense, Reef is more about connections – the ability to form a good relationship with somebody so that you like and understand each other- than interactions - possibility of exchanging conversations between two systems-. *Reef* is actually establishing new relationships between the living and the built in that the inhabitant is invited to live with the architecture, with its surrounding environment, as opposed to a part from it.

Reef is currently being prototyped. To date, we have achieved the optimization of the three sizes of electro-active modules, both in terms of geometry and actuation while activating 10 modules simultaneously. Nonetheless, many challenged are still to be faced: what are the limits of this proliferation? Does their association impacts on the quality of their actuation? Which level of temporal definition can they reach? How people will relate to the installation? How long the installation will remain alive?

Discussion of Reef in the context of a responsive architecture Drawing the outlines of an environment that feels and breathes at the pace of exterior, *Reef* share similarities and concerns with Sargasso Cloud, a responsive architectural installation by Philip Beesley and Mette Ramsgaard Thomsen (Ramsgaard Thomsen 2009) where aerial kinetic structure exchanges energy with its sub-layer as mean of actuation. Both structures are dynamic canopies driven by a cellular logic. They explore an architecture of foliage, where space become a 'timescape' (Adam 1998) defined by the interactions between each of its parts. While Sargasso Cloud is the design of a world in itself, it does not connect or exchange outside of its physical boundaries. On the other hand, by echoing wind through its surface, *Reef* establishes a tangible connection between the interior and the exterior. This relationship belongs more to the world of transmission than to communication. 'A transmission is a communication optimised by a body, whether it is an individual or collective one. If there is some immediate, direct, joyfully transitive communications, a transmission is neither immediate nor impersonal' (Debray 2000). If *Reef* establishes communication between the inside and the outside through the passage of encoded information (wind sensor signals), its interaction with the inhabitant is not immediate and certainly not acquired. It is inscribed in a longer time that do not operate between here and a elsewhere but rather establishing a continuity between a before and an after. By enhancing the perception of a natural phenomenon such as wind, *Reef* seeks to establish an intuitive relationship between nature and the inhabitant by the transmission of a temporality that is beyond control and predictability, where the temporality of real-time technologies is synchronizing with the time of nature, arousing a new awareness.

The two installations also distinguish from each other by their materiality. If they are similarly built on digital manufacturing processes, *Sargasso Cloud* presents a more diverse system of sensors-actuators (proximity and touch sensor, air muscle, shape-memory alloys, power cells), giving rise to a more sophisticated interaction. However, Reef is build upon radically new materials that have rarely been physically experimented at such scale and in such a context, which explains its relative simplicity of interaction. In terms of actuation, it could be argued that *Reef* could eventually be more easily, at least more directly activated through natural ventilation as Ned Khan's work proves (Khan 2009a). However *Reef* rather works as a metaphor, expressing the need for technology to synchronize with the time of nature as a mean to reintroduce a culture in which technology is less human-centred than environmentally interconnected.

5 Conclusion

Today, if the idea of a truly adaptive environment becomes tangible through recent development in material science and engineering, architect and designers have just started to engage with what smart materials and intelligent structures have to offer. The minimum energy structure design principle presented in this paper enables the efficient and fast manufacture of aesthetically pleasing constructs with an incredibly large design space. The inclusion of active materials allows the structures to express temporally varying influences. Minimum energy structures, and their active counterparts, form a new design principle that expands beyond the design of adaptive architecture. Nonetheless, by developing a vocabulary of electro-active movements and by pushing material research towards real-world applications, the research presented in this paper extends the emerging repertoire and techniques for the use dielectric elastomers actuators in an environmentally responsive architectural context. It also highlights a method in which kinetic behaviour that would otherwise be digitally driven can be directly programmed into a material composition, allowing the design of complex 3D adaptive structure through a simple manufacturing process while creating a new material nearness for architecture. Besides, *Reef* as an appropriation of these materials in a domestic context suggests new possibilities for reacquainting the concept of a home as a space interconnected with its natural environment.

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References

ADAM, B., 1998. *Timescapes of Modernity: The Environment and Invisible Hazards.* London, New York: Routledge.

ADDINGTON, M., 2009. Contingent Behaviours. *Architectural Design,* **79**(3), pp. 12-17.

ADDINGTON, M. and SCHODEK, D., 2005. *Smart Materials and Technologies for the architecture and design professions.* Oxford, Uk: Architectural Press; Elsevier.

ASHLEY, S., 2003. Artificial Muscles. *Scientific American,* (October), pp. 53-59.

BERZOWSKA, J., MAINSTONE, D., BROMLEY, M., COELHO, M., GAUTHIER, D., RAYMOND, F. and BOXER, V., 2007. Skorpions, Kinetic electronic garments, 2007, .

BEUKERS, A. and VAN HINTE, E., 2005. *Lightness: the inevitable renaissance of minimum energy structures.* 4th edn. Rotterdam: 010.

DEBRAY, R., 2000. *Introduction à la médiologie.* Paris: Presses Universitaires de France.

DECKER YEADON, 2010-last update, Homeostatic static façade system. Available: http://www.deckeryeadon.com/projects/HomeostaticFacadeSystem.html [02/07, 2011].

FOX, M. and KEMP, M., 2009. *Interactive Architecture.* 1rst edn. New York: Princeton Architectural Press.

HENSEL, M., 2010. Performance-oriented Architecture - Towards a Biological Paradigm for Architectural Design and the Built Environment. *FORMakademisk,* **3**(1), pp. 36-56.

HILDEBRANDT, S. and TROMBA, A., 1996. *The parsimonious universe: shape and form in natural world.* Springer-Verlag New York Inc.

HOFFMAN, E., 2009. *Time.* London: Profile Books.

HOLDEN DELEURAN, A., TAMKE, M. and RAMSGAARD THOMSEN, M., 2011. Designing with deformation -sketching materials and aggregate behaviour of actively deforming structures, *SimAUD 2011 - Symposium on Simulation for Architecture and Urban Design* 4-7th of April 2011 2011, .

KHAN, N., 19/10/2009, 2009a-last update, Wind. Available: http://nedkahn.com/wind.html [02/14, 2010].

KHAN, O., 2009b. Elasticity, the case for elastic materials for kinetic and responsive architecture, *11th International Conference on Ubiquitous Computing, Archibots workshop,* 30th September 2009b, .

KOFOD, G., PAAJANEN, M. and BAUER, S., 2006. Self-organized minimum-energy structures for dielectric elastomer actuators. *Applied Physics A: Material Science & Processing,* **85**(2), pp. 141-143.

KOFOD, G., WIRGES, W., PAAJANEN, M. and BAUER, S., 2007. Energy minimization for self-organized structure formation and actuation. *Applied Physics Letters,* **90**.

KRETZER, M., ROSSI, D., AUGUSTRYNOWICZ, E., GEORGAKOPOULOU, S. and SIXT, S., 12/10/2010, 2010-last update, ShapeShift. Available: http://caad-eap.blogspot.com/ [02/07, 2011].

KWINTER, S., 2002. *Architectures of Time, towards a theory of the event in modernist culture.* First MIT Press paperback edition edn. Cambridge, Massachussets; London, England: MIT Press.

LELIEVELD, C. and TEUFFEL, P., 2010. Smart composites for architectural applications, *International Association for Shell and Spatial Structures (IASS) Symposium 2010, Shanghai Spatial Structures – Permanent and Temporary,* November 8-12 2010, .

LENDLEIN, A. and KELCH, S., 2002. Shape-memory polymers. *Angewandte Chemie International Edition,* **41**(12), pp. 2034-2057.

RAMSGAARD THOMSEN, M., 2009. Sargasso cloud: environment and response. In: O. WEDEBRUNN, ed, *Climate and Architecture.* Copenhagen, Denmark: Royal Danish Academy of Fines Arts, School of Architecture, pp. 23-29.

RITTER, A., 2006. *Smart materials in architecture, interior architecture and design.* Basel: Birkhäuser.

VAN OOSTEN, C.L., BASTIAANSEN, C.W.M. and BROER, D.J., 2009. Printed artificial cilia from liquid-crystal network actuators modularly driven by light. *Nature Materials,* **8**(8), pp. 677-682.