Most designers of dynamic building skins that reconfigure themselves in changing conditions have utilised mechanical systems. However, when designing for dynamic responsiveness, these systems often involve intricate and high-tech mechanistic joints, actuators and control. This research investigates the possibility of the ‘soft’ form-changing material systems to minimise the use of ‘hard’ mechanical components for kinetic responsive architectural skins. The research goal is to develop a prototype system that can be used to retrofit an existing building with an application of a ‘second skin’ that performs well in various climate conditions and is visually compelling. This approach is tested by the prototype, namely “Curtain”. It serves two fundamental purposes: Comfort and Cosmetic, to improve the existing interior and exterior spatial conditions. As an early proposition, the significance of this research offers a practical method for realising a ‘soft’ transformable architectural skin that synthesises passive cooling, manipulates sunlight and is set as an active shading device. Parametric design is used to explore and simulate these climatic and visual design constraints.
1 Introduction

In recent approaches, architecture has adopted kinetic motion as a process of environmental adaptation and responsiveness. We now consider architecture as extendable and changeable in time as well as space. This growth is not merely relative to size or motion but concerns energy and the transformation of spatial forms and material substances (Brown 2003). However, this approach often focuses on expensive, intricate kinetic, mechanical systems and physical control mechanisms for actuation and structural transformation. The reliability and longevity of these systems is the main hindrance to them becoming mainstream in architectural design. The responsive robotic screen of L’Institut du Monde Arabe 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 behaviour 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 Zuk and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems (Zuk and Clark 1970). Two important attributes of kinetic architecture are integrated in the work of dECOi: Aegis Hyposurface (1999-2001) and of Chuck Hoberman: Aldar Central Market (2011). The two attributes are responsiveness and a transformable kinetic building skin. These building skins demonstrated the ability to manipulate the interior spatial conditions using a complex mechanical façade and a roof system. However, these solutions involving complex ‘hard’ mechanical components like multiple pistons to actuate transformation always come heavy and with high energy consumption. Since the ‘soft’ approach of architecture introduced during the ’60s and ’70s, there has not been 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 the use of day-to-day ‘soft’ elastic materials for constructing kinetic and responsive architectural model. This investigation takes the position that a more organic rather than mechanic 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). Omar Khan’s Gravity Screens provide a novel active response in which 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 the soft responsive architectural idea and there is still unexplored territory to expand this potential of responsive architecture, from ‘hard’ to ‘soft’ approach.

Current researchers attempting to address this ‘soft’ approach include Tristan d’Estrée Sterk and Kas Oosterhuis. While Sterk produced tensegrity components actuated by pneumatic muscle to design a responsive architectural structure (Sterk 2006), Oosterhuis used pneumatic muscle as an architectural membrane to respond to various spatial conditions (Oosterhuis 2003). Their research provided the insightful knowledge of the initial ‘soft’ approach for responsive architecture. However, there is lack of further research especially in terms of porosity of ‘soft’ architectural envelopes that respond to environmental and communication inputs.

Building on the success of pneumatic muscle 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 interchange of elasticity and memory in form-changing materials to affect physical transformation and kinesis in architecture. In contrast to the conventional kinetic system, ‘soft kinetic’ offers movement and change in response to material properties rather than changes in mechanical components such as actuated motors and gears. This shift challenges the current notion of kinetic structure relying on external
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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, liberates the transformable skin from heavy structure. The 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).

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### 2.1 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 2006). Living things achieve very high strength and elastic behaviour with soft and extendable tissues, and are able to carry loads and grow. Soft natural tissues are very strong, and achieve flexibility and adaptability with simple fibre members, arranged in complicated hierarchies. One potent way of approaching the design and production of the responsive structures is to examine the characteristics of elastic material behaviour. Elasticity is one of the most important characteristics of the physical world, and is the result of the chemical bonds between the atoms that a material is made of (Mangelsdorf and Happold 2004).

A critical characteristic of elastic materials is that they deform, in a reversible 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: architects have tended to shy away, cowed by questions of liability and lack of experience (Hensel and Menges 2006). Thus, the experiments presented here further investigate the understanding of the performance, capacities and behaviour toward the elastic architectural skin within the initial framework of 'soft kinetic' system.

### 2.2 Tensegrity

The tensegrity structural approach reduces the friction between mechanical joints and achieves a lightweight structure. Tensegrity structures are particularly interesting when considering the development of responsive systems. Due to the interdependent nature of all the elements, a slight change in any of their parameters can result in a significant form transformation (Frumar and Zhou 2009). 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 electric current changes. Electrical stimuli create heat causing the atoms of the metal to vibrate faster and 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 (shape memory alloys) are by nature dynamic and deformation occurs under electrical stimuli in this experiment, using: 12V for a 3.18 amp current (Figure 1). There are two stable crystalline states in their structures. When a temperature change occurs, a triggering from one crystalline form to the other occurs.

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 (Harti and Lagoudas 2007). 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 8% when heated and cooled (Figure 2). The typical expansion of SMA in relation to temperature is graphed in Figure 2. When SMA is below the ‘transform’ temperature (60 degrees) the material takes on an ‘elongated’ and neutral form, but if heated it contracts and returns to the ‘memorised’ form. This process creates a dynamic range or hysteresis in the way
that the SMA wire expands and contracts for various state changes.

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

We propose that the form-changing material embedded in the elastic tensegrity structural component is an alternative for less energy and simpler actuation to control and regulate the behaviour of responsive architectural skins. This material that operates inside the tensegrity 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 it has more potential, and is more economical and silent than conventional mechanical approaches. Figure 3 shows four potential profiles for ‘Soft’ actuation based on the process of Expansion and Contraction in specific parts of the SMA wire. While profile one and two show the potential for the pull and push actuation, profile three and four functioned 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 tensegrity 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 morph while minimizing complex mechanical components. This investigation will demonstrate a series of early physical and digital prototype experiments using form-changing materials to control and actuate elastic transformable skeletal structures and surface models. This prototype system, ‘Curtain’, is a design module for integration of skin and structure intended to improve the interior spatial conditions of existing buildings to allow us to attain a representation of the concept of ‘soft kinetic’ discussed in section 2.

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

3.1 Skeleton

The main intention of ‘Curtain’ is to fabricate a simple and lightweight skeleton. It is to minimize the complicated and heavy mechanism such as joints and actuators in order to produce a highly flexible structure. The tetrahedron modules form a tensegrity space frame (Figure 4). The integration of lightweight components such as MDF board and fishing string makes the physical model easy to construct (Figure 5).

Figure 3. Four potential profiles for ‘Soft’ actuations of SMA wire
Figure 4. Simple ‘inverted’ tetrahedron module formed the basic backbone of the skeleton of the “Curtain”
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 metaphor is not new; however, this approach still holds a lot of potential to develop responsive architectural skin especially in terms of lightweight and passive design implementation.

The multilayer skin of ‘Curtain’ explores the responsiveness to the porosity performance for the existing building fabric using elastic lightweight material. 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 porosity is inspired by the performance of the eye. This analogy of an ‘eye-like’ permeable louvre functioned as a skin muscle mechanism in the eye which allows various porosity patterns (Figure 6). The eye-like louvres in the geometry are determined by their relative curvature on the responsive undulating surfaces and actuated by SMA 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 term ‘soft kinetic’. This introduces two simple types of physical material transformation: Contraction and Expansion. This soft kinetic transformation allows the actuation to take place in any three-axis configuration resulting in complicated malleable performance of the transformable skin. However, the homeomorphic constraints of the architectural skeleton and skin provide the motivation and limitation to develop the skin surface transformation in three different types:

- **Morphological transformation**, the global surface curvature of “Curtain” is modifiable. It allows contraction and expansion while it maintains the continuous topology of any undulating or flat surface. 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 realtime analogue media effect can manipulate the various appearances of the skin, therefore the existing building envelope is in constant flux as part of a ‘dialogue’ with the environment and occupant interacting with it (Figure 8).

- **Porosity transformation**, the transparency of the surface is generated by the individual ‘soft’ opening that responds to sunlight penetration and shadows cast. 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...
‘Second Skin’ that creates a climatic and visual envelope. Therefore, in order to achieve this responsive phenomenon, a form fostering technique using sensors and actuators is necessary that roughly simulates the biologic behaviour (Salim, Mulder and Burry 2011). First, Grasshopper and Firefly parametric software together with Arduino microcontroller, light sensors and potentiometers, are used as design tools engaged with this simulation process (Figure 10). Second, the actuation is involved through the use of an SMA spring that serves as an actuator to reduce mechanistic components. The goal of this parametric model is to be an elastic tensegrity skin actively responding 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.

4 Application

There are currently two applications under investigation. The first application is a response to specific aspects of environmental conditions, such as altered shading response to changing light conditions. “Curtain” serves as a regulator between the exterior and interior environment by integrating digital sensing devices. 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

“Curtain” supports the application Comfort using the kinetic undulating surface to regulate shading and shadow control to improve the comfort level of existing spatial conditions. This function embeds a data input schema and form 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 photo resistor and the torchlight mimicking 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 improperly designed building. For instance, by creating a ‘transition’ space in-between ‘second skin’ and the existing roof structure, a new private usable area is formed. The spatial quality for the occupants of this new roof space is manipulated by the transformable ‘second skin’ in terms of air ventilation and light penetration. The ‘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 ‘eye-like’ permeable louvers discussed in subsection 3.2. This cosmetic intervention creates a new layer of communication between existing building skin and the surrounding urban fabric.
because of its constant malleable porosity through input of realtime information (Figure 13). The shadows cast into the existing interior space through this process provides a morphing atmosphere that suggests a continued relationship between exterior and interior (Figure 14). This is an alternative approach if compared to the conventional digital media screen lacking the consideration of its effect on the interior condition especially in porosity and permeability.

5 Conclusions and Future Work

From the early experiments of the “Curtain” model, we conclude there is a place for full-scale application of the ‘soft kinetic’ responsive spatial environment, and it has the potential to be developed further in terms of the reciprocal relationship 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 platform for a shift from hard to soft material system approaches to the architectural envelope. It also develops an appropriative method for studying soft responsive architectural skins that will improve the quality for our future experiments. Instead of inventing systems 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 vision.

This research investigates new possibilities of the softness and elastic in form-changing material systems for building skins that respond to various environmental conditions. The design of this soft responsive skin challenges the traditional ‘hard’ approach of the glass and steel building envelope. Building envelopes constructed from soft and elastic material seem ‘paradoxical’ because architecture is built to last, whereas soft material appear to be without structural integrity. However, advances in soft material technology such as Ethylene Tetrafluoroethylene (ETFE), Polydimethylsiloxane (PDMS), Electro-Active Polymer (EPA), Aramid 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 architect. Examples are inflatable membranes, braided cables and metal mesh. This soft structural system is full of potential for further development of kinetic responsive architectural skins and envelopes in terms of climatic and visual control. The flexible and lightweight characteristics, with few, or no mechanical components needed for actuation mean that it reduces energy consumption as well. The textile structural approach therefore will be part of our future research into experiments for architectural performing skins within existing building contexts. This future research will include the realtime analysis of textile architectural skins in terms of thermal comfort, solar energy and global geometry with live connections between the physical and the digital model.
References


