Smart Autonomous Flexing Modules: A Shading System that Acknowledges the Materials' Performative Capacities

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Abstract— **As an alternative for the energy consuming and complex mechanical architectural responsive systems, a seamless approach is emerging employing performative shape changing materials in creating autonomous systems which rely solely on the material's performative capacities and molecular intrinsic attributes. This paper introduces two designs for smart autonomous shading systems that are implemented within building envelopes. In fact, they incorporate the shape changing smart material; shape memory polymer (SMP) in which its shape changing effect is triggered by temperature increase in a self-propelled manner. Laboratory experimentations are conducted to test both designs utilising SMP sample representing shading surfaces that can be attached to the building. The surfaces are flat; closing (providing shade) when the temperature is 35 degree Celsius or more and bend to open (allowing light penetration) when it is 25 degree Celsius or less. The experimentation verifies the notion behind the designs as a promising green alternative exhibiting preliminary success. This experiment is an exploratory trial towards investigating the possibilities of the applications of shape changing smart materials architecturally driven by the primal aim of saving energy.**

Index Terms—**responsive material system, shape changing smart materials, autonomous response, shape memory polymer, self-propelled shading system.**

I. Introduction

Smart buildings are manifested through myriad design approaches and applications; most of which usually rely on computational control systems. One particular application is the utilisation of smart materials within building envelopes; however, thus far, the application of smart materials architecturally is limited to static applications such as thermochromics and piezoelectrics. Shape changing materials have been thoroughly examined and implemented within various fields; space and aircraft applications, biomedical devices, textiles (smart clothing) and structural repairs for buildings. However, within the architectural field, their application is yet in its infancy as many distinct factors have to be examined in order to create a well-functioning smart material system. Thereby, this paper aims at setting a further step to address such research gap.

This paper is divided into two main parts; the first introduces two design scenarios for a shading material system that can be implemented within the building envelope. In fact, the designs are based on the shape changing materials attributes. Two simplified prototypes for both designs are then constructed and their behaviour is experimented to test the behavioural shape change when the temperature rises to 35 degree Celsius. The material tested is a sample for shape memory polymer which is imported from Japan with a glass transition temperature (T_g) 35 degree Celsius. These experiments are considered to be an initial verification for the smart design scenarios proposed.

II. Responsive Architecture

In the sixties, the prevailing approach concerning building envelopes enhanced delineation and accelerated the material boundary creating a hermetic division between the exterior and the interior spaces. This was paralleled with the encouragement of enclosed environments which eventually led to the advent of mechanical electrical interior climate modulation [1]. The beginning of mechanical system automations in the fifties eventually grew into intelligent buildings movement in the eighties and the present smart environments which is much about strategy as it is about technology [2].

One definition for responsive architecture is introduced by Sterk (2006) stating "*those that actively change in response to new environmental conditions and patterns of use… responsive architectures actually consist of intelligent frames, skins and systems*." [3].

A. Principles of Responsive Building Element (RBE)

There are four key principles for a responsive building element; Dynamic behaviour, Adaptability, capability to perform different functions, and intelligent Control [4].

Dynamic behaviour represents the features, functions and/or thermo-physical properties of the elements that may change over time to suitably fit specific needs or requirements. It is a dynamic response for a specific influence such as direct sunlight or high temperature.

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Adaptability represents the way the 'adaptive' concept of the responsive element fits to different building occupants' requirement/needs (heating/ cooling, higher/lower ventilation, etc..) and to different boundary conditions (meteorological, internal heat/ pollution loads, etc...) [4].

Both the "dynamic" and "adaptable" concepts are crucial principles that must be a part of a successful responsive building element. On the contrary, the third principle which is the *capability to perform different functions* is an extra optional principle. A responsive element could have one main function responding to a specific influence; whereas, in some cases the system could have different functions. One example is a system that responds to direct sunlight intercepting its path, which eventually causes a reduction in the indoor temperature as well as the light intensity; hence, the system indirectly performs more than one function [4].

Intelligent control is responsible for fitting and tuning the proper functionality of the responsive element at the component level where controls the whole process of responsiveness including the initiation and the ending. RBEs must be integrated under the supervision of intelligent control and a suitable strategy, in order to effectively exploit their potentials and accomplish optimum balance between energy efficient and indoor conditions. Conventional mechanical systems rely to a large extent on external computational intelligent control, whereas, the proposed material approach rely mainly on its behavioural pattern as its intelligent control [4].

B. Conventional Responsive Systems

Responsive systems mainly depend on two components; Physical components which allow the system to adapt and respond and Computer programs which provide information on how to respond and what to do [5]. Altogether, any adaptive system consists of three main components; sensors, actuators and control unit as illustrated in Fig. 1.

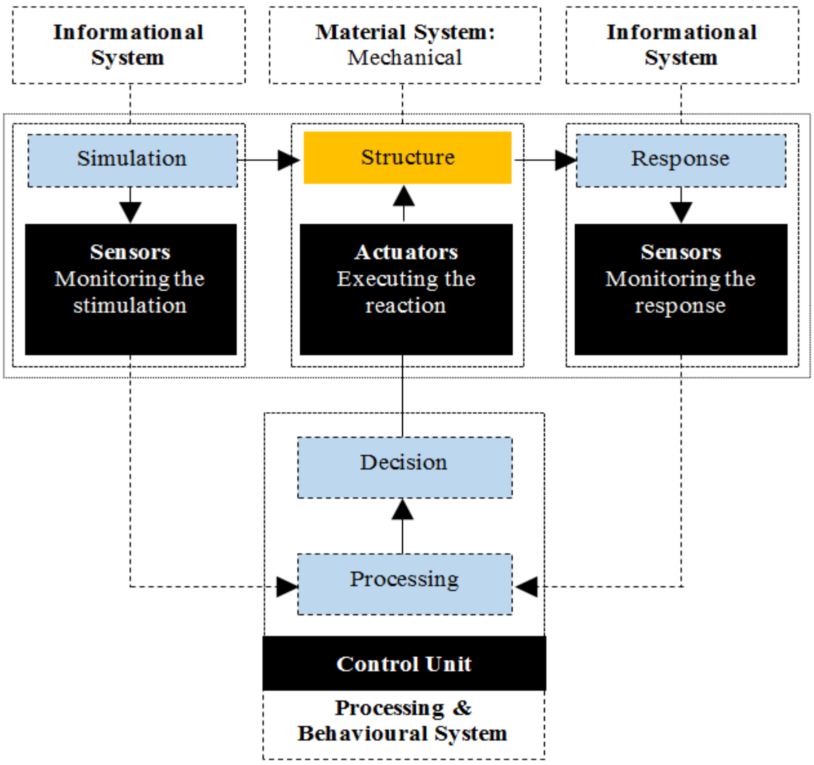

Figure 1. The components of adaptive systems.

Physical components in a responsive system, are defined as all hardware and devices required to generate such system. Despite the diversity in their function, all hardware parts share one aim which is generating a valid responsive system [6].

Two main parts are required in intelligent automation; a sensor, which identifies the influence and its changes; and an actuator, which carries out the appropriate responsive action. Sensors operate actuators, triggering a wide range of kinetic responses which alter space in a physical manner, services that alter the environment or materials altering their state. This is considered the simplest form of a system; however, in complex arrangements, there are much more components; a computer program is the most common providing an interface and maintaining control. Such components consume a considerable amount of energy to function [7].

When the numerical input data is processed and computed into information which could be usable as responsive output information, output data is sent to actuators. Actuators are devices which receive information and act upon them, either by moving, illuminating, etc. [6]. An example of a unique combination of sensors and actuators is dECOi's Aegis Hyposurface. The project uses many sensors for sound, presence, light and movement to execute a single reaction, which is a change in its surface topography.

C. Mechanical Kinetic Facades

The idea of *'the machine'* has been always considered by architecture as an intriguing concept where ideas are reflected upon and it is easily attached to terms such as progress, efficiency and technology [8]. In fact, such kinetic approach was and still is achieved through the implementation of mechanical systems and intelligent technologies. Various machines both discrete and as parts of a building's services, are considered a feature in contemporary architecture, which is likely to intensify in the future rather than diminish. However, although buildings nowadays utilize more sophisticated technological features and mechanisms, the way the building is used is fundamentally non similar to a machine's use [7].

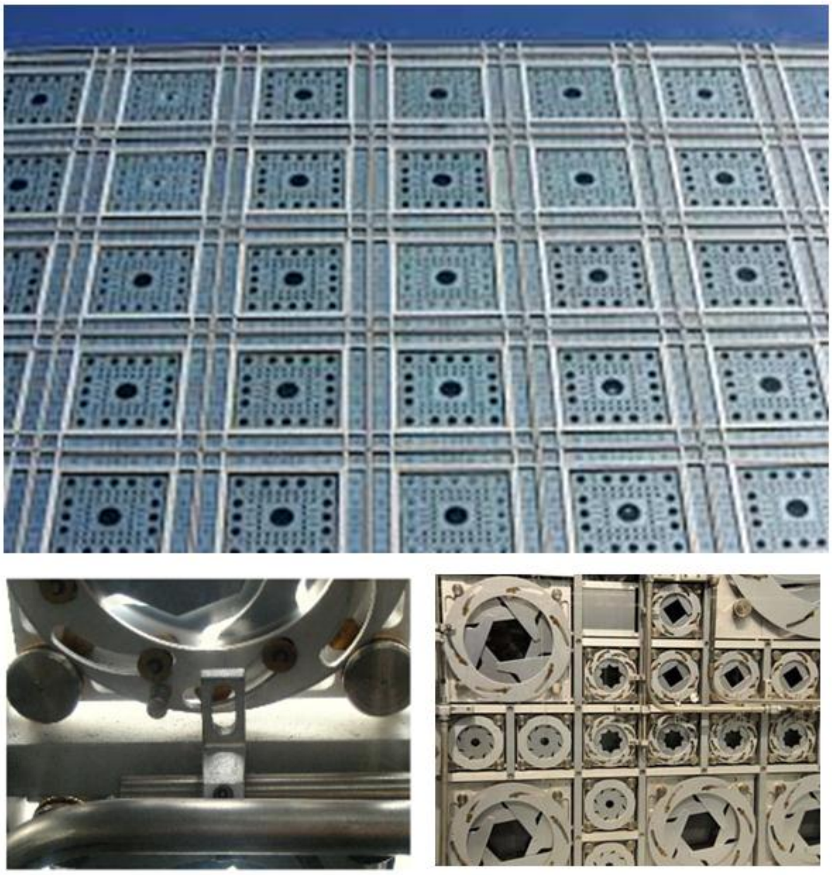

Figure 2. The kinetic responsive Façade of Institut du monde arabe in Paris consisting of light regulating apertures. The bottom figures illustrate the complex hard components, interrelations and the intricate diaphram actuator.

Indeed, mechanical systems allow centralizing control and monitoring; in addition to being reliable, and relatively inexpensive. Nevertheless, these systems require an independent energy source to power their actuating operations. In addition, mechanical systems have particular requirements and technical problems which face them regularly due to the complication of such system mechanisms and myriad physical components.

One critical example is the considerable number of mechanical joints and complicated configurations that operate behind the mechanical shutters in the façade of the institut du monde arabe which eventually caused a short lifetime for these devices. Another example is dECOi's HypoSurface which employs a heavy bed of 896 pneumatic pistons that actuate the transformation while consuming a considerable amount of energy.

III. Smart Materials

The world has witnessed two material ages; the plastic age and the composite age, while in the midst of these two, a new era has emerged namely smart materials era. Smart materials are those that receive, transmit or process a stimulus and respond by producing a useful effect that may include a signal that the materials are acting upon it [9]. Interestingly, Smart materials could be introduced as a material, a composite, an assembly or a system. Such definition denotes smart materials as a series of actions rather than a static artifact [10].

A. Properties

Smart materials and systems exhibit five main characteristics namely, immediacy, transiency, self-actuation, selectivity and directness. Immediacy is the ability to respond in real time while transiency is responding to more than one environmental state. Self-actuation entails the internal intelligence and innate performative capacities, while selectivity denotes that the response is discrete and predictable. Finally, directness means that the response is local to the 'activating' event, and this feature is particularly challenging [11].

Many of the smart materials demonstrate reversibility or bi-directionality reversing their input and output energy such as piezoelectric materials that produce a current from an applied strain. Bidirectional behaviour can be illustrated by shape memory alloys allowing the material to replace components comprised of several parts. Additionally, the precise makeup of the material's internal structures and bonding forces between them predominately determine the materials' properties such as the mechanical, electrical ones and others; subsequently, they are the determinants of material behaviour [11].

B. Classification

Smart material systems exhibit smartness in two approaches, which could be applied to a single material directly, and to a compound system conceptually; property changing and energy exchanging [11].

The first mechanism is ***property changing*** materials where they exhibit changes in one or more of their properties (chemical, mechanical, magnetic, thermal, etc.) in response to an external stimuli's change. One example is the photochromic material which alters its colour responding to the incident ultraviolet radiation. The second mechanism is ***energy exchanging*** where the material transforms an input energy to an output one in another form, in a direct reversible manner. An electro-restrictive material that transforms electrical energy to elastic (mechanical) is an example of this type [11].

C. Shape Changing Materials (SCM)

Shape changing materials exhibit mechanical deformation under the influences of direct or indirect stimuli. They are by nature dynamic, in addition to the static properties that are featured in other conventional materials. In fact, shape changing materials encompass property changing smart materials in addition to other materials such as natural ones for instance, wood or soft flexible materials such as elastomers [12].

SCMs have been thoroughly examined and implemented within various fields; space and aircraft applications and structural repairs for buildings. However, within the architectural field, they are still in their infancy; mainly experimented in the form of prototypes with no practical application on existing buildings so far implemented. The most commonly used ones are shape memory alloys (wires, springs or as stand-alone actuators) and shape memory polymers (SMP) [13].

D. Shape Memory Polymers

Shape memory polymers were first introduced in Japan in 1984 [9]. Different types include cross-linked poly-ethylene, amorphous poly-norbornene, and shape memory polyurethanes. SMP shape change is triggered by two types of stimuli; heat and light. These could be applied directly or indirectly such as IR-light or electricity; both can be used to heat the polymer [14]. The thermo-responsive feature has a glass transition temperature which ranges from 25 to 100 degree Celsius [15].

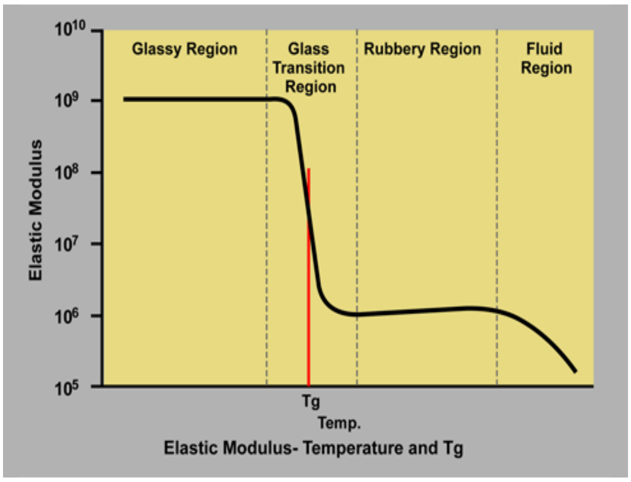

Figure 3. The different states of the shape memory polymer against the temperature. The shape change is triggered when the temperature reaches Tg within the Glass Transition Region.

SMP demonstrates large deformations due to the low tensile strength in the rubbery phase where the material can be elongated to up to 200% without plastic deformation [15]. The original shape of SMP refers to the shape in which the SMP was casted in from the molten pellets or by cross-linking the SMP resin inside a mold. T_g is the transitional temperature where when reached, the polymer regains its original shape. During the design of a particular component involving SMP, it is greatly essential to select the appropriate T_g [14].

Below T_g the polymer is in a glassy state where the molecular coils lose their flexibility causing it to be stiff and hard to re-shape; a solid glassy form. Hence, to deform a SMP, unconstrained heat must be applied with a temperature $T > T_g$; it can be stretched, compressed, twisted, or bent; a rubbery state. To maintain such deformed shape, constraining the deformed shape while cooling it below T_g will freeze the temporary shape which at this point exhibits lower entropy. When SMP is re-heated with $T > T_g$, it regains its original shape since this is the state of highest entropy [15].

IV. Smart Autonomous Flexing Modules (SAFM)

In an attempt to employ the intrinsic materials shape changing capacities within architectural applications, two designs for self-propelled shading systems are created and modelled computationally. In fact, these were specifically designed according to the behavioural attributes of the smart shape changing material (materially-driven design); shape memory polymer. This particular material was selected to be examined for two particular aspects; physical behaviour and experience.

A. Physical Behaviour

1) Thermo-responsive nature and Lower transition temperatures

SMP changes its shape according to change in temperature. This particular aspect is primarily significant as when the temperature increases, the shape change is triggered to provide shading to the indoor spaces. Additionally, SMP exhibits shape change at relatively lower transition temperatures than other materials like shape memory alloys (SMA); the temperature range starts from 25 to 45 degree Celsius. This specific range is found to be the most appropriate when utilized architecturally as this is the hot ambient temperature needed to trigger the movement of the shading elements.

2) Lower density and higher strains

SMP exhibits lower densities compared to SMA in addition to much larger strains; 400% compared to 8%, respectively.

B. Experience and Context

1) Partial opacity

SMP is characterized by transparency; however, this feature depends on the thickness of the manufactured surface; the thicker the SMP element is, the less transparent it becomes. For the purpose of being utilized within a shading component, such transparency can easily turn opaque through one of these two methods; dying or emery. Thereby, dying the material with a colour will reduce its level of transparency; likewise, increasing the surface roughness through creating tiny bumps on the surface by emery significantly reduces its transparency. In fact, absolute opaqueness is disadvantageous as this would block the view for the outdoors when the shading element is applied within a building envelope; hence, partial transparency is indeed a complimentary attribute.

2) Anthropomorphic Experience

SMP provides the users with an anthropomorphic experience; a life-like seamless, silent and smooth motion reminding them of the ‘liveness’ of the interacting buildings emulating the human body reactions.

C. The Working Mechanism of the Shading System

Designs A and B manifest self-propelled flexing modules which are positioned along the building façade to provide shading. The first design is composed of interlocking rectangular modules as depicted in Fig. 4. When the temperature increases the modules bend creating a chessboard pattern on the façade. The other design encompasses apertures within a larger surface as illustrated in Fig. 4. The apertures are created with a smaller scale compared to the latter design to provide more dispersed shading.

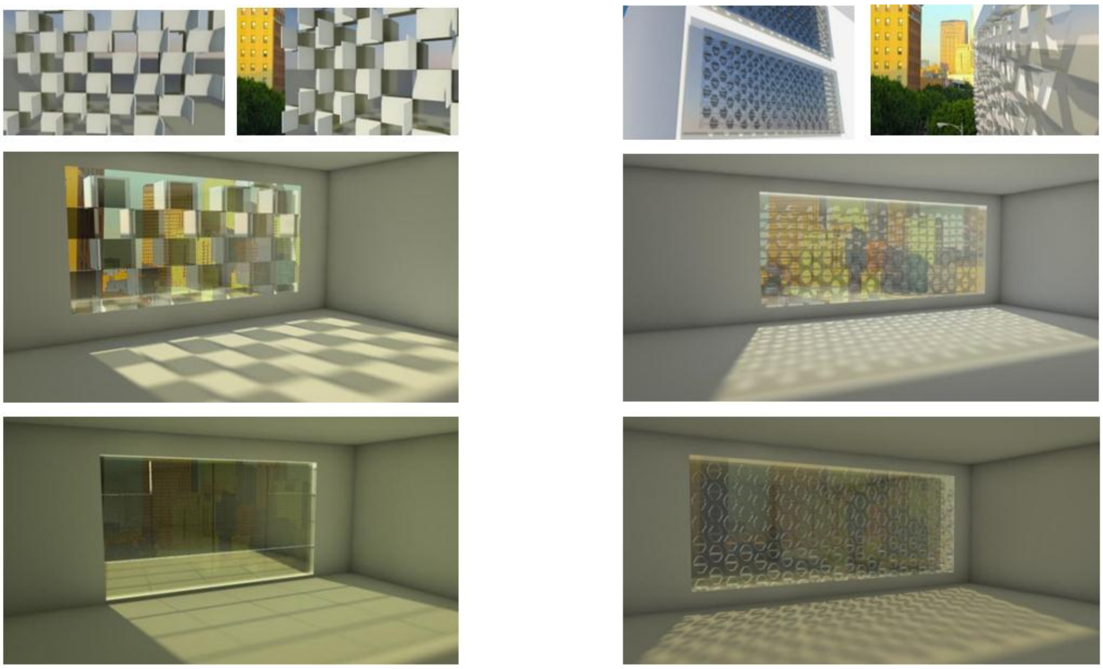

Figure 4. Right: Design A. Left: Design B.Self propelled flexing modules that are place along the building façade.The bottom photos demonstrate the interior space while the modules are opened and closed

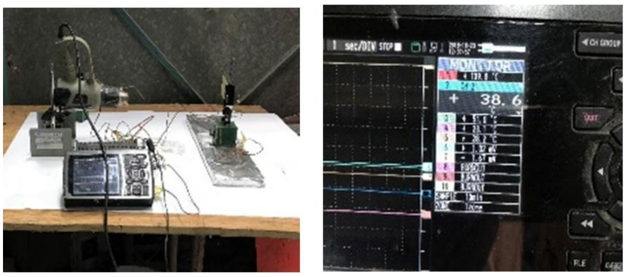

Figure 5. Left: The experimentation setup. Right: The thermocouple displays the temperature at which the shape memory polymer started its shape changing response; 38.6 degree Celsius.

Both designs function with the same shape changing mechanism; the modules bend opening when the temperature is 25 degree Celsius or below to allow sunlight penetration. On the other hand, when the temperature rises to 35 degree Celsius or above, the modules remember their flat memory shape and close, providing shade for the interior spaces. It is noteworthy to mention that such motion is autonomously iterative without the need for the users' intervention to initiate the response. In case the need for the user's control emerges, an external control system can be attached utilising sensors and other system components; however, in this case the whole system will not be utterly autonomous and will exhibit more complexity.

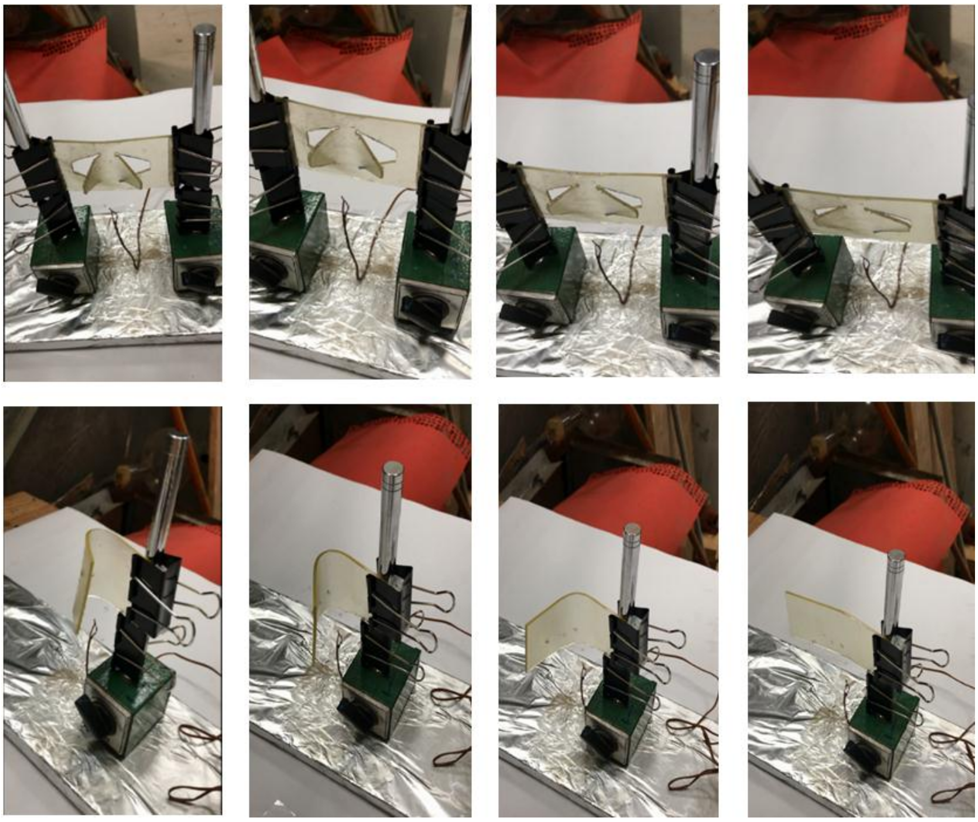

Figure 6. The self-propelled response of the shape memory polymer simulating Design A. The apertures are opened at room temperature of 25 degree celsius then it undergoes a closing process when hot air is introduced.

In fact, such reversing process of opening and closing requires utilising a two way memory shape polymer; remembers the bent position when the temperature is 25 and the flat position when the temperature is 35 or higher. However, due to the accessibility limitations and for the purpose of merely verifying the motion mechanism of such design, one way shape memory polymer is examined.

D. *Physical Experimentation*

1) *The tools*

The experimentations were conducted on a sample of SMP which is imported from Japan with a transition temperature T_g 35 degree Celsius. In order to set for the experiment, a number of tools were needed including a heat gun, a thermo-couple and magnetic base stands. The heat gun emits a stream of hot air emulating the outdoor hot air, the thermocouple is a sensor to measure the temperature at different positions and the magnetic base stands hold the SMP sample while being introduced to hot air from the heat gun. The experimentation setting is illustrated in Fig. 5.

2) *Experimentation*

The experimentations took place at the *Housing and Building Research Center* in Cairo, specifically in the *Lab of Building Physics Department*. As a preliminary testing to verify the working mechanism of the flexing modules, a rectangular SMP sample with dimensions 100 mm long and 5 mm wide is used. The sample was bent manually as an initial state to begin with (normally bent at room temperature of 25 degree Celsius) since this is a one way SMP.

In order to test the mechanism of Design A and the module's ability of returning flat and closing to create shade, the sample was held from one side and was subjected to hot air blown from the heat gun. The SMP started returning flat when the temperature reached 35 degree Celsius and higher till 38.6 degrees, reaching a flat state in a total duration of one minute and 20 seconds. Similarly the aperture of Design B is laser cut within the SMP sample and the bending behavioural properties were tested showing similar results to the previous experimentation.

The behaviour of the SMP is considered to be successful in changing its shape when introduced to hot air; nevertheless, in order to be applied in real time on actual building envelopes, it is advised to be used within a vacuumed double skin facade to protect the SMP from the distinct climatic conditions such as rain and dust which will affect its performance on the long run.

3) *Achieving the Principles of RBE*

The four aforementioned principles of a responsive building element are attained in the design of the SAFM. The Dynamic behaviour is manifested through the bending motion of the SMP in addition to achieving Adaptability where the SMP responds and adapts according to the ambient temperature. Both the Capability to perform different functions and the intelligent control are two of the most significantly critical principles to be discussed when designing responsive material systems. In fact, the material performs various functions replacing both the sensors and actuators; the SMP molecular structure enables the material to continuously sense the temperature and accordingly decides whether to maintain its current position or reforms to a different shape (actuators function). Such process denotes its intelligent intrinsic control without the need for an external processing and control unit.

V. Conclusion

In order to attain more environmentally aware architectural environments and designs, more attention should be heeded to creating smarter energy saving technologies and applications. Usually, smart responsive systems entail the implementation of complex mechanisms; sensors, actuators and processing units which manifest a number of technical issues; most importantly their energy consumption. The emerging alternative of utilising smart shape changing materials is considered a promising notion which neccessitates collaboration with material scientists due to its highly multi-disciplinary nature.

The experimentations conducted have demonstrated transient and autonomous shape changing response to the stimuli of high temperature. Such specific notion can be implemented within building facades in hot climate areas to provide self-propelled shading to the indoor architectural spaces. Nevertheless, such dynamic domain encompasses a great variety of factors which come in to play and interact to create various results and impacts ranging from functional, economic, environmental, technical, social and cultural aspects. In fact, these are equally significant and should be examined conjointly. Technically, a great amount of experimentations are necessary to be conducted to furtherly validate its applicability and determine its ability to endure the climatic conditions and numerous cycles.

The possibilities of employing such smart shape changing notion architecturally are endless starting from their application as responsive systems within building envelopes as demonstrated in this research, among their applications within the indoor spaces such as self-propelled partitioning systems.

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