adaptive[skins]: Responsive building skin systems based on tensegrity principles

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ABSTRACT:
The project investigates responsive building skin systems that adapt to the dynamic environmental conditions to regulate the internal conditions in a habitable space over different periods of time by exhibiting a state of motion and dynamism. Heat and Light are the primary parameters for regulation, leading to energy efficiency and dynamic spatial effects. Passive and active skins using shape memory alloys and pneumatic actuators are developed through investigations of smart systems that integrate smart materials and smart geometries. The precedents in this domain have rarely dealt with individually controlled multiple parameters of heat and light in a single system, which is attempted in this project. Owing to the complexity of the multi-parametric system, genetic algorithms are developed for system optimization and calibrated with physical prototypes at varied scales. The developed systems are tested against two distinct climatic models- New Delhi and Barcelona, and evaluated for performance, based on heat and light, which are quantified as solar gain and illuminance as principles, and daylight factor for evaluation purpose. The use of genetic algorithms makes the problem solving faster and accurate. New tool-sets are developed in the process by combining various digital tools, to create a real-time feedback and memory loop system.

KEYWORDS:
Adaptive architecture, Building skins, Genetic algorithms, Tensegrity, Smart materials.
1. Domain

Our lives are surrounded by constantly changing forces of nature and environment. Everything is in a constant state of flux, with varying degrees of dynamism. Our lives too, are always in motion. The spaces we inhabit are constantly changing as well, although the change is slow and occurs through non-physical conditions. The physical state of the inhabitable spaces are more or less constant and not in motion. A building envelope consists of vertical (facade) and horizontal (roof) components which protects the building from direct external environment and helps in maintaining comfortable interiors along with providing structure and stability to the building. A traditional building skin thus provides stability, regulates air pressure (fenestrations) and protects the interiors from direct environmental factors (sunlight, rain and wind). Building skins are a vital component to resolve the issues of responsive architecture as they are a medium through which the intelligence can be imparted to the building system to respond to an environmental stimulus. Thus key characteristic of an effective intelligent building skin is its ability to modify energy flows through the building envelope by regulation, enhancement, attenuation, rejection or entrapment.

The project adaptive [skins] questions the static nature of architectural spaces, and engenders dynamism and motion in architecture in a complex and dynamic environment. The line of research is responsive and dynamic architecture, where developments and advancements have been made in the past, dealing with dynamism and kinetics in architecture. However, a major setback in the current precedents lies in the use of mechanical control to create dynamism, which in most cases, is only for spatial effects and aesthetics. An attempt has been made in the research to deal with a bigger issue, for creating dynamism and response, for dealing with multiple environmental parameters which affect the internal conditions and energy efficiency. Also, there is an attempt to embed material intelligence into the system, to rule over the use of mechanical control, partially or completely. The use of two parameters - heat and light is very critical in the research, being individually controlled in a single system, as the issue becomes complex and requires efficient use of computation for problem-solving.

1.1 Adaptive Architecture

“Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations, and is one of the basic phenomena of biology.” (Charles Darwin, p1959).

The term ‘adaptation’ is commonly used in architecture in relation to the changing morphologies of the architectural artefact. These changing morphologies have been a result of timely changes and evolution of architecture as a social entity, technological product and as a practice. Through years of architectural evolution, changes have occurred in notions of how buildings are conceived and built. The architectural morphologies adapt to the time, in which they are conceived and realized. These adaptive morphologies are a resultant of changing times, social form, economic support, user needs and environmental effects. The environmental changes that occur in a given time, such as a day, can be a constant force of changes that need to occur in an architectural object, leading to local adaptations. The global climatic change, occurring over a course of time, creates forces for architectural object to change over the years, in order to survive and sustain itself. Adaptation in architecture is a long-term process that occurs with time and generations, where improvements in the technology, economic support as well as human thought-process, contribute to the adaptive response.
An intelligent pre-programmed mechanism of response and feedback is to be embedded in architecture, with a real-time response and improvisation, for it to be termed adaptive. It is a complex phenomenon with a multi-layered non-linear process.

1.2 Responsive Architecture

The term responsive suggests immediate action against a stimulus. The phrase Responsive architecture was coined by Nicholas Negroponte, who first envisioned it during the late nineteenth century when spatial design problems were being explored by applying cybernetics to architecture. He proposed that responsive architecture is the natural product of the integration of computing power into built spaces and structures, and that better performing, more rational buildings are the result.

It is an evolving subject in architecture which measures actual environmental conditions (via sensors) to enable buildings to adapt their form, shape, colour or character responsively (via actuators). Its aim is to refine and extend the discipline of architecture by improving the energy performance of buildings with responsive technologies (sensors / control systems / actuators). Responsive architecture is defined by Meyboom et al (2010) as an architectural "system that causes change to its environment."

The three main aims of the project are - energy efficiency, regulation of internal conditions and achieving a new sense of aesthetics and dynamic spatial effects. Energy efficiency is aimed by developing a component based system, where a small actuation can lead to an emergent effect, and by having a system where material intelligence is embedded. The internal conditions are aimed to be regulated by a state of motion in the system as a response to the changing weather conditions. Phenomenal conditioning can be achieved in a habitable space by modulating the building skin. Novel spatial effects can be a part of the desired output, creating a new sense of aesthetics by the virtue of its form and dynamism.
3. Methods

The two major parameters that drive the research / project are heat and light. These are articulated in terms of building science as SOLAR GAIN and ILLUMINANCE, respectively. These two become the input parameters to develop and evaluate the system.

Solar gain is controlled by changing the angle of incidence on a surface, which can change the angle at which sunlight hits the surface, controlling the amount of radiation that passes through. This simple principle is used as a parameter to control solar gain in a space.

![Diagram explaining the principle of solar gain](image)

Illuminance is altered by changing the light infiltration and regulating the amount of direct and diffused light that enters a space. By changing the angle of incidence of a surface, openings can be altered through which light can pass through, either directly as direct exposure or indirectly as diffused light.

By aiming for a dynamic system that changes the angle of incidence of the surfaces of a system, solar gain can be controlled by seasonal movements of the system. In summers, solar gain can be reduced to bring the internal conditions to a thermal comfort zone by INCREASING the angle of incidence of the overall surface / skin. In winters, the effect can be reversed by DECREASING the angle of incidence and increasing the solar gain to bring the temperature up to thermal comfort zone.

With the changing angle of incidence, direct light can be altered and converted to diffused light by configuring the surfaces in a certain way. Increasing the direct light also contributes to an increase in temperature and this effect can be used in a controlled way depending on the seasonal requirements. Also, direct light leads to glare, which needs to be controlled and changed to diffused light, for a good illuminance in a given space.

4. Interconnected Systems

4.1 Folded Geometry

A series of folded geometries are developed from a single surface of sheet, with folding based on ridges and valleys. The level of complexity is varied in different models by changing the overall pattern to understand the range of effects that can be produced. Since heat and light are the primary parameters guiding the evaluation of the effect, changes in the face angles is studied, along with general deformation and movement in the system. In some of the experiments, holes are punctured at strategic positions on the crease and on the faces, and shadows patterns are studied in different states of motion.
4.2 Triangulated Mesh Geometry

PHYSICAL MODEL
The next experiment is started as a physical model to create a mesh system, using rigid members and flexible joints. The resultant geometry is a triangulated mesh system in the form of a double layered space frame. All the joints in the system are made flexible and kept loose. Light-weight cardboard struts are used as the compression members in the system, tied with strings at joints to create flexibility. Force is applied to the mesh from two points and four points without restraining the model at any joint. Different physical states of the mesh are observed. It is concluded that the control-ability factor of the kinetics of the mesh is low because of no constraints or restrictions at the joints, with respect to angles or axes. The degree of freedom is very high, leading to a number of permutations of physical states.
4.3 Material Experiment | Nitinol Spring

A compression spring made of nitinol is used and tested by supplying an electric current. The nitinol spring is first stretched to its full length – 100 mm and current is supplied from both ends. The spring shows a significant change and comes back to its original compressed state (20 mm), within a time of 3 seconds. The force produced by the spring compression is observed to be large, as it pulls the connecting wires with ease.

![Figure 6 – Nitinol Spring Experiment](image)

5. Tensegrity System

Due to high degree of freedom in the interconnected mesh geometry experiment and no component behaviour present, Tensegrity Systems are explored. Tensegrity systems have the potential to be developed from a component scale, and the principle of interconnectivity can be integrated with it. These are light-weight structural systems that have loads distributed as tension and compression into individual members of the structure.

3 Strut Tensegrity Component
The simplest tensegrity structure which consist of three compression members (struts) which are similar in size and thickness are connected by tension members (cables) as shown in Fig 7. The cables provide tension and hold the struts in position.

4 Strut Tensegrity Component
A similar arrangement as the previous component but with 4 compression members as Fig 7.

![Figure 7 – Various physical models of tensegrity system (3 strut and 4 strut) developed to study the component behavior](image)

DEVELOPMENT OF PHYSICAL MODELS TO UNDERSTAND TENSEGRITY

![Figure 8 – Study of flexibility of the components (Bottom)](image)
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The use of springs replacing the cables / rubber bands gives rise to enormous flexibility. The springs are in state of tension, but with an external force applied, the side springs sustaining the compression while the other tension members exhibit more tension, thereby maintaining a structural equilibrium.

5.1 System Development – Component Scale (Local)

Figure 9 – Building the 3 strut Tensegrity Component using Nitinol Springs as Actuators
(Source: Authors)

The nitinol springs are chosen to replace the side tension members which can expand to a maximum dimension of 1 unit and compress to a length of 0.3 units. This data is fed from the material experiments carried in the previous phases of research and is computed digitally now. Based on this dimension a proportional tensegrity component is built using steel springs as tension members, aluminium struts as compression members and tensile membrane / fabric as the top surface. The springs chosen for the experiment have the ability to compress or return to 1/3rd or 0.3 of its original length on the application of heat.

Figure 10 – 3 Strut Tensegrity Component showing different arrangements of actuators (Left); Actuation of nitinol wire (Right)

A series of experiments are carried out to understand the behaviour of the component on actuation of each nitinol spring, individually and collectively. The actuation deforms the component as shown in Fig 22. A parallel digital simulation is carried out to calibrate the kinetic motion of the component as shown in Fig 23.
5.2 System Development – Global Scale

Several components are aggregated to form an interconnected system in which each component has 3 actuators. The system is assembled by aggregation of the components on a triangular grid at the base. The components are rotated at 60° leaving a triangular gap on the top side, which is filled up by connecting through small springs in a small triangular grid.

To understand the collective behaviour of the system, each actuator of each component is actuated simultaneously as shown below. The actuation leads to various forms which are stored in the digital medium and studied. Each type of actuator of each component is collectively actuated to understand and study the morphology exhibited by the system.
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5.3 Tensegrity System as a Skin

When actuated, the system changes its form, where the components rearrange giving rise to openings at different angles by changing the orientation of the surfaces. This collective effect is studied to optimize the system according to requirements. The openings formed by the surface are manipulated in order to increase or decrease diffused light, depending on the local condition requirements for the system being installed. This manipulation is done by altering the angle of the opening. The above effect is also optimized for the incident solar radiation on the surface. The combination of multiple evaluation parameters add complexity to the system and the generative algorithm, thereby creating a requirement for a digital real-time multiple evaluation analysis which has the possibility to evaluate the efficiency of the model with respect to the actuation, returning with the appropriate values of actuation, which can be re-input to get the final states desired after motion.
5.4 System Development | Variation of Surfaces

The 3 strut tensegrity component is further developed and tested based on the location, orientation and number of surface(s) inside the component. Each type of component developed, is aggregated to form a system. The surface(s) are triangular patches which are anchored at 3 points between the struts and springs without affecting the overall motion. The system can have more than one type of component, which can vary in their orientation of surfaces but arranged through a set of rules. For example in the 3 Strut Tensegrity - Option 2 there are two types of components which are used where one component has the surface on the top while the other having it on the bottom. The components are placed alternately thereby following a pattern.

![System Development of 3 Strut Tensegrity Components](image)

5.5 Algorithm Development – Comparative Analysis

Each developed system is evaluated for various fitness criteria using the Genetic Algorithm. The types of actuators are taken as gene inputs, which are simulated by a physics engine based on the evaluations scripted by the exposure analysis and incident radiation analysis. The evolutionary solver iterates the maximum possibilities and finds out the most optimum state of the system according to the selected fitness criteria. This evaluation is carried out for every system, and outputs are compared and studied. The aim of these simulations is to find the system with maximum possible range of each parameter, within the constraints of their actuation range. The simulation outputs the actuation limits of each system as well.

![Algorithm explaining the genome and fitness criteria](image)
The evaluated results of the various developed systems for every fitness criteria are tested separately, which are compared and studied to find the efficiency of each system within that criterion. The system having the maximum range for a fitness criterion, which would in turn have the maximum flexibility, is chosen, as the system is required to optimize over extreme ranges of climatic conditions over the year.

6. Architectural Development

Building skin systems that have potential to behave and perform in a multitude of ways are developed in the research phase and the most appropriate models are required to be further developed into design models of architectural scale. To proceed with the flow of research, climatic classifications of the world are studied to choose the most appropriate climatic models where the developed building skin systems could be tested, further developed and evaluated. Considering the potentials of the developed systems, climatic models with a high range of temperature variation and with hot climates are considered. Also, the precedent study carried out during the early phase of research threw light on some cities that have issues with internal condition regulation due to high fluctuation levels in weather conditions. The idea of choosing a climatic model is to develop a context-based building skin system that has potential of being deployed in multiple cities, sharing similar climatic data.

With due consideration of these aspects, New Delhi (INDIA) and Barcelona (SPAIN) are chosen as the testing climatic models where we test the building skin. Climatic study of both these cities is done and temperature range variations are observed. Owing to the material experiments and behavioural studies of NITINOL, solar radiation is considered as a factor for climatic consideration.

6.1 Design Proposal – Passive System

Nehru Place in New Delhi, INDIA is chosen as a testing site for the passive system. It is a commercial market where a linear pedestrian street is chosen as the site, which currently faces the problem of excessive heating and exposure to sun. A roof system is proposed for this linear street, where internal conditions can be controlled and regulated without the use of any electronic or mechanical device in place. The material intelligence with nitinol springs take control of the roof which is moving with the solar radiation falling on it. As the temperature in Delhi can rise up to 45°C during peak summers, and even higher surface temperatures can be achieved, the energy can be harnessed to drive the mechanism of actuation. A mesh system is proposed based on the density analysis of the existing street, designed algorithmically using rules based on simulations of the 3-strut tensegrity system. The roof system has 30 triangular meshes with an infill of the 3-strut tensegrity system skin, which individually create dynamism within their respective constraints of anchor points, to control the internal conditions on the street.
6.2 Design Proposal – Active System

The Museum of Contemporary Arts in Barcelona is chosen as the testing site for the active system, due to vast range of programmatic use of the atrium which faces the south-east. The south-east façade which currently exists as a glazing with horizontal louvers to control the light entering the atrium behind it, is used as the testing façade and replaced by the active system with 4 - Strut Tensegrity components and pneumatic actuators, which come as steppers to control the actuation in steps.
7. Evaluation

The passive system developed for the roof of Open Market in Nehru Place, New Delhi is digitally analysed at different times of the day through daylight factor simulations. The average day light factor at a given time of the day without the proposed roof for a non-overcast sky condition is found to be 80% and under similar conditions with the proposed roof, cuts down approximately 70% of direct solar exposure which is a major requirement in summers due to harsh sunlight. The daylight factor (average) after the proposed roof is found to be 20 to 22%. The resultant daylight levels are around 1800 lux which is a suitable light condition for an open street-market. The analysis is done for two actuated states of the roof, for a designated patch on the ground surface (to minimize the time due to complexity of the simulation). The results of the second actuated state shows similar values of daylight factor, even though it is done for a different time of the day.
The active system developed for the south-east facade at Barcelona is analysed at 10am on 15th August which is the hottest day of the year in 2012 and 15th January which is the coldest day of the year in 2012. It is shown in the results that the system can manipulate the incident solar radiation on the surface between 10-15% by changing the angle of incidence of the surface during summers and 7-10% during winters.
8. Conclusions

PASSIVE SYSTEM
- The significance of the passive system is its potential to reduce Direct Solar Exposure, which curtails the harsh sun during summers while minimally affecting the day light levels inside the space by increasing diffused light, which is controlled by alteration of the angle of openings.

LIMITATIONS
- The system does not respond to decrease in light levels and cannot be changed for a different programme inside the space as it is controlled by the change in actuation with respect to temperature. This flexibility of the system is a major drawback due to absence of user input.
- Due to size and scale constraints in shape memory alloys available in the market, the behaviour of this system cannot be scaled up, without intensive material computation studies.

ACTIVE SYSTEM
- The variation in Incident Solar Radiation on the surface of the system could be found by achieving the desired form (actuated state) led by a precise actuation on particular actuators given by the developed genetic algorithm for that particular time of the day.
- The development of active system signifies the MULTI-RESPONSIVE feature to various parameters through a single system where each actuator can be individually controlled through a BIM. This feature of the system is exploited, resulting in phenomenal conditioning in the space, only through modulation of a single skin. This brings about a change in light intensity only in required areas, saving energy by actuating only the required actuators.

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References
