When form really follows function

Developing the prototype of a responsive exhibition pavilion

Luis Quelhas Marques¹, José P. Duarte², Joaquim Jorge³
TU Lisbon, Portugal
¹luis.q.s.marques@ist.utl.pt, ²jduarte@fa.utl.pt, ³jaj@vimmi.inesc-id.pt

Abstract. The paper describes research developed with the aim of enquiring into the concepts of adaptability, transformation, and interactivity between the built space, its users and the surrounding environment to find appropriate responses to variations in spatial and functional needs, prompted by different uses and activities. After a look into the roots of kinetic architecture and a brief survey of the state of art, it presents the prototype of a responsive kinetic structure for a multi-purpose pavilion, concluding that by the integration of existing and emergent technologies, we now have the basic means to design and implement such structures.

Keywords. Architecture; kinetic; responsive; adaptability; interactivity.

INTRODUCTION

The concept of kinetic systems can be traced back to the beginning of human evolution and the primordial nomadic civilizations, in which humans travelled constantly searching for food and adequate survival conditions. Consequently, these civilizations developed various types of light-weight and portable shelters, capable of being quickly assembled and disassembled and easily transportable, nonetheless providing for protection and security to their occupants. Although these types of temporary shelters, commonly known as “tents”, derive from simple and rudimentary technologies, they explored the concepts of portability, flexibility, and movement, which have an important role in the field of kinetic architecture today. (Kronenburg, 2007)

With technological and social evolution and the consequent development of static architecture, the concept of kinetics was maintained until modern days through the use of simple configurable elements like doors, windows, and blinds or even more complex structures like draw bridges, retractable roofs, and movable partition systems, among others. Most of these kinetic systems are designed for specific uses and applications and, therefore, have a limited functional scope. The concept of kinetic architecture as an integrally dynamic, adaptable and interactive structure is yet to be achieved, even though recent technological developments in mechanical and electrical engineering, together with the use of innovative materials, offer an immense potential in this regard.

KINETIC SYSTEMS IN NATURE

Nature has been a powerful source of inspiration for technological development ever since. This is due to the singularity of its biological systems and mechanisms, which are the result of evolutionary processes that took millions of years. The influence of nature in
architecture is not only aesthetic but also functional and it is aimed at integrating new forms, processes and materials based on various biological systems and mechanisms by combining architectural approaches with emerging technologies in an attempt to search for new concepts and solutions. Kinetic architecture is also based on the application of certain biological principles that exist in living beings, such as dynamism and adaptability. As these organisms have the capacity to move, grow and change their shapes and biochemical characteristics in response to changes in the environment, so may kinetic architecture metaphorically be considered a living organism that can feel, move and reconfigure its physical and spatial properties according to variation in internal and external conditions.

Although perceived as static organisms, some plants possess remarkable capabilities of adapting to the environment by reacting to different external stimuli using various movements like tropisms and nastisms. (Zeiger and Taiz, 2006) These movements are enabled by constant variations in cellular growth induced by complex sensitive capabilities that can detect the presence or absence of certain stimuli. In animals and, particularly, in humans movement also is one of the essential survival and adapting strategies. It results from the contraction and extension of muscles induced by the nervous system, which actuate on the bones to which they are linked, thereby causing them to move around the joints. These natural systems have considerable potential for exploration and application in the development of new architectural concepts and approaches that use kinetic systems to enable buildings to adjust to user and environmental conditions.

**KINETIC SYSTEMS IN ARCHITECTURE**

Kinetic architecture is a vast and general concept that may encompass different fields of knowledge like mechanical, structural, robotic, and electronic engineering. Kinetic systems may be implemented at different scales and with different levels of control, such as simple autonomous mechanisms for partitioning interior spaces, computerized sensing devices for thermal control, or even large scale structural mechanism that guarantee flexibility and enable adaptation to internal and external conditions. In this sense, kinetic architecture may be defined as “buildings and/or building components with variable mobility, location and/or geometry.” (Fox 2003, 163)

**Typologies**

Kinetic systems possess different formal and spatial transformation capabilities depending on the type of kinetic structures used, which may be roughly classified into three categories, namely deployable, dynamic or embedded kinetic structures. (Fox and Kemp, 2009) (Fig. 1) The work described in this paper uses an embedded kinetic structure, which is characterized by the integration of kinetic systems in the structure of the building. Its main function is the adaptation and control of the architectural system as a whole, in response to various factors and needs. Although scarcely explored, this typology

![Figure 1](Typological classification of kinetic structures: deployable (left), dynamic (middle), and embedded (right))
has been used in several successful projects, such as the Hoberman Arch in Salt Lake City (Utah, USA) by the engineer Chuck Hoberman, the Kuwait Pavilion in the Expo’92 in Seville, and the planetarium in the City of Arts and Sciences in Valencia, both in Spain and designed by architect Santiago Calatrava.

Control Mechanisms
The capacity to control transformation and movement aims to guarantee the operability of the kinetic system and its structure, enabling an adequate formal and spatial adaptation in response to user needs or environmental conditions. Traditionally, kinetic control was achieved using manual mechanisms; recent technological evolution led to the development of computerized control systems that permit to explore the kinetic potential of various types of solutions. Through the use of various mechanical and robotic components like servomotors, sensors, and microprocessors, the control system may collect and process various types of sensing information, thereby guaranteeing improved structural adaptation, responsive and interactive capabilities. Kinetic systems possess various types of control, depending on their functional features and on the transformation and movement features desired. In general, kinetic control systems may be classified into six categories: internal control, direct control, indirect control, responsive indirect control, ubiquitous responsive indirect control, and heuristic responsive indirect control. (Fox, 2003) (Fig. 2) When developing an architectural solution, one may use various kinetic systems that integrate and combine various types of control systems, depending on their function, so as to guarantee an improved response to the context. Both designed solutions used a ubiquitous responsive indirect control system, which combines different sensors and servomotors that may be actuated independently following an algorithm that processes information gathered by the sensors and decides how to actuate the kinetic mechanisms accordingly.

DESIGNING THE RESPONSIVE PAVILION
The core of the described research was the development at the 1/20 scale of the prototype of a flexible and adaptable kinetic structure for a multi-purpose pavilion. The idea was to enable the pavilion to respond to changes in spatial and functional needs.

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Figure 2
Type of control mechanisms: internal control (1), direct control (2), indirect control (3), responsive indirect control (4), ubiquitous responsive indirect control (5) and heuristic responsive indirect control (6).
Spatial and structural concept
The basic shape selected for the pavilion was a cylindrical dome because its simple configuration allowed one to concentrate on the exploration of the kinetic and functional capabilities of its structure. This was based on the use of scissor-hinge mechanisms, a primary type of kinetic structure that permits the creation of a large variety of configurations from a simple basic shape. The result is an adjustable interior space with variable dimensions that can be self-regulated or manipulated by the user, in response to the need for accommodating various events or activities. The scissor mechanisms can permit either linear or curvilinear transformations. (Fig. 3, left) Given the cylindrical shape of the pavilion, the implemented prototype used curvilinear transformations. Two different structural solutions were developed, each with different transformation and adaptation capabilities, particularly in terms of accessibility and re-dimensioning.

Solution 1 - Accessibility
This solution aims to guarantee a greater visual and physical permeability between the interior and exterior spaces by creating openings on both sides of the pavilion that permit user to cross the pavilion transversally. To fulfill this requirement, it was conceived a scissor-like structure composed of several mechanisms whose transformation and movement occur along an arc rather than a line. (Fig. 3, middle) Since all the mechanisms in the structural modules act together, applied forces are transmitted between them until reaching the mechanisms located at the extremes of the structure which then transmit these to the soil. The structural modules possess dynamic features that enable a total control of their degrees of freedom so as to enable or restrict various types of movement according to the needs. In order to create openings and guarantee the adequate movement of the structure, structural modules may be compacted to one side or the other while maintaining structural stability. When compacted to one side, the structural support on the other side is automatically disconnected thereby enabling the structure to raise and originate an opening. This solution guarantees greater permeability and accessibility to the pavilion. This mechanism is activated by sensors that detect in real time changes in functional needs as described further below.

Solution 2 - Re-dimensioning
This solution is intended to guarantee an improved response to a wider range of spatial needs, prompted by diverse uses and activities in the pavilion. This is accomplished by reconfiguring the structure of the pavilion so as to vary its width and height. As in solution 1, the basic shape of the structural modules is an arc. However, unlike solution 1 whose mechanisms only permit transformations and movements along such an arc, this solution permits transformations and movements in other directions to obtain the desired changes in width and height. This was achieved by modifying some of the scissor mechanisms in the structural module to introduce a joint that increases the degree of freedom of its movement, which also changes the behavior of the connected mechanisms. (Fig. 4, left and middle) The modified scissor mechanisms fragment the structural module into three subparts enabling them to transform and move.
independently. They remain, nonetheless, connected to one another to permit joint operation and control. By shrinking or expanding the subparts, it is possible to vary the width and height of the pavilion thereby creating a space with a varying span (Fig. 4, right). To take advantage of these structural capabilities several sensing mechanisms were implemented, leading to increased interaction and guaranteeing response in real time to changes in user needs.

**Covering Solutions**

Several types of covering were researched to be placed on the top of the structure and protect the interior space of the pavilion from adverse atmospheric conditions. Since the structure needs to adapt to changes in the form of the structure, this was the basic condition that guided research at this level resulting in the identification of two possible types of coverings: flexible and rigid. Flexible coverings are made of thin and light materials that may deform when subjected to traction causing them to expand. They are connected to certain points in the structure and due to their internal resistance they may affect structural stability, requiring complementary structural elements placed transversally to the main structural modules to tie them together and maintain stability. Rigid coverings use other strategies to adapt to structural transformations, since they have considerably less flexibility. In order to explore the geometric transformation capabilities of rigid coverings, principles and techniques from the traditional Japanese art of paper folding called Origami were researched due to their dynamism and transformation capacities. Origami is based on the creation of a geometric pattern on a flat surface, according to which it is folded, thereby enabling it to acquire various tridimensional configurations through compacting, expansion and flexing. (Lang, 2009) (Fig. 5) The application of these geometric transformation techniques permits the design of rigid coverings that can adapt to the pavilion's structural transformations. In reality, it also may be necessary to create complementary structural components to connect the main structural modules transversally to guarantee stability. However, at the scale of the prototype these were not necessary and, therefore, this was the type of covering selected for the pavilion.

**Figure 4**

Modified scissor-hinge mechanism (left) and the consequent fragmentation of the structural module into three subparts in Solution 2 (middle); transformation of the structural modules in Solution 2 (right).

**Figure 5**

Origami technique used in the exploration of rigid coverings: geometric pattern, folding, and resulting shape.
IMPLEMENTING THE RESPONSIVE PAVILION

In order to analyze the behavior of the two structural solutions and the corresponding mechanisms designed for the pavilion, prototypes of both solutions were built at 1/20 scale. For this purpose, it was used structural and mechanic components from LEGO Technic due to the variety of existing standard components, which permitted the construction of the prototype in an easy and efficient way. In the implementation it was also used robotic components and systems from LEGO Mindstorms NXT [1], Mindsensors [2] and HiTechnic [3] because they were compatible with the remaining structural and mechanical components. These components included infra-red sensors, touch-sensors, light sensors, analogue and interactive servomotors, controllers and a micro-processor. Those systems also included their own programming software, which enabled full control of the structure's transformations and the exploration of its kinetic and interactive capabilities.

The interactive capacities of the prototypes were based on the analysis of the possible structural transformations as a function of different types of stimuli from the various sensors used. The variety of responses to such stimuli results from the processing of information collected by the sensors according to algorithms that were specifically developed for each prototype, which determine how to activate the kinetic control devices. These algorithms were implemented in the visual programming language NXT-G (Kelly, 2010) using LEGO Mindstorms NXT programming package. Once implemented, the algorithms permit to define and control interactively the movements of the prototypes' robotic and structural components. The type of kinetic control that was implemented may be classified as ubiquitous responsive indirect control as the various mechanisms are networked, but may be controlled independently.

Despite the success of the implementation, the structural and robotic kits used present some limitations due to the use of standard and predefined components, which constrained the design and behavior of the pavilion's mechanisms. In some cases, it was necessary to modify some of the components by cutting and paste and even to produce components and mechanisms with specific dimensions and functions. There were also some limitations in terms of programming due to the reduced memory of the microprocessor (just 256 Kbytes with half being used for the operative system) [4]. In summary, the design and implementation of the prototypes were constrained by the features of the LEGO, Mindsensors e HiTechnic kits used.

Prototype - Solution 1

The goal of the first prototype was to analyze Solution 1 and it included the construction of three of its structural modules. (Figs. 6 and 7) As explained above, these modules are composed of scissors-hinged mechanisms and their movement is controlled by robotic interactive systems programmed to respond to various sensorial stimuli. These systems are located on the extremes of the structural modules and they were conceived to support and control them at the same time. They are composed of screw gear systems and continuous rotation servomotors that act upon the structural module forcing it to compact to the opposite side when activated by the control system. This is composed of a microprocessor connected to a servo-controller. All the movements executed by the six servomotors are controlled independently by the microprocessor, which analyzes and processes information collected by the sensorial system. This is composed of two short-distance infra-red sensors placed on both sides of the structure. These sensors detect the presence of any object in their action zone and transmit this information to the control system, which processes information from all the sensors and decides whether or not to activate the corresponding servomotors forcing structural module compact to the side opposite to the one where the object was detected. The prototype is completed with the placement of the covering on the top of the structure. Due to the constructive and mechanical limitations imposed by the LEGO components, the
placement of a flexible covering would significantly reduce structural stability and so it was decided to use a simplified rigid covering.

Prototype - Solution 2

The goal of the second prototype was to analyze Solution 2 and it also included the construction of three of its structural modules. (Fig. 9) As explained further above, to increase the transformation capabilities of the structure, some of the scissor mechanisms used in the structural modules of the Solution 1 were modified in Solution 2, dividing them into three subparts. The transformations of the structural modules are controlled by interactive robotic systems specifically developed for this solution. These systems are located on the extremes of the structural modules and they were conceived to support and control them at the same time. They are composed of bearing systems, screw gears and reels, which are actuated by several servomotors. (Fig. 8, right) These mechanisms permit the controlled and independent movement of each of the structural modules supports, causing them to expand or to contract and, consequently, changing the width and height of the pavilion. These mechanisms are actuated by the control system, which is composed of a servomotor and a microprocessor that processes the information collected by the sensors. The control system was designed to determine changes in the functional and spatial needs of the pavilion using a series of metaphors that interpret the information collected by the sensors, which detect the presence of objects with certain dimensions and colors, in terms of changes in the location, quantity and flow of people. There are three types of touch sensors with...
specific dimensions sequentially placed at one of the entrances to the pavilion. Through the activation of these sensors, independently or in combination, it is possible to detect the presence, location and shape of certain objects, thereby transforming and adapting the pavilion accordingly in real time. In the opposite entrance it was placed a light sensor, which measures the intensity of the light reflected by objects, thereby determining their color and, consequently, their dimension according to a predefined color scheme. The pavilion is then transformed according to a set of predefined rules codified by the algorithm developed and implemented for this solution. For the same reasons described in the case of Solution 1, it was decided to use a simplified rigid covering.

**CONCLUSION**

This paper describes research aimed at exploring the use of kinetic structures in architecture by developing the scaled prototype of a responsive exhibition pavilion. The pavilion has the shape of a cylindrical dome and uses scissors-hinge mechanisms to create two solutions for the kinetic structure that differ in terms of the type of movement allowed, and origami tessellations to form the adjustable covering. The hardware was implemented using existing kits from LEGO.
Mindstorms NXT, Mindsensors, and HiTechnic, whereas the software was developed in NXT-G, the scripting language available in Mindstorms.

By implementing the prototypes of the two solutions and the corresponding robotic systems, it was possible to analyze their kinetic performance both from the structural and mechanical viewpoints, as well as their responsive potential. Although the design of the prototypes was constrained by formal and dimensional limitations of the standard structural and mechanical parts of the kits, they possess nonetheless a considerable potential from the spatial and functional viewpoints.

The robotic control systems implemented in both solutions were intended to guarantee the structural and kinetic performance of the prototypes, while permitting the desired interactive and responsive behavior. These were implemented using a series of metaphors to represent changes in the programmatic needs of the multi-functional pavilion and various types of sensors that were programmed according to limitations of the software.

Despite all the limitations, research results hinted at the enormous potential of using kinetic structures coupled with state-of-art computer technology to develop buildings that respond to changes in user requirements or environmental conditions. Future research will address the design and construction of full scale prototypes. The development of this dynamic architecture will require integrating expertise from different fields.

REFERENCES


