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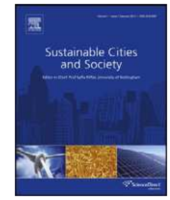

Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings

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ABSTRACT

Kinetic architecture is a design concept in contemporary architecture, which explores the physical transformation of a building with the objective to redefine traditional applications of motion through technological innovation. The use of robotics, mechanics and electronics is essential to this new approach.

Using these new technologies, architects are not any more tied up to traditional ideas of structural balance; the wall now is to move, the roof is to be folded and the whole building is to revolve.

This paper is about to discuss this new trend and answer some questions about how far could it introduce real solutions to architectural problems, to how extent could these solutions be supportive to environmental control systems, and how could they help developing the interaction between the building and its context.

1. Introduction

> If a building were to have the human body's stability and flexibility, then it has to be built like one – a system of bones, muscles, tendons and a brain that knows how to respond (Than, 2006: p. 1).

The previous statement by Guy Nordensen summarizes the ultimate objective of this contemporary architectural movement that promotes the idea of structures – unlike traditional ones – that can balance dynamically and not statically. This movement invites architects to get benefit from the great development in digital information, sensing systems and electronic control systems in order to develop innovative architectural systems known as *kinetic systems*.

Kineticism has always been in architecture. Traditional doors and windows are actually primitive kinetic elements that represented this idea in earliest constructions. Since then, these systems had experienced great development, from manual to mechanical and then to electronic and intelligent systems. They also appeared in variety of forms, being parts of circulation systems, elements of services systems, or parts of building envelop systems.

The concept of *kinetic architecture* had started to come strongly into vague in the last three decades and started to attract attention in both professional and academic fields, being embraced by some important architects and architectural groups, such as Santiago Calatrava, Chuck Hoberman and the MIT Institute.

The hypothesis of the paper is that these systems introduced innovative and practical possibilities that might be employed to develop some ground breaking environmental and context-sensitive architectural solutions. In order to prove this hypothesis, *the paper aims to* review the types of technologies included in it, review the different classifications that had been put to categorize these systems, and then presents a new classification for these systems based on their environmental performance and the possibilities offered by each of these systems.

The paper depends on a qualitative methodology, which is a non-numerical method that depends on practical and experimental case studies, as will as theoretical reviews, in order to seek empirical support for research hypotheses. The case studies/examples in this method are not randomly selected, but rather purposefully selected, according to whether or not they typify certain characteristics or contextual locations.

The paper consists of four main parts: the first overviews the evolution of kinetic systems and their development; the second introduces some examples for the use of kinetic systems in architecture; the third demonstrates some classifications of kinetic systems; and the forth suggests a new classification of kinetic systems (by the researchers) as environmental control systems.

1.1. The evolution of kinetic systems in buildings

Since very early times in history, kinetic systems were included in ancient and historical architecture. Doors and window shutters are the simplest and the most common example of this. Since then, these systems had been developing until they reached the phase

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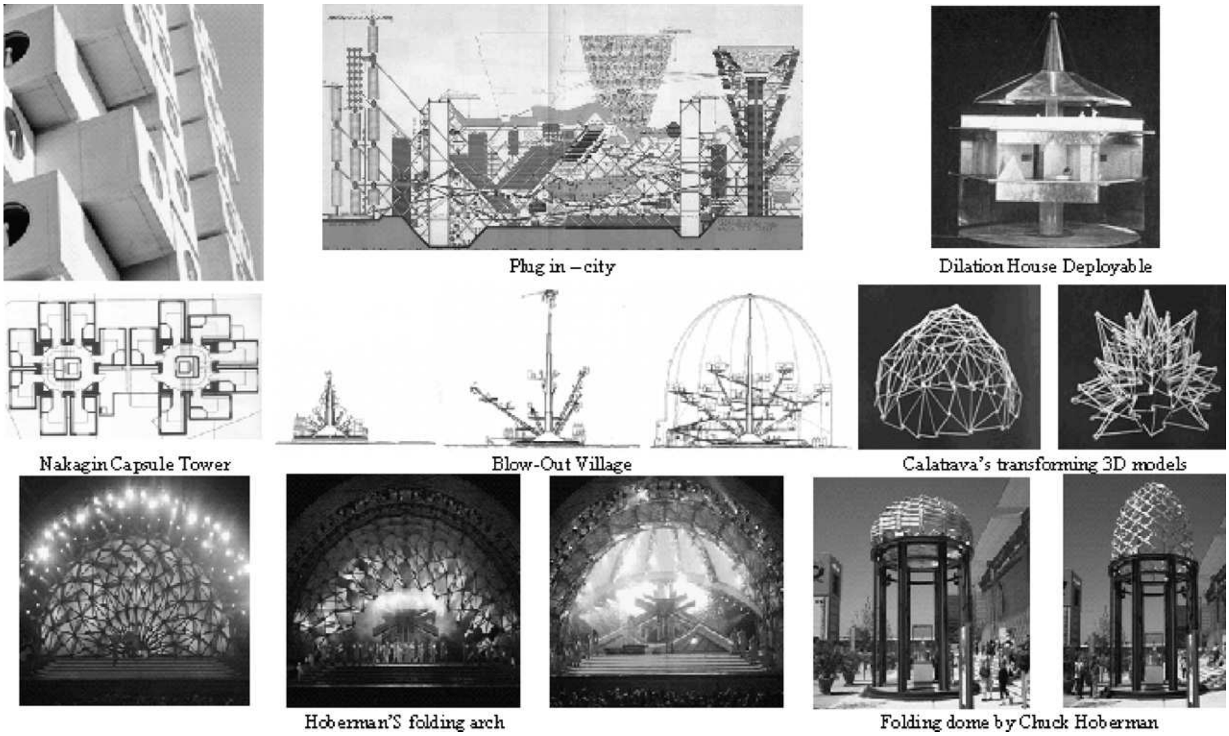

Fig. 1. kinetic systems in twentieth century architecture [*by researchers*].

of robotic and intelligent systems such as these that is to be seen today. In the following are some of the main thresholds of this development.

1.1.1. Primitive kinetic systems (pre-industrial revolution)

Primitive lunatic systems and traditional *tents* introduced the earliest example of kinetic architecture in historical epochs (Mollaert, 1999: p. 2). *Traditional doors and windows* were also examples of such early systems. Unmovable openings in buildings were already known by 5000 B.C, but pivoting sliding openings was a remarkable step towards human comfort and environmental control in buildings (Melki, 2006: pp. 2–3).

Later examples of early kinetic architecture included also *wooden drawbridges*, as well as *hoists or lifts*, which were already in use as early as 300 B.C. and were first empowered by human or animal power, and later on by mechanical or hydraulic systems.

1.2. Premature kinetic systems (industrial revolution)

Motion techniques had experienced great development since the launch of the industrial revolution. Machinery, steam engines and then electrical engines represented revolutionary development in this regard and inspired architects with completely new ideas such as *high-rise architecture*, which was enabled by the invention of electrical elevator in the 19th century by Werner von Siemens. Another remarkable step was the appearance of *futuristic architecture*, which was all about the promotion of movement, dynamics, and speed. These ideas appeared in their visualization for the utopian city as seen in Antonio Sont'Elia's drawings for *Citta Nuova* or New City, in which buildings are to simulate machines.

The designs introduced by the architecture of *the Russian Constructivism*, despite in most cases had never been realized, also had important role in the evolution of kinetic architecture in a whole building and not only elements, such as in the works of Vladimir Tatlin, Nikolai Ladovsky, Georgy Krutikov and Kazimir Malevitch (Abu-Deya, 2001: pp. 282–283).

1.3. Developed kinetic systems (twentieth century)

Techniques that support kinetic systems had largely developed in the second half of the 20th century. The development of electronic and digital systems enabled remarkable development in this direction, encouraging pioneering architects to embrace it and include it in their designs (Fig. 1).

The first remarkable works in this direction were introduced by the architects of the *Metabolism and Arshigram Schools*. The architects of these schools believed that architecture should reflect some liveliness and energy as in living creatures. They also believed that – unlike in classical and traditional styles – a building should not last for hundreds of years, but rather be easily demolished and replaced. Meanwhile it should be able to alter and even grow; using a system of capsule units hanged in or split into a mega-structure (Awida, 1984: pp. 119–138).

Richard Buckminster Fuller, Frei Otto, Santiago Calatrava, and Chuck Hoberman also introduced pioneering steps in this direction. *Richard Buckminster Fuller* was mainly concerned with developing new structural systems, in which light materials are utilized (Sennott, 2005: pp. 900–901). His most important achievement in kinetic architecture was the pre-cast movable unit of Dilation House Deployable. On another hand, *Frei Otto* was distinguished by his research in tensile and suspended light structures, developing a computer program to support the design of such systems. He also developed these systems to include folding roofs.

The designs of *Santiago Calatrava*, which are always inspired by nature and natural composition, are well known by utilizing advanced technologies. His designs, such as the study models of the transformation/compression of 3D models, had

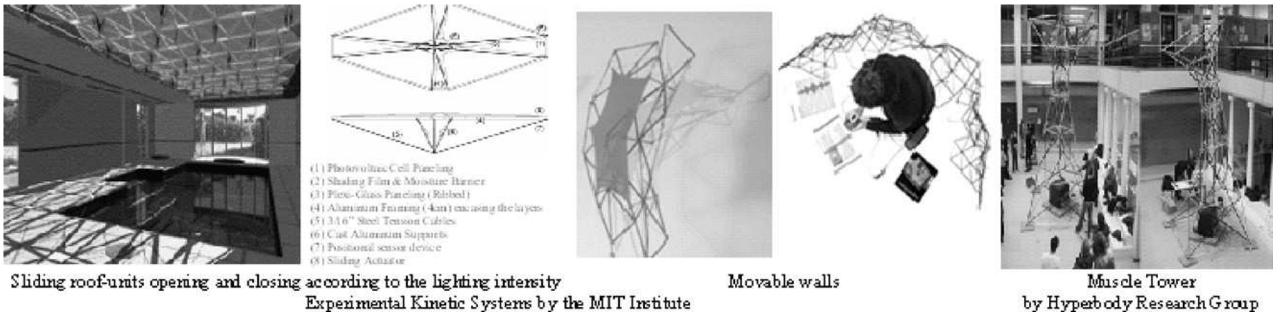

Fig. 2. Intelligent biomechanical kinetic systems [*by researchers*].

remarkably contributed in the development of kinetic architecture (http://smu.edu/newsinfo/releases/m2013b.html). However, the most successful designs in kinetic architecture are those of *Chuck Hoberman*, who developed a mechanical, light and flexible structural system using a group of hinged units, mostly from aluminum, to form movable designs. He also shared adding kinetic systems to some of Norman Foster's designs (http://archrecord.construction.com).

1.4. *Advanced kinetic systems (the age of artificial intelligence)*

By the end of the 20th century, the term "*artificial intelligence*" started to come strongly into vogue. It is about creating computerized machines that have the ability to do similar jobs like that enabled by human brain; of these are the robots and the remote control systems.

In the last decades, this trend started to take place also in some architectural application and especially in developing intelligent kinetic systems that includes the former application that had been developed in the twentieth century in addition to new applications such as intelligent elevator-systems, automatic car parking-systems and intelligent biomechanical kinetic systems (Fig. 2), which are still mainly experimental.

2. Examples for the use of kinetic systems in architecture

The application of kinetic systems brought in wide range of architectural solution and possibilities that had not been available before. One of the fields in which these applications could be particularly useful is the filed of environmental control. In the following are some examples showing some of these possibilities.

2.1. *The Stadium of Phoenix University*

Location:	Arizona, USA
Architect:	Peter Eisenman and HOK office
Cost:	455 million US$
Capacity:	63000 spectator
Date:	April 2006

One of the most challenging elements in the design of stadiums is the design of the roof, which have to cover wide spans without intermediate structural elements that may block the sight.

In this stadium (Fig. 3A), a system of *retractable roofing* is used to make the central part of the roof movable. Here, not only the roof is movable but also the floor of the playground can slide to outside. This sliding playground helped saving some extra 50 million US$ that should have been spent on a fully movable roof (not only the central part of it) to allow sufficient natural lighting needed for the growth of the grass (http://archrecord.construction.com/resources/conteduc/archives/0606edit-6.asp).

The structural system of the retractable roof, which covers about 47 000 m^2 consists of two giant Brunel Trusses[1] each with eight vierendeel trusses. The opening that results in by the motion of these two parts is 110 m × 73 m. This whole roof is covered by PTFE panels – a translucent material that allows natural light to penetrate into the whole space even when the movable part is closed (http://www.birdair.com/projectGallery).

The sliding playground is 13.5 m × 70 m, with a thickness of 1 m divided into the following layers:

- 5-cm natural grass
- 25-cm natural soil with irrigation pipes and sprinkles imbedded in it
- thick layer of Geotextile Fabric to allow extra water to pass through it
- plastic pipe-network for gathering the extra water
- 15-cm concrete with sewage holes to get rid of extra water
- corrugated metal sheets
- 45-cm skeleton of iron beams in which the wheels are imbedded, with a computer system controlling this motion and monitoring each part of it (http://archrecord.construction.com/resources/conteduc/archives/0606edit-6.asp)

2.2. *Rothenbaum Tennis Centre Court*

Location:	Hamburg, Germany
Architect:	Schweger & Partner, Hamburg
Cost:	455 million US$
Area:	5300 m^2
Date:	1997

The 5300-m^2 stadium (Fig. 3B) is covered by a permanent roof for the stand and by a retractable roof for the playground with transparent outer canopy as shelter for the entrances and areas on the periphery of the stadium. For the exterior ring, Fluorpolymer membrane was chosen. For the retractable part and the stand roof, a single layered PVC-coated polyester fabric membrane was used. The concept is based on the idea of an open-air stadium that could be weatherproofed by closing it within few minutes without interrupting or disturbing the match (http://www.hightexworld.com).

The retractable system is enabled by group of tensile cables connecting the outer rim with the central point by means of hubs, forming a so-called *spoke wheel system*. The translucent membrane has a light transmittance of 10% and can be easily folded when being retracted, even at dimensions of 3200 m^2. Special belt reinforcements along the ridges and suspension areas allow for very

[1] Named after the British engineer *Isambard Brunel*.

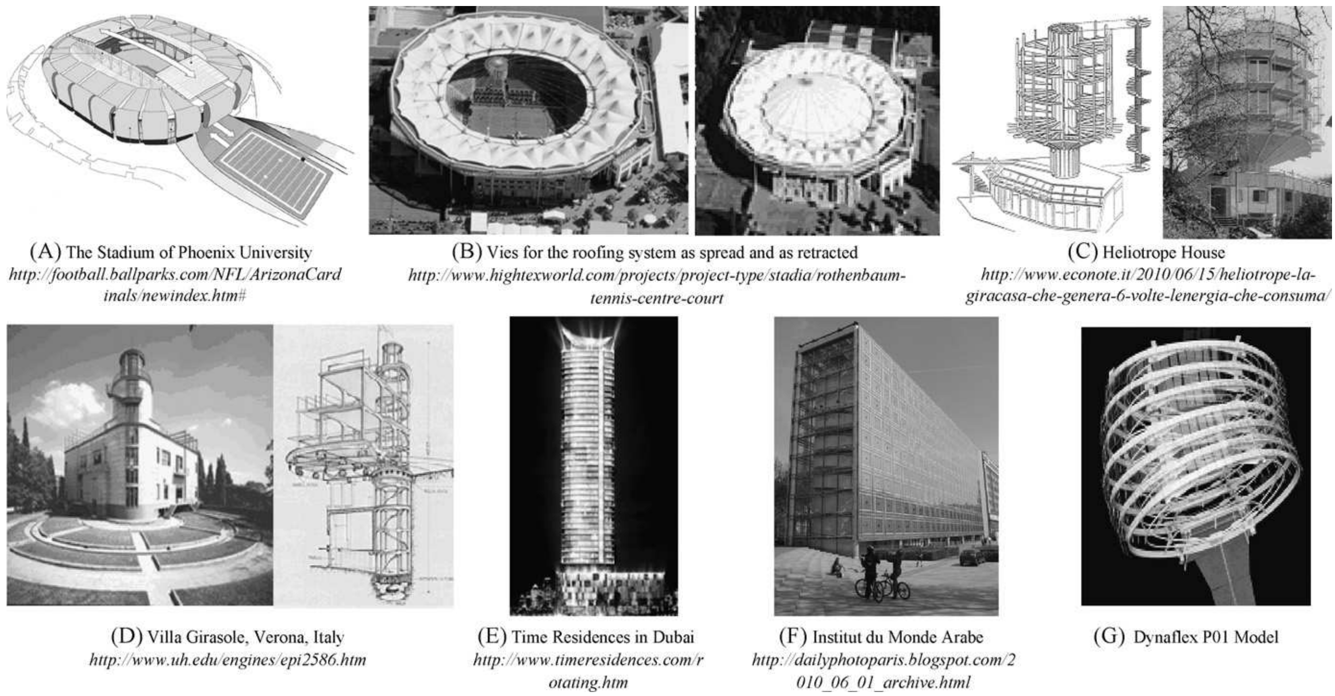

Fig. 3. Examples for the use of kinetic systems in architecture.

smooth folding and minimum volume when being folded (Walter, 2006: pp. 10–11).

2.3. Heliotrope House

Location:	Freiburg-im-Breisgau, Germany
Architect:	Prof. Rolf Disch
Date:	1994

It is a relatively light structure (100 tons) that revolves around itself 1° each 10 min from 3 a.m. to the sunset, allowing variable views and more benefit from the solar energy, which is collected by the photocells on the roof. It consists of residential unit as well as an office; the latter occupies the basement level, while the former is occupying a 14.5 m high tower, topped by a roof garden (Fig. 3C). Wide glass areas cover the façade from one side while the other side, in which services areas are located, is almost totally blocked, except of few small openings.

The building has two separate kinetic systems, one for the tower and the other for the photocells. A wooden core contains a spiral stair together with the kinetic system that enables the rotation of the tower. The wide areas of glass windows remarkably helped lightning the tower for easier rotation.

Each room has sensors to measure the temperature and the occupancy of the room, so that the air-conditioning system and the motion system are adjusted accordingly. Motion is enabled in 400°, with extra 20° on each direction according to the intensity of sunrays. It is automatically programmed, but it can be disabled and manually controlled to adjust the building to a specific position, with a possibility to adjust the building's environmental performance throughout the different seasons by changing the angles and the speed of rotation.

The motion of the photovoltaic arrays is programmed to follow the position of the sun. It is a composite motion around two axes; the first follows the Solar Altitude Angle and the second follows Solar Azimuth Angle. The purpose of this system (which is totally independent from that of the building itself) is to allow the photocells to face the sun as long as possible during the daytimes, enabling it to produced 30–40% more energy than that produced by a similar fixed system (Wigginton & Harris, 2002: pp. 115–120).

2.4. Villa Girasole, Verona, Italy

Location:	Verona, Italy
Architect:	Angelo Invernizzi
Date:	1929–1935

Villa Girasole (Sunflower) is a revolving wooden house (Fig. 3D). The two-storied L-shaped house rests on a circular base, which is about 44 m in diameter, in the middle of which is a 42 m tall turret that the rotating movement hinges on. A diesel engine pushes the house over three circular tracks where 15 trolleys can slide the 1500 tons-building at a speed of 4 mm/s. It takes hence 9 h and 20 min to fully rotate. Built in 1935, the system is manually controlled to allow altering orientation of façades and more environmental comfort for users (http://www.uh.edu/engines/epi2586.htm).

2.5. Time Residences in Dubai

Location:	Dubai, UAE
Architect:	Glenn Howells Architects
Date:	Expected to be complete in 2012
Cost	400 million Dh

The building is a 70 000-ton tower rising 170 m (30 stories) and revolving around itself powered by solar energy (Fig. 3E). Built in an arid climate receiving lots of sun light throughout the year, the Time Residences will need all this power for its gigantic motors to turn the building a full rotation over the course of 7 days, providing changing panoramic view for all units. Architects had developed a façade system that not only provides residents with full, energy efficient, control of their internal environment, but will also create a dynamic, multi-layered appearance from the outside (http://www.timeresidences.com/rotating.htm).

2.6. The Institute of The Arab World (Institut du Monde Arabe)

Location:	Paris, France
Architect:	Axel Ritter
Area	16,894 m^2
Date:	1981–1987

The river facade of the building follows the curve of the waterway and helps reduce the hardness of the rectangular block. In contrast, the opposite facade is uncompromisingly rectangular (Fig. 3F). Over the glass-clad storefront, a metallic screen unfolds with moving geometric motifs, which are actually 240 motor-controlled apertures opening and closing like the people of the eye according to the intensity of the light, acting as *brise soleil* (French for sun breaker) to control the light entering the building and creating interior spaces with filtered light in a modern resemblance of the traditional Islamic window-screens *Mashrabiah* (http://architecture.about.com/od/findphotos/ig/Jean-Nouvel/Arab-World-Institute-.htm).

2.7. Dynaflex P01 Model

Location:	Wiesbaden, Germany
Architect:	Axel Ritter
Date:	1995

This model was designed as an experimental intelligent structure that may adjust its geometry and dynamically control the light intensity penetrating into its inner space according to the life-loads affecting it, as its envelop system responds to the users' footsteps.

The model is composed by seven modular units (Fig. 3G); each unit consists of major outer circle and two inner circles, each one fixed to the one next to it. The whole model is fixed to the ground by portable traverses supported by flexible spring bearings. Each traverse has a load distribution board that moves vertically and horizontally influenced by the life-loads affecting it, causing the traverse to reshape, and accordingly the circles to be reshaped.

The outer envelop of the model is made of strips of electro-voltaic glass, which is an intelligent material that transforms light-energy into electrical energy. It is also provided with filaments of PZD, which is another intelligent material that generates electricity as being affected by pressure forces resulting from the vibrations caused by the wind or the movement of the occupants. This energy is transmitted through electronic units to the glass strips, changing them from transparency to translucency according to the intensity of these vibrations (Ritter, 2007, p: 162).

3. Classifications of kinetic systems in architecture

In the following are some classifications of kinetic system that had been suggested by researchers and research-group in trial to categorize these systems in architecture.

3.1. According to system configuration

This category, as classified by the Kinetic Design Group in the M.I.T institute, includes the following three subcategories.

3.1.1. Deployable kinetic structure

These structures typically exist in a temporary location and are easily transportable (Fig. 4). This includes foldable/expanding structures like tents, movable structures like caravans, mobile homes, capsule units and balloons, as well as movable towns like aircraft carriers and oversees ships/airplanes. This category includes also movable intelligent structures and some experimental systems such as Muscle spaces (http://www.oosterhuis.nl/quickstart) and Transformer Models (Fox & Yeh, 1999: p. 6).

3.1.2. Dynamic kinetic structure

Usually exist within a larger architectural whole, but act independently with no respect to the control of the larger context. These structures may include:

I- Controllable kinetic elements (with unresponsive control systems): like the above mentioned Stadium of Phoenix University (Fig. 3A)
II- Movable circulation systems: like the intelligent elevator-systems and the automatic car parking-systems
III- Revolving structures: like the above mentioned Heliotrope House (Fig. 3C) and Villa Girasole (Fig. 3D)

3.1.3. Embedded kinetic structures

This category is concerned with systems that exist within a larger architectural whole in a fixed location (Fig. 5). The primary function is to *control the larger architectural system or building*, in response to changing factors. This may include:

- *Responsive facades/roofs*: responding to both outer circumstances and inner activities of users
- *Pre-empting spaces*: with structural system that responds to the needed changes in inner spaces
- *Balanced structural system*: with structural system that may kinetically respond to outer forces (winds) and use this movement

3.2. According to control techniques

The items of this category are divided by the researchers of the Kinetic Design Group in the M.I.T institute into six subdivision according to the techniques used to control/enable the motion:

- Internal control
- Direct control
- Indirect control
- Responsive indirect control
- Ubiquitous responsive indirect control
- Heuristic responsive indirect control heuristic (Fox & Yeh, 1999: p. 6)

3.3. According to utilities

Kinetic systems are usually used to facilitate one of the following purposes:

- To enable using the building in different places, such as caravans and mobile homes
- To enable easier circulation (vertical and horizontal) inside buildings such as intelligent elevators
- To enables better environmental control and more interactions between the building and its context, such as revolving buildings or responsive roofs
- To enables more flexibility and better performance for inner spaces, such as movable partitions and multi purpose built-in furniture

4. A classification of kinetic systems as environmental control systems

Reviewing the previous examples, in which kinetic systems had been employed to serve environmental control issues, it could be realized that these systems may offer wide variety of solutions in this regard. These solutions range from limited and manually controlled systems with trivial effect that concerns issues like pen-

Fig. 4. Deployable kinetic structure [*by researchers*].

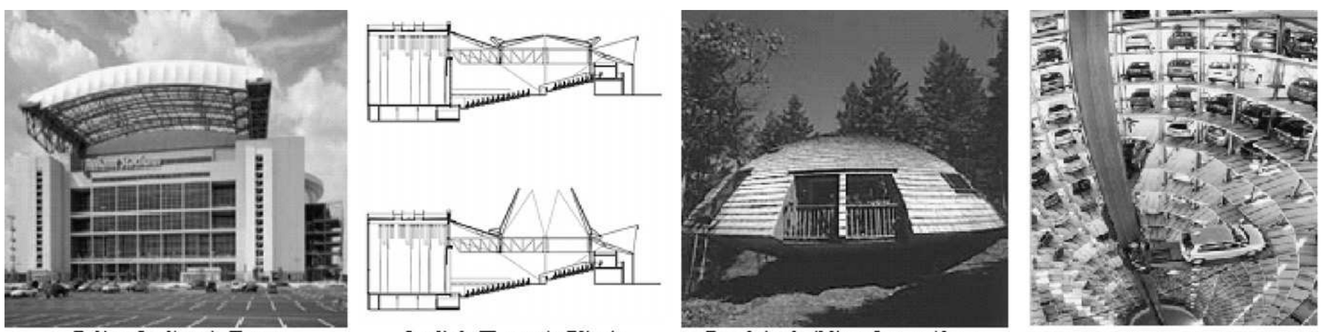

Fig. 5. Embedded kinetic structures.

etrating the light, to radical and advanced environmental treatment offered by revolving buildings or intelligent systems.

4.1. Criteria of the classification

Studying the systems used in the examples in part 2, it is obvious that their performances are widely variable. In some cases, the kinetic system is only slightly movable and its influence is hence very limited, while in other cases the motion includes the whole body of the building, with much more obvious architectural and environmental effect, but also with much higher costs. Accordingly, kinetic systems can be categorized according to the following criteria, which are the leading points that distinguished the systems in the above-mentioned cases.

The classification here, unlike the previous types addresses the actual human needs that might be fulfilled using possibilities offered by each of these systems.

- *Kineticism*: the limit of motion resulted in by the system, and whether it is partial motion, inclusive motion, or motion that depends on small movable units
- *Control techniques*: how motion is initiated according to the previous classification in Section 3.2
- *System configuration*: as in the previously mentioned classification in Section 3.1

Fig. 6. Responsive skin units [*by researchers*].

Table 1
Testing the suggested categories against the classification-criteria [*by researchers*].

Kinetic system	Kineticism	Control technique	System configuration	Control limit	Cost
Skin units systems	Limited	Direct or Responsive	Embedded	Minor	Small
Retractable elements	Medium	Internal or Direct	Embedded	Medium	Medium
Revolving buildings	Major	Direct or Responsive	Dynamic	Significant	Big
Biomechanical systems	Variable	Responsive Indirect	Dynamic or Embedded	Variable	Huge

- *Control limit*: the degree of environmental changes offered by the system, and how much difference does it make in regard of human comfort and interaction with the building context
- *Cost*: the cost of the system compared to its environmental performance

Using these criteria, the following classification for kinetic systems as environmental control systems is suggested.

4.2. Suggested categories

4.2.1. Skin-units systems

This category includes kinetic systems in which one (or more) element of the building envelop/skin system (roofs or walls) is *divided into small movable units* that have limited possibility to move, shift or revolve with *no remarkable changes* in the building's configuration (form and position) (Fig. 6). This system has limited range of environmental performance as viewed in the following:

(A) *Responsive/interactive façades*: such as the façade of the Institute of the Arab World. Another example of this system is an experimental model, designed by Michael Fox, which interactively responds to the motion of the pedestrian around the building.
(B) *Flare skin*: an outer skin covering the building and consisting of metal units programmed in a way to move with the sun to reflect the sunlight during the day (Wigginton & Harris, 2002: p. 99).
(C) *Movable louvers*: aluminum or fibber louvers that moves manually or automatically along the day-hours to protect the users from the strong glare in southern facades.

4.2.2. Retractable elements

This category includes retractable architectural elements (roofs, walls, floors, etc.) that have the possibility *to fold or expand as a whole element*, according to the needs of the users, resulting in *remarkable changes* in the building's configuration with wider range of environmental performance. Examples of these are the previously mentioned systems in:

- The Stadium of the University of Phoenix
  Retractable roofing
  Sliding playground
- Rothenbaum Tennis Centre Court
  Retractable roofing

4.2.3. Revolving buildings

This category includes buildings, that have the possibility to *revolve around themselves or along a certain track*, empowered by wind-power or solar energy, allowing varying views and altering orientation for the different spaces of the building and by this enabling *very high environmental performance* as in the previously mentioned examples of:

- Heliotrope House
  Rotation system for the tower
  Double motion system for photocells
- Time Residences in Dubai
- Villa Girasole, Verona, Italy

4.2.4. Biomechanical systems

Biomechanical systems are dynamic kinetic structures or embedded kinetic structures that may *kinetically adjust themselves in respond to some inner or outer forces* received or measured by system of sensors or any other triggers. These structures, which represent the ultimate target of kinetic systems that has both the stability and the flexibility of human body and may allow *unlimited possibilities* in all aspects, are so far only experimental models.

- Dynaflex P01 Model:
  Control the light intensity

Testing these categories against the above-mentioned criteria, it is to conclude that each of these categories has the following chrematistics as in the table below (Table 1):

5. Conclusion

Kinetic systems in architecture, despite integral to buildings from the oldest times, are still in their formative years. The degree of kineticism in a building widely varies according to the levels of machines' sophistication used in it. Simple movable elements may include sliding panels and pivoted screens, while elevators, escalators and conveyor devices represent more sophisticated elements of notable importance.

Kinetic systems may also include systems or elements that may automatically fold, slide, expand, and transform in both size and shape. However, architects and researchers who work in this field are aiming to develop considerably sophisticated systems that are to include buildings able to change their postures, automatically or dynamically correct any deformation in their structures, reduce their weights and physically re-configure themselves to meet users' needs.

In this study, it is suggested that these new systems and possibilities might be especially useful to enhance the environmental performance of buildings, allowing more human-comfort and better interaction between the building and its context. Throughout the study and the different examples that had been overviewed in it, it is to conclude that these systems are able to play important role in the following aspects:

- Enhancing the environmental quality of buildings
- Providing better control for temperature and glare and reducing air-conditioning expenses
- Providing varying views for each space in the building
- Allowing altering orientation for spaces to cope with the weather in different seasons
- Making solar energy systems more efficient
- Facilitating very ambitious ideas like varying transparency of glasses or responsive alteration of solids and voids to cope with different weather condition or with the occupancy level of the space

The paper also introduces a trial to classify these systems according to the degree of kineticism, control technique, system configuration, control limit and cost as the following:

- Skin-units systems: with limited performance and no remarkable changes in the architectural configuration of the building
- Retractable systems: medium performance with notable changes in the architectural configuration of the building
- Revolving buildings: high performance with the possibility of changing the building orientation
- Biomechanical systems (still experimental): unlimited possibilities with the building kinetically adjust themselves according to any measurable factor

The best performance and the ultimate benefit from these system is to be reached by making use of the right combination of technologies included in these different categories and defining the right objective of the selected system(s) and not being just fascinated by the dazzling possibilities that they offer. Otherwise, the ingenuous use of such systems may have very negative influences and, above all, result in extreme and unneeded raise in expenses, both in construction phase and throughout the whole lifetime of the building.

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