Exploring Sensing-based Kinetic Design for Responsive Architecture

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Abstract. This paper outlines the features of responsive architecture with emphasis on sensing-based kinetic design. The emphasis of our work is mainly on developing kinetic design methods that apply to responsive architecture. The kinetic design method is demonstrated by an experimental system called *Mimosa*. *Mimosa* is a responsive architecture prototype that can alter its shape in response to climate conditions. The implementation, experience, and lessons learned from the development of sensing-based kinetic design for responsive architecture will be reported in this paper.

Keywords. Kinetic Design, Responsive Architecture, Smart Space

1. Introduction

Current practice in architecture is limited by the lack of *flexibility*, where spatial configuration is static and can be hardly changed after it is built. Architects have no way to access the future user needs in the design process while there are constant demands for adding flexibility in our built environments. Yet, because of the inherent nature of changing needs, there are constant problems of environmental and ecological cost with respect to the occupants' living quality. There are more demands to add further considerations: adaptive response to users, automation, energy saving, and natural interactions. Current approaches must be inherently expanded to support significant increases in complexity of design.

Trends in ubiquitous and pervasive computing are opening up new opportunities for developing a new vision of a smart, interactive, and responsive architecture [Fox, 2003, Jeng et al. 2007]. Industry and research efforts are quickly moving to this area. A common approach is to augment buildings with *kinetic* capability, allowing buildings to alter their physical shape in response to climate conditions [Beesley et al., 2006]. The other approach is to augment physical space with *sensing* capability. It has attempted to change the way people interact with space through embodied computation. The goal is to improve the quality of living experience [Jeng et al., 2007]. What may appear to be shifts in emphasis is the convergence of smart, interactive, and responsive architectures on a single goal: *dynamics, flexibility,* and *adaptability* of architectural space.

These trends introduce new challenges for research in exploring sensing-based kinetic design for responsive architecture. One challenge is to explore the dynamics of architectural space by re-thinking architecture beyond conventional static and single-function spatial design. Adaptive response to change should be considered in the preliminary design process prior to the stage of construction and use. The other challenge is to accommodate a new way of manifesting human-computer interaction in architectural design systems. Given inevitable growth in the range of use of sensors and actuators in buildings, architecture becomes an interaction interface between human and computation. When integrating computational devices, software, and information into the design of physical space, it demands a new way of thinking about how spaces sense, move, move, and reconfigure itself in response to changing needs.

The objective of this paper is to explore the dynamics, flexibility, and adaptability of architectural space. The emphasis of our work is mainly on:

- dynamic configuration of physical space with respect to constantly changing needs, and
- Kinetic design primitives and methods for developing adaptive response in building design.

This paper describes work in progress for developing the kinetic design primitives, methods and the sensor/actuators integrated responsive modules. There are many types of kinetic design. Our interest is in the development of building responsiveness with respect to climate conditions and user activities. The experience and lessons learned from the development of responsive architecture will be reported in the paper.

1.1 RESPONSIVE ARCHITECTURE

The term *responsive architecture* is commonly defined as a dynamic shape-shifting building system that is susceptible to alter its shape and physical properties in response to environmental conditions, user activities, and social contexts. The idea of responsive architecture comes from bionics and mechanics. The overall characteristics of responsive architecture can be better understood by simulating bionic behaviours from human and natural systems.

Architecture can be considered as a *living* system that can sense, move, move, and reconfigure itself in response to changing needs. In order to understand the potential of responsive architecture, it is necessary to study how living cells respond to nature. Living cells change shape, move, grow, and alter their biochemical functions based on cues from their local environment. They reorganize their forms and functions as required for their growth and survival. For example, mimosa folds its leaves when touched or exposed to heat. Many other plants also fold their leaves in the evening. We can learn from the sensitive plants such as mimosa. There are simple rules and regulations under the complicated phenomenon of self-organization. We argue that the principle of bionic organisms can be applied to the dynamic structure of responsive architecture.

1.3 AN EXAMPLE DESIGN SCENARIO

In order to give substance and later demonstrate the methods of kinetic design, we apply them to an example. The example is drawn from a museum design where the building alters its shape in response to climate change. The complexity of climate responsiveness and user responsiveness are considered simultaneously. To support user activity in different seasonal time, the building can change the form of external roof surfaces and move internal partition walls in response to changing needs and climate conditions. A set of section drawings shows the design scenario in Figure 1.

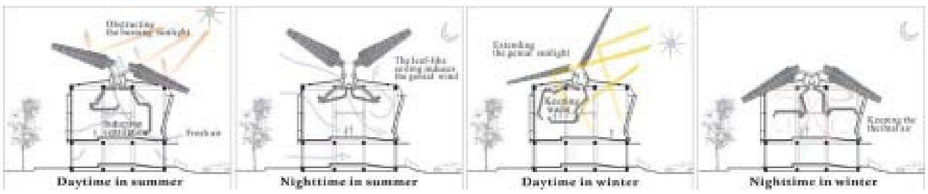

Figure 1. Section drawings shows the building shape altered in response to climate change

2. Building Responsive Primitives

In order to understand how responsive architecture works, it is necessary to study the basic unit of building responsive primitives. In this work, we define *a kinetic pair* or *joints* as the unit of building responsive primitives.

The basic unit of living nature is *cells* whereas the basic unit of responsive structure is *joints*. As cells to organisms, joints have their logic of design to aid designing building responsiveness. When two units are joined with a specific relationship, it could produce physical force and motion in relation to other units. We refer to it as *a kinetic pair* or *joints*.

There are three kinds of kinetic pair (joints): *twisting joints*, *rotating joints*, and *sliding joints*. Each joint is constructed with *tectonic interface*. In light of tectonic interface, the distinction between material and structure is blurring. Central to the joint is the *physical* design. *Perceiving*, *computing*, and *execution* are the major features of the joint, which forms the three dimensions of sensing-based kinetic systems, as shown in Figure 2.

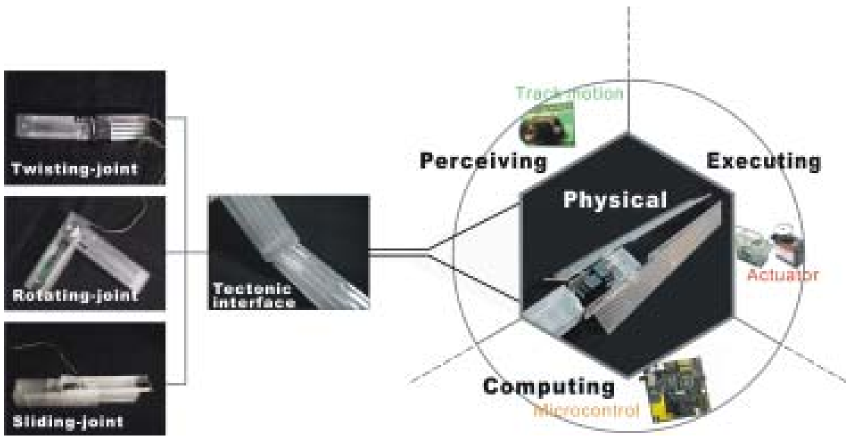

Figure 2. Three kinds of primitives (twisting joints, rotating joints, and sliding joints) are designed with tectonic interface; each of which can perceive, compute, and execute to adapt to change.

The physical entity of responsive primitive anticipated to hold sensing technology equipments is designed according to two kinds of building components: *skin* and *skeleton*. The skin primitive is a small mechanism attached on the physical structure frame, embedded with light sensors, wind sensor, mini servomotors or microcontrollers. The skeleton primitive is the kinetic joint of dynamic frame, embedded with webcam and infrared sensor to detect people's motion. We utilize the microprocessor through wireless communication, connecting the central server to control the primitives.

3. Kinetic Design Method

Composing the responsive primitives to produce various dynamic structures could develop a particular style of kinetic design language. The kinetic design language is based on a *vocabulary* of kinetic schema and a set of *tectonic rules* that correspond to different composition of motion joints. A set of composition rules defined in terms of those tectonic relations, together with an initial kinetic schema, comprise a kinetic design method.

1. The kinetic schemas have three basic actions: sliding, rotating and twisting. The composition defined in terms of those tectonic relations can be classified by *point* (kinetic schema), *line* (frame) and *plane* (board). One can start with an initial schema, and then specialize it to a frame. We can sort out the dynamic frame of six

kinds (i.e. A-F). Then we add a board to the frame when two frame intersecting in different positions (e.g. side or middle). The derivation process is shown in Figure 3.

2. Six classes of frames could be further developed to produce diversified dynamic structures from A-B to F-C.
3. *Figure 4* is the implementation of some combination of joints, resulting in a population of potential responsive architecture modules.

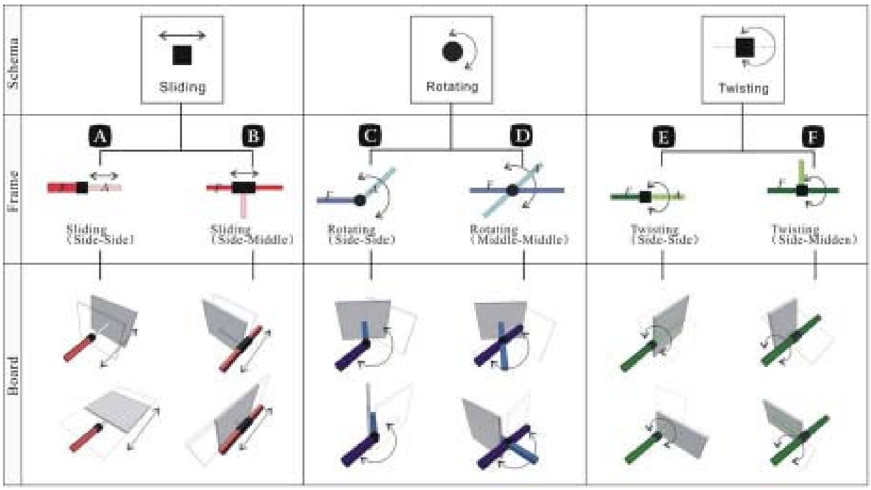

Figure 3. A set of composition rules defined in terms of those tectonic relations (i.e. schema, frame, and board), together with an initial kinetic schema (i.e. sliding, rotating, and twisting), comprise a kinetic design method.

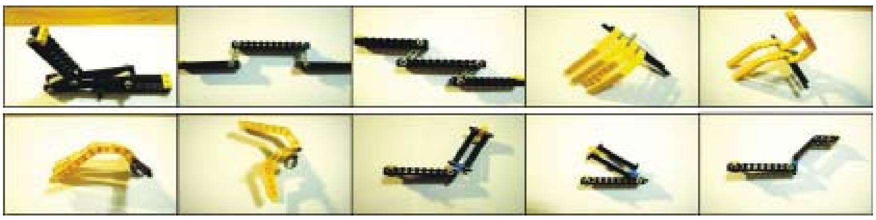

Figure 4. A population of potential responsive architecture modules

4. Physical Prototyping of Responsive Architecture

Based on the kinetic design methods presented here, Figure 5 shows the development process of responsive architecture corresponding to the design example presented in Section 1.3:

1. Associating two servomotors together as the driver of the rotating-twisting joint.
2. The light sensors and wind sensors are embedded in the physical structure.
3. An *Arduino* chip is used as the microcontroller that receives sensor signals and dispatches action commands to the actuators.
4. A physical entity is built by embedding sensors, motors, and microcontrollers, which provides the functionality of architectural roof primitives (i.e. exterior skin).
5. A kinetic skin primitive is tested by iterating the above four steps.
6. After testing the kinetic skin primitive, a dual skin primitive is further studied for developing the main structure of buildings.
7. The skeleton of interior wall is developed according to the pervious kinetic design method and added interaction behaviours in the main structure.

8. A simple building section model is built by integrating the external skin primitive and the interior skeleton primitive.

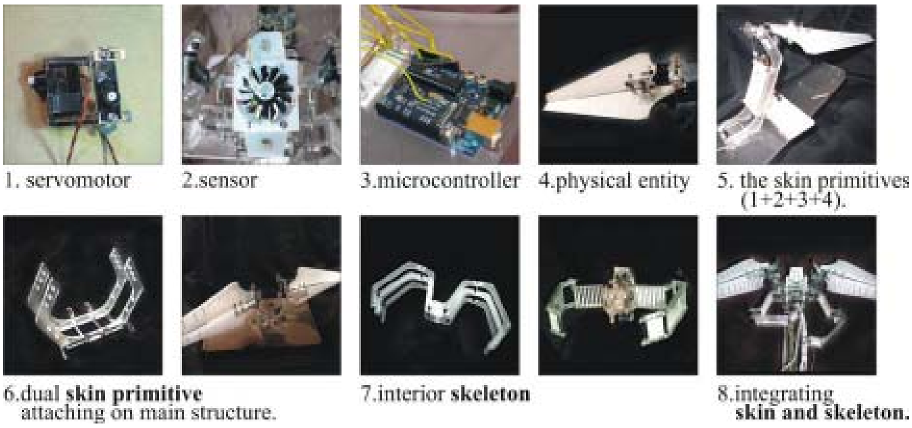

Figure 5. The development process of physical prototyping

In the implementation of actuators, we use the servo motors in the beginning stage. Because the rotating-joint requires strong torsion, we found that the linear servo is more suitable than motors. In the implementation of physical making, we use CNC tool to shaping model materials such as acrylic and aluminium. The planks of light materials make up the frame of skeleton joints in interstitial way that can enhance the strength of the model. The interval space of these interstitial planks could be connecting interface between primitive modules. The bearing force from the linear motor needs to translate into rotator movements by improving the design of kinetic pair of joints.

5. Mimosa - The System Implementation

We have implemented a responsive architecture system prototype called *Mimosa*. The *Mimosa* system collects input through an array of sensors and triggers the movement of the leaf-like roof surfaces in response to the sun's position. The *Mimosa* system is a building section model that is a part of the responsive architecture prototype. The motion of *Mimosa* from the transition of varied seasons and time could be optimized through manipulating the sensors, actuators, and microcontrollers, as shown in Figure 6.

In contrast to other kinetic systems, the Mimosa system coordinates the external and internal kinetic behaviours by mediating climate-responsive and user-responsive interactions correspondingly. That is, the *Mimosa* system changes the external roofs and internal walls simultaneously. In addition to respond to the sun's position, the interior walls can be reconfigured in real time, which gives the single space multiple functions to adapt to varied user activities.

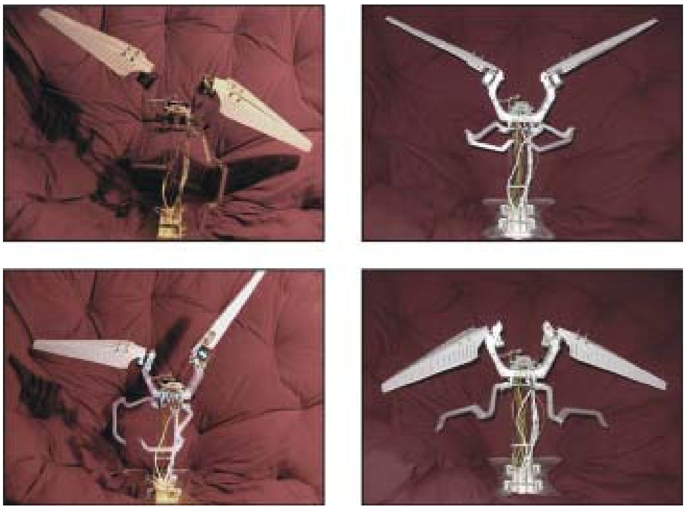

Figure 6. The Mimosa prototype alters its shape corresponding to the sun's position. The views of the prototype are mapped to the example design scenario (Figure 1).

6. Discussion: Robotic Automation vs. Human Augmentation

The implementation shows that the *Mimosa* system is sensitive enough to change the external roof shape and the internal wall space in response to sun's position. Based on our observations, the potential is promising, yet some deficiencies in the experimental study are found. First, because of the limitation of apparatus, the motion behaviour is not quite smooth as we expected. Secondly, the interaction between the autonomous skin primitives needs to be enhanced in order to maintain the quality of energy saving. Thirdly, there is a strong demand for developing kinetic design rules for responsive architecture. The rules can be formalized and embedded in the control programs of microcontrollers, which will largely improve the capability of motion and autonomous transformation for adaptive response.

Inspiring from bionics and mechanics, sensing-based kinetic design systems can operate at varied degree of *automation*. The first level of automation is *autonomy*. The autonomy mode means that every kinetic pair of joints works independently and reacts autonomously to adapt to the local environment. The behaviours are self-controlled, the components are self-organized, and the space is self-configured.

Augmentation is the second level where automation stops and humans take over control. The system augments human intelligence, rather than the other way around. In the *augmentation* mode, the sensors embedded in the kinetic pair of joints convey message from the local environment to the brain, that is, the central computer server. The actuators receive commands from the server and execute an action. Before the action is executed, the central computer server intercepts the communication signals between sensors and actuators and waits for users' input. The goal is to support partial automation while preserving user autonomy.

Previous research works in responsive architecture deal with two levels of complexity: *climate responsiveness* and *user responsiveness*. The climate-responsive architecture is focused on the *external* skin of buildings that transforms its physical properties to respond to varied climate conditions. For instance, the building transforms its shape to avoid direct sun light and offer suitable ventilation through controlling fa ade openings. In contrast to climate responsiveness, the user-responsive architecture is focused on human-computer interaction for adaptive activities. For instance, the internal wall partitions can be move, transformed, and reconfigured to support user activities.

Together, the level of automation coupling with varied situations defines the requirements of responsive architecture in a matrix, as illustrated in Figure 7. The matrix clarifies the complexity of responsiveness for any single responsive architecture project.

Level of Automation/Complexit y	External	Internal
Autonomy	Climate responsiveness	User responsiveness
Augmentation	Explicit interaction	Implicit interaction

Figure 7. The level of automation coupling with varied situations defines the requirements of responsive architecture

7. Conclusion

The paper explores the dynamics of architectural space by exploring the fundamental aspect of adaptive responsiveness in kinetic design systems. One important aspect is to develop *joints* as the basic kinetic primitive, and a set of *assembly rules* that correspond to varied kinetic behaviours of responsive architecture. The joints and *assembly rules* together define the kinetic design method. The method can be applied to any single responsive architecture project. Inspired by bionics and mechanisms, we develop the *Mimosa* system prototype by investigating the phenomenon of self-organization of living organisms. The *Mimosa* system is a *living* building prototype that can sense, move, and reconfigure itself in response to constantly changing needs.

The *Mimosa* system prototype presented in the paper has been fully implemented. The limitation the prototype has encountered based on initial testing and some assessments of the sensing-based approach to responsive architecture are also reviewed. To a certain extent the promise of creating responsive architecture yields real world benefits- supporting dynamics, flexibility, and adaptability in architectural space. We are considering the actual construction of the *Mimosa* system coupling with the *Aspire Home*, a long-term Smart Living Space project reported in [Jeng et. al., 2007].

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