Armanshahr Architecture & Urban Development, 10(18), 1-12, Spring 2017

ISSN: 2008-5079

EISSN: 2538-2365

A New Foldable Kinetic Architectural System: Through an Evaluative Approach of Built Examples, Case Studies: Resonant Chamber, Cheiljedang Research Center, Madina Shadi Project*

Maziar Asefi[1], Mandala Mitton[2] and Shanelle Currie[3]**

[1] Associate Professor of Architecture, Department of Architecture and Urbanism, Tabriz Islamic Art University, Tabriz, Iran and Visiting Faculty, Department of Architectural Science, Ryerson University, Toronto, Canada.

[2] Graduate Student of Architecture, Department of Architectural Science, Ryerson University, Toronto, Canada.

[3] Graduate Student of Architecture, Department of Architectural Science, Ryerson University, Toronto, Canada.

Received 13 January 2016; Revised 24 December 2016; Accepted 11 February 2017

ABSTRACT: Transformable elements of all different types have become increasingly utilized in architecture in order to respond to varying building conditions. Adaptive strategies and geometries found in nature have inspired a need for buildings to respond to the changing environments in their immediate context. In today's realm of environmental awareness, transformable architecture has the ability to respond to environmental conditions, and in turn increase the efficiency, occupant comfort and energy consumption of building systems. This paper discusses different movements, mechanisms and applications of transformable architecture, specifically foldable systems using pantographic elements. Case studies have been examined and evaluated in order to develop a final façade system with the ability to control the penetration of sunlight to a building under variable conditions. Sunlight can enable the passive heating of space, but may be detrimental and increase cooling loads and occupant discomfort through the summer months. In order to reduce the consumption of energy throughout the year, an occupant or computer controlled transformable façade system, like the one proposed, can be utilized. The proposed design seeks to emulate the adaptive nature of plants and animals when it comes to being light sensitive or light responsive. This shading system, when applied to buildings, will attempt to provide a solution which can help buildings become more transformable, and ultimately, more efficient. Despite of many transformable proposals, this four-panel shading system is to transform itself responsively and is able to function not only in fully open configuration but also in various stages of deployment. The proposed design not only provides occupants with natural lighting conditions or protection from solar glare, it optimizes solar heat gain through the heating season or mitigates it throughout the cooling season, satisfying both the energy efficiency and occupant comfort.

Keywords: Transformable, Foldable, Pantographic, Origami, Kinetic Facade, Responsive.

INTRODUCTION

Architecture and the constructed environment have historically been built to serve the immediate needs of humans. However, in a world where technology is advancing and the state of the environment is changing radically, the requirements of buildings often change as well. The idea of creating transformable or kinetic architecture is not a new idea; however it is constantly being developed and pushed to the next level in order to reach new levels of innovation. The following paper will look at just one type of transformable architecture: responsive architecture that employs foldable (pantographic) or origami-like elements to achieve

* This paper has been extracted from a research-based design project (Advanced Construction Case Studies) by master students: Mandala Mitton and Shanelle Currie carried out at the Department of Architectural Sciences, Ryerson University, Toronto, Canada, Under the Supervision of Dr. Maziar Asefi.

** Corresponding Author Email: masefi@tabriziau.ac.ir

transformation.

Embedded within nature is a naturally occurring geometry which allows plants and animals to function in their given environment (Asefi & Foruzandeh, 2011). Some develop based on fractals and discernible mathematical equations. Some take forms that are rigidly geometric, others more abstract. However, whether geometries are defined from the human world, or from nature, the benefits remain the same. Plants, animals, buildings and structures that can adapt to their surrounding environment have the potential to be immensely more efficient than their rigid counterparts.

Foldable architecture, whether rotating bars or origami inspired structures, has many benefits. Their compact nature gives them immense potential when it comes to deployable structures. When combined with sensor technology, foldable systems have the ability to expand, contract and fold in response to their surrounding environment.

The research categorizes foldable architecture and its elements and explores case studies to better understand the means and methods taken to achieve responsive systems. The study culminates in a design proposal for a kinetic facade system which developed from the improvement of already existing systems.

CATEGORIZING FOLDABLE SYSTEMS

Types of Kinetic Structures

According to Fox & Yeh (2011), there are three general typologies for kinetic architectural systems: Embedded, Deployable or Dynamic Kinetic Structures. Embedded systems are those which exist within and control the overall workings of a building (Fox & Yeh, 2011). Deployable systems are those in which the transformable elements are the basic structure of the building (Fox & Yeh, 2011). This is generally temporary or collapsible architecture. Dynamic systems are those which are independent of the buildings structure (Fox & Yeh, 2011), and are generally attached as an application or appendage of the main structural system. This includes things like transformable shading systems, second building skins or installations. Responsive foldable architecture generally falls into one of the latter two categories. Foldable architecture appears as deployable structures in foldable or collapsible pavilions which change size and shape in response to changes in environment or occupant movement. However, foldable architecture is also seen as dynamic kinetic systems: as elements separate from the main architectural structure. This means moveable building elements rather than a moveable structure. Case studies such as RVTR's Resonant Chamber, and Cannon Design's CJ Research Centre in Korea (see Case Studies), fall into the realm of dynamic kinetic systems.

Elements and Connections

The range of motion a foldable system can achieve is directly relative to the way in which its components are connected and the amount of freedom they have to move (Rosenburg, 2010). The types of connections between elements in foldable architecture fall into one of two general categories: systems of plates and hinges, or pantographic systems. Pantographic, or scissor-like elements are made up of straight bars with pivot points (Asefi, 2013).These bars can be arranged in single layers, or double layers (Rosenburg, 2010) (Fig. 1.).

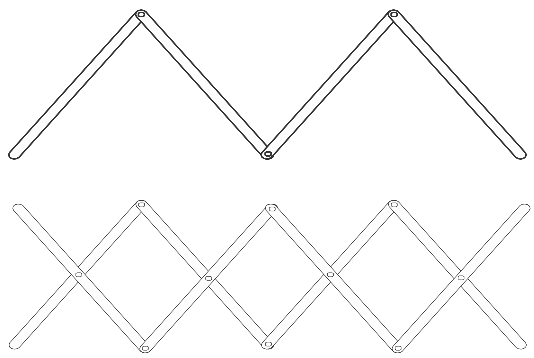

Fig. 1. Single Versus Double Layers of Pantographic Elements.

Single scissor pairs can expand much farther than double scissor pairs; as elements are added in, they limit the motion of the existing elements. The more layers or elements added in, the more controlled or limited the motion will be. These scissor elements, when connected together, allow for expandable cage-like systems, which can be covered in any applicable material. Pioneers of these types of systems are firms including Hoberman Associates, who have created complex pantographic systems, installations, and buildings (Fig. 2.).

Systems which employ hinges appear to be much simpler but actually have many underlying issues. Generally, a solid surface is fragmented into geometric, similarly shaped elements. These elements are connected together via hinges, and moved manually or by motor. The surface is then able to ripple or undulate. Movement is usually restricted to one direction: perpendicular to the surface. However, as the surface moves, it undergoes changes in length and width which can, at times, give it a very irregular size and shape. This can be difficult to apply to buildings as facade systems, let use as structure. Origami systems are often seen as installations, or in applications with a significant space buffer around them.

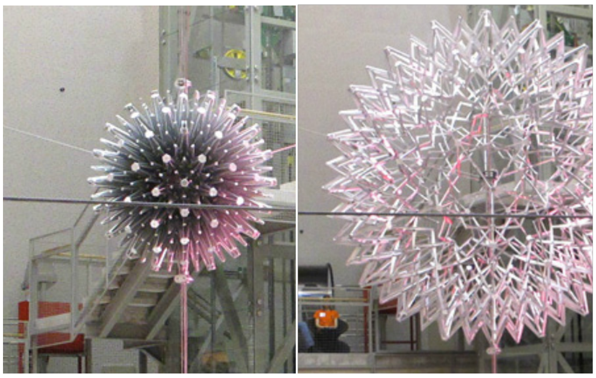

Fig. 2. Expanding Sphere, by Hoberman Associates. These Complex Systems of Pantographic Systems Allow for Immense Amounts of Expansion and Contraction, Picture Taken From (Hoberman Associates, 2013)

Motion

The motion of transformable structures can either be a rotation, translation or some combination of the two (Asefi & Foruzandeh, 2011). Foldable architecture falls into the category of rotation. In pantographic systems, pivot points between elements, also referred to as bars, allow for rotational movement around that point. In origami structures, the pivot point is extruded to become a whole surface edge. Rather than points and bars, the elements are edges and planes, though the concept remains the same.

El-Zanfaly (2011), in Active Shapes, maintains that movement of transformable architecture if determined by the arrangement, control mechanisms and geometry of the system (Rosenburg, 2010). This means that the arrangement of bars and their angles to one another directly affects the range of mobility a pantographic system will have. Rosenburg, in his paper Indeterminate Architecture, mentions the importance of this in deployable or collapsible architecture. The more movement that can be achieved, the more compact a design can be when fully closed. However, Rosenburg stresses the importance of the “in between states” between transformations. This idea was extremely important to the design proposal that follows. In a pantographic structure, between the fully closed and fully open state, the bars change angles an immense number of times. That ability to change orientation can be extremely useful for application such as deflecting light rays away from a building to prevent solar hear gain (as in the design proposal to follow). When combined with sensor technology, it represents the potential for immense accuracy.

CASE STUDIES

RESONANT CHAMBER | RVTR ARCHITECTS

Resonant Chamber, introduced by RVTR Architects in 2011 is a transformable origami-inspired acoustic ceiling panel, using a foldable plate and hinge system to deploy and retract. The structure is programmed to be responsive to sound, with the intent to produce a system that can create optimized sound conditions within the confinements of any space. This can be especially applicable in multi-functional performance spaces where sound conditions can vary from event to event.

The project is composed of triangulated elements that fold in or out in order to expose a different ratio of reflective, absorptive or electro-acoustical panels or cells. When the installation is in a fully deployed configuration, all of the panels are exposed absorbing sound in the space (Fig. 3.).

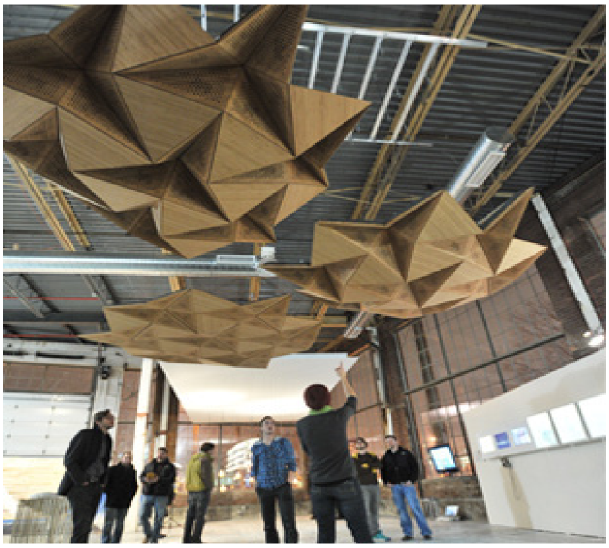

Fig. 3. Resonant Chamber, by RVTR Architects. These Acoustical Panels Expand and Contract Based on the Noise Conditions of the Adjacent Space, Picture Taken from (RVTR, 2011).

The physical space is therefore transformed in order to produce efficient quality of sound for the activity at hand. It responds to social activity through advanced technology and geometric construction, and has the potential to be played like an instrument.

Mechanism of Movement

The Resonant Chamber structure, composed of the three panel types mentioned above which is arranged into different triangulated cells (Fig. 4.). An electronics panel controls the amplification of the DML embedded speakers, linear actuation and sensing inputs of the environment. (RVTR, 2011) One of these panels may control up to three flat folding cells within the composite assembly. Each of the triangulated electro-acoustical cells responds to the sound in the environment through the use of the linear actuators mounted on top. These actuators respond to pulse-width modulation signals sensed by the speakers, which then control the proportion of the absorptive or reflective cells that are exposed by designating a fold angle (RVTR, 2011).

Fig. 4. Resonant Chamber, by RVTR Architects. Electro-acoustical, Reflective and Absorptive Cells Make Up the Large Origami Inspired Installation Panels, Picture Taken from (RVTR, 2011).

The angles created by the origami elements have allowed for flexibility within the form. The triangulated elements have the ability to fit together in a number of ways. As shown in figure 5, the geometry of the system is developed through connecting symmetrical lines through the triangles, from midpoint to midpoint. This allows for the acoustical panels (right angle triangles) to fold inwards based on sound requirements thus, allowing the reflective panels (equilateral triangles) to fold together (Fig. 6).

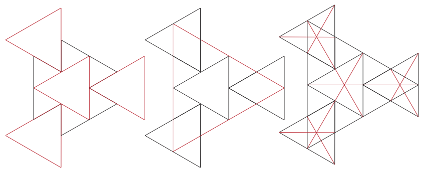

Fig. 5. Resonant Chamber, by RVTR Architects. The Origami Elements are Developed from the Geometries of Triangles.

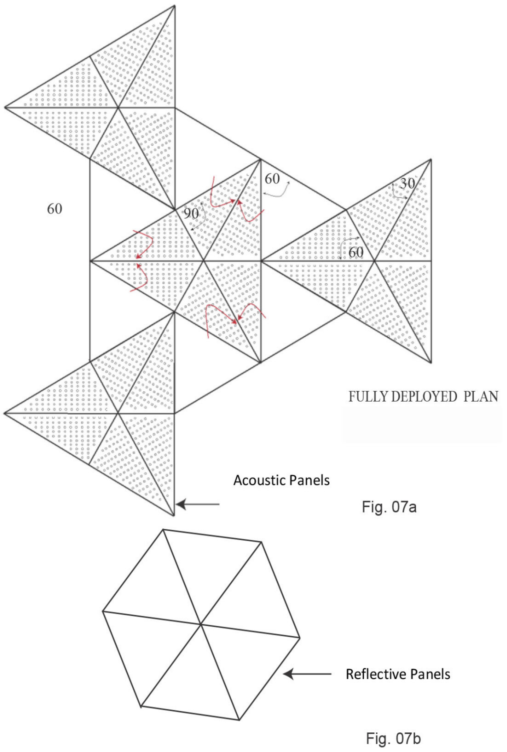

Fig. 6. Resonant Chamber, by RVTR Architects. The Angles Created by the Origami Elements Result in the Ability for the Panels to Deploy and Fully Close. Fig 06a Shows a Completely Deployed Plan with Origami Angles and Fig 06b Shows a Completely Closed Plan.

The flexibility of the system allows it to be utilized in more than one way and applicable in many different environments in order to increase the efficiency of the space. The basic elements and ideas of the Resonant Chamber can be applied to façade systems or shelters by responding to a multitude of environmental issues and constraints.

MEDINA HARAM PIAZZA SHADING PROJECT | SL-RASCH GMBH

The Medina Haram Piazza Shading Project was completed in 2011 by SL-Rasch GmbH; a German engineering company with a specialization in structures (MakMax, 2012). The massive 250 retractable umbrellas provide shade from the harsh Saudi Arabian sun, for the many pilgrims that visit the Mosque piazza.

The umbrellas provide average of a 14 degree reduction in temperature during the day. ("Archi Expo", 2013) Not only do the umbrellas offer functionality to the harsh climate, they are aesthetically pleasing, finely painted with gold detailing and intricate ornamentation. Whether they are fully deployed or in a fully closed position, the umbrellas add beauty to the vast mosque space. Each umbrella spans an area of 625m^2 and is 49 feet tall. The membrane material is made of decorated polytetrafluoroethylene or PTFE developed specifically for the project. (Orell, 2010)

Weather resistance and maintain functionality in order to make sure it withstands a long life expectancy. When closed, the umbrellas are encased in a fiberglass column (Orell, 2010). The structural elements are made of a lightweight composite sandwich structure of glass fibre epoxy resin laminate. (Orell, 2010) These materials were chosen in order to withstand the climatic conditions and provide high torsional stiffness.

The umbrellas contain two rings, supporting pantographic elements. The lower most or 'primary ring' (Fig. 7) moves up or down in order to promote the folding or unfolding of the umbrella. ("Archi Expo", 2013).

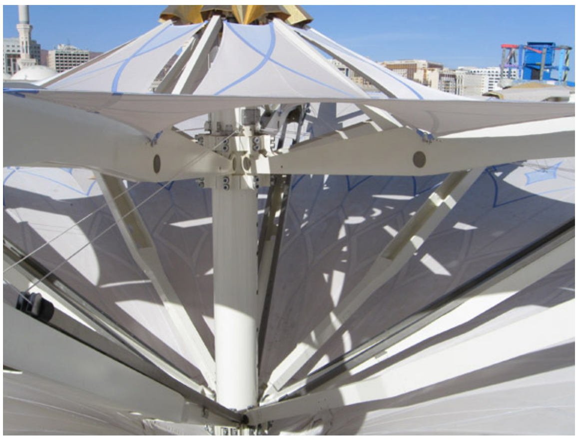

Fig. 7. Medina Haram Shading Project, by SL-Rasch GmbH. The Structural Positioning of the Fully Deployed Umbrellas, Picture Take from, (Premier Composite Technologies, n.d.)

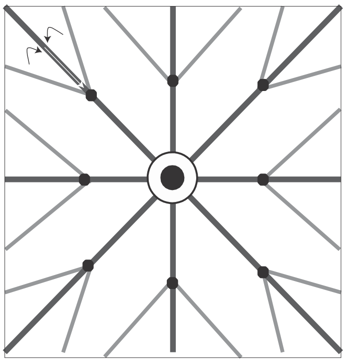

Fig. 8. Medina Haram Shading Project, by SL-Rasch GmbH. A Plan Diagram of the Structural Components Connected to the 'Primary Ring'.

There are 8 primary arms attached to the primary ring. Each arm supports two additional arms with the ability to fold out, in order to hold the membrane tight in its deployed, square position (Fig. 8.). The main structural column has been decorated and contains the built in lamps used to light the piazza at night. Incorporating the structural elements with the architectural components has benefited the aesthetics of the project.

MECHANISM OF MOVEMENT

An electronic motor promotes the deployment and closing of each individual umbrella structure and their respective pantographic elements. In order to ensure that they do not contact one another through deployment, the umbrellas have been set to deploy at different times. (Orell, 2010) Although the sun is seen to have a negative impact on the space, rather than strictly protecting from unwanted sun, the umbrellas have the ability to harvest the harsh solar exposure in order to utilize it for the electrical energy consumption or built in lighting.

CJ CHEILJEDANG RESEARCH AND DEVELOPMENT CENTER | YARZDANI STUDIO / CANNON DESIGN

Responsive facade systems are an important stream of research for Yazdani Studio & Cannon Design. CJ Cheiljedang Research and Development Centre (Fig.9.) is a proposed project which would consolidate CJ Corporations many disparate businesses under one roof ("Cannon Design", 2013).

Fig. 9. CJ Cheiljedang Research and Development Center, by Yarzdani Studio / Cannon Design. The Foldable Facade Wraps the Whole Building in Ribbons, and is Sectioned Such that Pockets Can be Opened and Closed Where Needed, Picture Taken from (Yazdani Studio, 2011).

The project, a proposed research facility in Seoul, South Korea was designed to give the company an environmentally responsible image (Michler, 2012). The building's program required protecting the research labs from solar glare, yet still maintain views and natural day lighting. The solution is a responsive kinetic facade made up of pleated panels ("Cannon Design", 2013).

When fully open, the system provides diffuse daylight into the labs, protecting labs from the glare of high summer sun. When folded, the system allows direct day lighting into the labs. The folds and perforation in the foldable second skin of the building are carefully arranged to maximize efficiency indoors ("Cannon Design", 2013).

MECHANISM OF MOVEMENT

The foldable facade wraps the entire building and is arranged in bands of 3 bi-fold ribbons connected together. The system uses motor driven pantographic elements in order to extend and retract. The ribbons are segmented such that portions on one side of the building can be opened while portions on the opposite side can be closed. They do not have to work in unison, as lighting conditions on opposite sides of the building would be very different.

PANTOGRAPHIC ELEMENT AND CONNECTIONS

Each unit consists of six shade panels, with pantographic units spaced regularly between them around the circumference of the building. Six main pantographic elements (which support the six shading panels) are connected to the main arm (Fig. 10.). Secondary and tertiary pantographic elements push and pull the main elements in order to fold down units in the system. Opening several adjacent anchors to different degrees allows for pockets of the facade to be opened, while others remain closed.

There are three critical connections which determine the movement of the system. Primary and secondary pantographic elements are attached via fixed connection. Tertiary pantographic elements are connected via one sliding connection and one fixed connection. This sliding connection is motorized, moving all of the pantographic elements.

The building has increased thermal efficiency due to the envelope and optimized solar heat gain (Michler, 2012), with the added benefit of increasing the company's perceived corporate responsibility (Yazdani Studio, 2013).

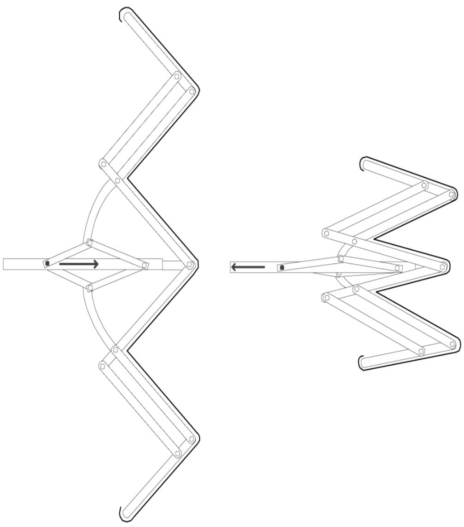

Fig. 10. The System in the CJ Research Centre Offers Only One of Two Deployment.

The project functions extremely well as a full building facade. The building claims to be designed for "optimum flexibility and efficiency", however there are many improvements that can be made. However, weaknesses of the project involve the limited functionality of the system: there are only three positions: opened, closed or somewhere in between to which the shades can be oriented, meaning that the system does not reach maximum flexibility. The shades are segmented, yet still attached together. Each unit shares its supports with adjacent units (Fig. 11.). When one unit opens, it drags the other units open as well, creating almond shaped openings on the exterior.

Maintenance and accessibility issues aside, the system is simple and elegant, with the potential to be developed into more organic or complex system and geometries in future designs.

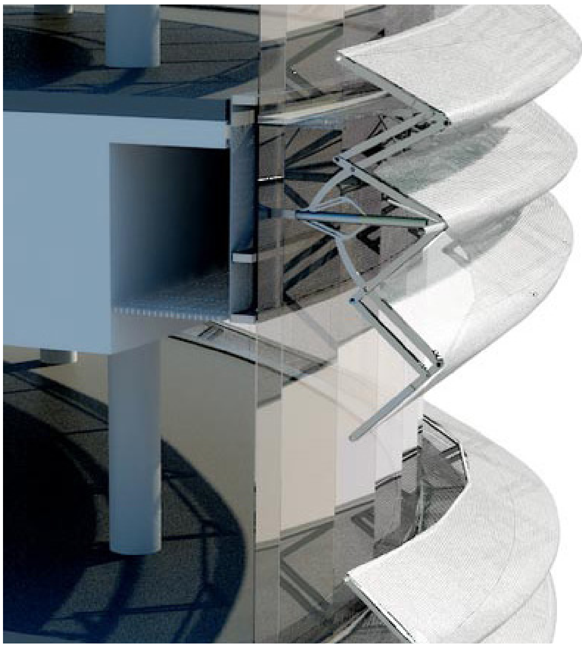

Fig. 11. Sectional View of Folding Facade Panels, Picture Taken from (Yazdani Studio, 2011).

EVALUATION OF FOLDABLE ARCHITECTURE- IMPROVEMENTS

The case studies present strengths and weaknesses associated with the application of responsive kinetic architecture which can be used to develop more effective foldable systems. In terms of movement, there is a clear difference between origami architecture and pantographic architecture. Origami architecture, though it provides a wide range of shapes and patterns of movement, is extremely irregular and difficult to apply. Pantographic structures, being pivots rather than whole surface edges, have a higher degree of freedom, pantographs can be arranged to support flat surfaces or entire structures with much more ease.

In terms of technology, the computer systems which control the case studies are extremely effective. The technologies applied in the Resonant Chamber, Shading Project and Research Center successfully respond to interior and exterior conditions and significantly improve energy efficiency. Incorporating technology into design may prove to have maintenance related issues and in some cases, failure. Both examples are highly dependent upon technology, but have been produced in a way in which problems are fairly easy to troubleshoot. Technology can be a major operational cost in the building, and though useful, its control and precision is a critical factor in the success of the system.

There is much to be learned from the case studies in order to create an improved model for a foldable responsive facade. Resonant Chamber's research in the idea of orientation and presenting different materials to an environment in order to improve its acoustics was highly successful. This idea that orientation and materiality can improve an environment is something that will be carried over into the research for the following design proposal. However, it will be formally applied to a different system, as the size and shape changes induced by origami-like folds result in a shape too irregular to tessellate across a building facade.

With more precedents for success, pantographic architecture will be the main stream of research going forward. With both vertical and horizontal applications, umbrella structures like those seen is Rasch's and Cannon's provide responsive solutions to changing exterior environments. Both have limited degrees of freedom based on their arrangement and geometry. In order to bring a focus on orientation to an umbrella like pantographic system, the arrangement of bars needs to be one which allows for a vast array of in-between states. By decreasing the number of bars, and adjusting the stopping mechanisms which limit the movement of the pantographs, a wider range of movement and positions can be achieved. The following improvements will be the focus of the design proposal that follows:

1. Allowing for a wider range of movement between pantographs.

2. Allowing shading panels to change orientation as required.

DESIGN PROPOSAL

The design exploration proposed to investigate the combination of two of the aforementioned case studies with the intent of increasing the range of movement for foldable architectural systems. Based on the evaluation of foldable architecture, movement is often limited to one, or several very specific directions. The CJ Research Centre project presented a system which can open and close in order to provide shading. However, this shading is limited in the sense that the orientation of the panels cannot change; orientation is an important aspect of any shading system. SOM, in a design study, determined that a change in orientation as small as six degrees can reduce heat gain in a building by around 25% (Aqtash, 2009). Rasch's Medina Shading Project's pantographic elements allow for two orientations or directions of movement based on the location of the sun. It is limited in a sense that there are also only two degrees of shading: fully shaded or none at all. Resonant Chamber, however, attempts to provide shading which changes orientation based on the needs of the room. When it folds in one of two ways, it presents panels that absorb, or panels that reflect sound. Combing the variety of orientation present in the Resonant Chamber system with the pantographic structure of the CJ Research Centre and Shading Project, provides an increased range of movement and options to create a very useful adaptive shading system.

The proposed system is a dynamic kinetic system (Fig. 12.) applied as a moveable façade. The intent is that such a system can be programmed to be responsive to changes in light conditions, and that panels can be re-oriented to optimize solar heat gain in the heating months, and control it in cooling months.

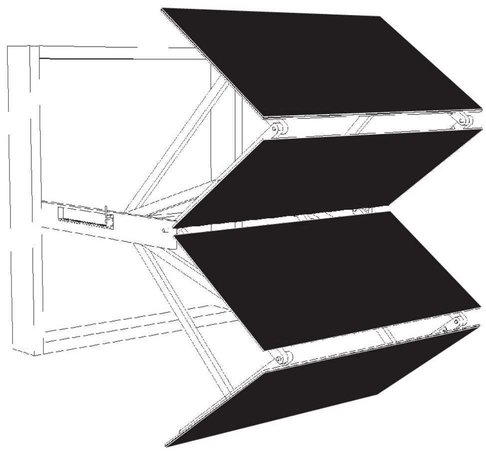

Fig. 12. Proposed Adaptive Shading System.

The system features four shading panels which fold out like wings, moved by a mechanism very similar to an umbrella, but with several important improvements.

ORIENTATION AND MOVEMENT

Two identical sets of pantographic elements, located at opposite ends of the shading panels provide support to the panels and allow for movement. One set of pantographic elements will hereby be referred to as one assembly. Two assemblies supporting four shading panels will hereby be referred to as a unit. The pantographic elements themselves are arranged in a hierarchy within each assembly (Fig. 13.).

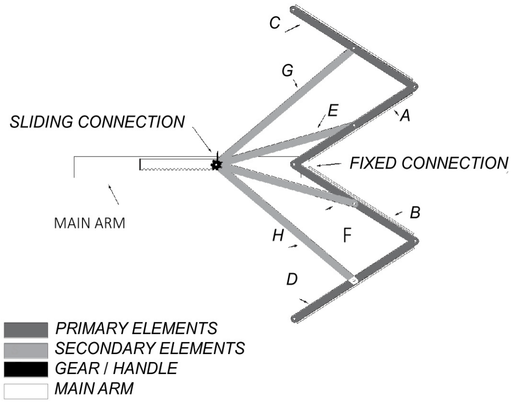

Fig. 13. Primary and Secondary Components of One Assembly.

Four primary elements (A-D) in each assembly support the shading panels, while four secondary elements (E-H) interact with both the primary elements and the main arm of the assembly in order to facilitate movement. This main arm is the element which transfers the self-weight of the shading system to the building's main structure.

A major limiting factor in the CJ Research Centre is that the panels cannot change orientation. This is because elements are fixed in an umbrella-like pantographic system, and cannot over-extend, or move in both directions. The sliding component in an umbrella is created such that it only allows pantographic elements to fold out to a point where the interior angle between primary elements in less than 90. As many people have experienced, if an umbrella overextends, it gets stuck, and the movement mechanism is not able to bring it back to a closed position. In the devised system, this "over-extended" position represents an important second orientation for the panels. By allowing the sliding joint to slide further, it allows primary elements to have an interior angle of more than 180 degrees without compromising the ability of the system to return to a closed position (Fig. 14.).

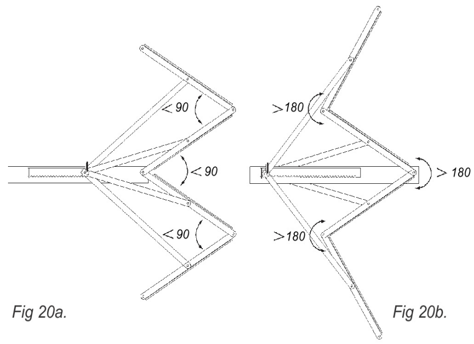

Fig. 14. Typical Umbrella Structures have One State of Deployment. By Increasing the Range of Movement between the Primary Elements, Different Orientations of the Shading Panels can be Achieved. Fig. 14a Shows the Typical Umbrella Structure. Fig. 14b Showes the Increased Rotation.

PANTOGRAPHIC ELEMENTS AND CONNECTIONS

In a simple pantographic system, pantographs are connected end to end. In the proposed system, primary pantographs are connected end to end. However, secondary bars are connected to the primary bars at mid-span (Fig. 13.). This position optimizes the amount of movement for the least amount of length. The main arm and the primary elements function perpendicular to one another, and the secondary elements make up the diagonal length between them.

The combination of fixed and rigid connections are what determine the direction and extent of movement. These critical connections all converge at the main arm of the system. Where primary elements are attached to the main arm, a fixed connection support the arms but does not allow them to move in any direction other than perpendicular to the main arm. The sliding connection is located where the secondary elements are secured to the main arm. This is approximately mid-span of the main arm. The connection is located at the center of a pinion, part of a track and pinion system, which allows this connection to slide along the main arm. The secondary elements then push and pull the primary elements, changing the orientation of the panels.

To facilitate further compression, where the secondary elements G and H meet the sliding, they are slotted such that they can change length. This allows the system to compress as much as possible when in the closed position.

MECHANISM OF MOVEMENT

Several mechanisms of movement were explored. A system of cables lacked the ability to be pushed as well as pulled, and would have required a multiple sets of systems, complicating an otherwise simple and elegant system. Simple sliding mechanisms lacked the control or smoothness required. Gear systems, though effective, required more hardware than was necessary (Fig. 15.). It required that the arm be twice as deep, increasing its weight and material cost.

A more simple track and pinion system was chosen for being the most simple (Fig. 16.).

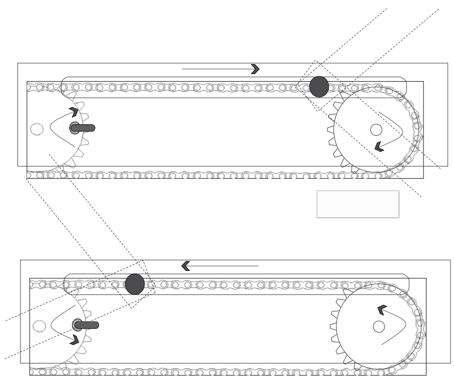

Fig. 15. Gear Systems which were Explored Required too much Hardware. The Main Armature had to Endure not Only its Own Increased Weight, but the Weight of the Hardware as Well.

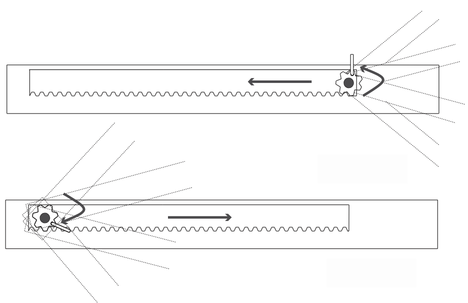

Fig. 16. Final System of Movement. The Devised Track and Pinion System Required much less Hardware and is much Easier to Operate.

The slotted main arm form the toothed track in which a gear sits. This gear, the "sliding connection" has a joint fixed at the centre, where the secondary elements E though H are connected. A handle, located on the outside of the gear is the mechanism of movement. When turned, the gear flows along the track, forcing the arms to push and pull the primary elements perpendicular to the direction of movement.

PRACTICAL APPLICATIONS

In order to be adapted for actual applications, several elements of the system would need to be altered. Firstly, the mechanism of movement would need to be motorized rather than manual. Though very small home or shelters could still rely on manual movement, large ICI (Institutional Commercial or Industrial) projects would likely require that the track and pinion system be motorized. Sensors tracking and evaluating exterior weather conditions would communicate with actuators and motors to give the system to have the precision it needs to be extremely efficient.

In terms of size, there is much room for flexibility. The primary elements which support the shading panels would span floor to floor when fully deployed. This would provide the entire building with shade when necessary. In terms of width, the pantographic assemblies can be positioned at main structural intervals, or at the mullions between windows. Not all units need to be the same width or height; a series of large and small units may be tiled across a facade to create a vast array of patterns depending on the designer's wishes.

Materially the system is designed to be made of any number of materials. Likely metal, the main bars can be and desired color of finish. The shading panels themselves could be adapted to whatever is necessary functionally or is aesthetically compatible with the design. This could mean metal or wood panel, glass, or any number of perforated materials. The system was designed to be not only extremely transformable, but extremely customizable in size, shape and material.

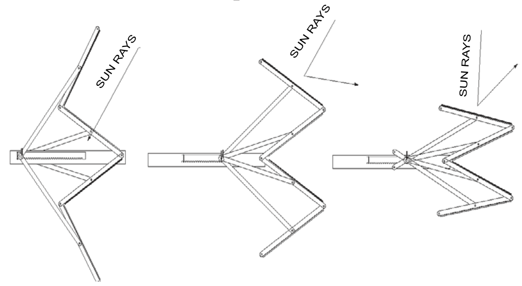

Fig. 17. Different Deployments of the System Orient the Panels in Different Ways Towards the Sun.

CONCLUSION- FUTURE OF RESPONSIVE ARCHITECTURE

As technology advances, architecture has the ability to become more and more complex and efficient by responding to human activities and occupant needs. Building requirements are also ever changing, requiring the systems that cater to the activities to respond almost instantaneously. Responsive, foldable architecture when applied in combination with technology, has the ability to achieve this efficiency while still creating aesthetically interesting buildings.

There are a number of architectural projects existing today that set the precedent for designs which aspire to respond to their space requirements and occupant needs. The Resonant Chamber, CJ Research Centre and Medina Shading Project use foldable systems in a variety of ways in order to respond to the human environments in which they exist and are extremely successful. However, the proposed design is to improve and adapt existing precedents, the design uses structural pantographic elements in order to increase efficiency and flexibility of a building facade. In spite of the precedent designs, the proposed design not only provides occupants with natural lighting conditions or protection from solar glare, it optimizes solar heat gain through the heating season or mitigates it throughout the cooling season, satisfying both the energy efficiency and occupant comfort.

The proposed system is a dynamic kinetic system applied as a moveable façade. The intent is that such a system can be programmed to be responsive to changes in light conditions, and that panels can be re-oriented to optimize solar heat gain in the heating months, and control it in cooling months. The system features four shading panels which fold out like wings, moved by a mechanism very similar to an umbrella, but with several important improvements. The system will present a multitude of shading options, based on the needs of the occupants and space heating and cooling requirements. Figure 17 shows the different deployments of their systems and their benefits. Deployment A allows light into the interior spaces to maximize solar heat gain, where Deployment B reflects light when solar heat gain is detrimental to the building. Deployment C, the fully closed position, compresses the system

REFERENCES

Aqtash, A. (2009). SOM and SCI-Arc on CF: *Responsive Kinetic Facade, Core. Form-ula*. Form-ula Architecture, 15/04/2009. http://www.core.form-ula.com/ category/built/page/8/, 17/01/2013.

Archi Expo (2013). *Retractable Tensile Structure: Medina Haram Piazza Shading Umbrellas*. Archi Expo, http:// www.archiexpo.com/ prod/ premier-com- posite-technologies/ retractable- tensile-structures- 89104-828024. html.

Asefi, M. (2013). *Advanced Construction Case Studies*. Toronto: Ryerson University.

Asefi, M., & Foruzandeh, A. (2011). Nature and Kinetic Architecture: They Development of a New Type of Transformable Structure for Temporary Applications, *Journal of Civil Engineering and Architecture*, 5(6), 513-526.

Cannon Design (2013). *CJ Corporation CJ Only One Centre*. Cannon Design.http://www.cannondesign.com/projects/project-catalog/cj-only-one- center/#engineering 01/13/2013.

El-Zanfaly, D. (2011). Introducing Guidelines for Designing Kinetic Architectural Structures. XV *Conference of the Iberoamerican Society of Digital Graph- ics*, Argentina: Santa Fe.

Fox, M., & Kemp, M. (2009). *Interactive Architecture*. New York: Princeton Architectural.

Fox, M., & Yeh, B. (2011). *Intelligent Kinetic Systems*. Cambridge: Massachusetts Institute of Technology Department of Architecture.

Hoberman Associates (2011). Expanding Sphere. Hoberman Associates Inc, http://www.hoberman.com/portfolio/sphere estonia.php?rev=0&onEnterFrame =[type+Function]&myNum=6& ategory = &projectname = Expanding + Sphere+ %28 Estonia %29, 6/04/2013.

Michler, A. (2012). *CJ Reserach Center's Kinetic Folding Facade / Yazdani Studio*, eVolo. http://www.evolo.us/architecture/cj-research-centers-kinetic-folding-facade-yazdani-studio, 17/01/2013.

Orell, R. (2010). Snapshot: Medina Haram Piazza. *Architectural Record*, http://archrecord.construction.com/features/snapshot/2012/1201 Medina-Haram-Piazza. asp.

Premier Composite Technologies (n.d.). *Medina Haram Piazza Shad- ing Umbrellas*. Premier Composite Technologies, http://www.pct.ae/compos- ites_projects. php?project=5.

Rosenburg, D. (2010). *Indeterminate Architecture: Scissor Pair Transformable Structures*. Cambridge: Massachusetts Institute of Technology.

RVTR (2011). *Resonant Chamber*. RVTR Architects, http://rvtr.com/research/resonant-chamber/

Sl-Rasch (2013). *Umbrellas*. SL-Rasch GMBH, http://www.sl-rasch.de/,6/04/2013.

Yazdani Studio (2013). *CJ "Only One" Reseach & Development*. Cannon Design, http://yazdanistudio.com/projects/#, 01/17/2013.