The Pennsylvania State University
The Graduate School
College of Arts and Architecture

DESIGN OF A COMPUTER CONTROLLED SUN-TRACKING FAÇADE MODEL

A Thesis in
Architecture
by
Mahzad Tashakori

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Architecture

May 2014

The thesis of Mahzad Tashakori was reviewed and approved* by the following:

Ute Poerschke

Associate Professor of Architecture

Thesis Adviser

Loukas Kalisperis

Professor of Architecture

Jeffrey Brownson

Associate Professor of Energy and Mineral Engineering

Mehrdad Hadighi

Architecture Department Head and Professor, Stuckeman Chair of Integrative Design

*Signatures are on file in the Graduate School.

Abstract

This thesis describes the development of a computer controlled sun-tracking device model that aims at improving the environmental performance (daylighting, shading, energy harvesting) of a building façade system. During the process, advanced computational modeling and simulation tools, such as Grasshopper and Ecotect, were utilized to create and analyze an environmentally responsive building envelope with an integrated sun-tracking device. Physical models of the simulated sun-tracking system were built. They are equipped with light sensors that gather solar information to detect the optimum angle for absorption of solar radiation. The sensors are connected to a micro-controller to process, store and send the information to micro-servos that mechanically actuate the sun-tracking elements to be oriented to the light source. The thesis discusses the benefits of this adaptive device, i.e. maximizing the efficiency of energy harvesting from mounted photovoltaic cells while providing an enclosure for the inner space, and regulating daylight, shading and visual contact between inside and outside. The incorporated energy generating photovoltaic cells make the kinetic façade modules completely self-sufficient with no need for a centralized control system. Ultimately this thesis contributes to the question of how a computer controlled sun-tracking device can be integrated in a façade system.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

The subject of this research originates from a series of questions and concerns regarding the necessity of improving the energy performance in architectural design and the need for application of new technologies to that end.

Environmental issues are the driving force in many architectural design projects today. After the 1970's energy crisis, many architects and engineers put their efforts into engaging "the environment in a way that dramatically reduces or eliminates the need for fossil fuel" (Strategies for Design Schools, 2011), because they are clearly aware of the huge environmental impact of buildings. U.S. Green Building Council in its 2003 report on the costs and financial benefits of green buildings indicates that buildings are one of the largest sources of greenhouse gas emissions in the United States. Based on the USGBC report, "buildings account for 39% of CO_2 emissions" in the country. (USGBC, 2003)

This awareness along with energy conscious programs such as the Architecture 2030 Challenge[1] has contributed to wider adaptation of various active and passive environmental measures in architecture to reduce the energy consumption and GHG emissions of buildings.

The environmental impact of the building industry underlies this design research. The author is concerned with improving the energy use and renewable energy production of a proposed building envelope through application of computer automation and sun-tracking technology.

Renewable energy producing technologies that are available today, specifically the solar technology in form of photovoltaic cells are being treated as eyesores that need to be hidden on the roofs. To raise public awareness and make these technologies more appealing the design and technology should merge. The combination of the two and its challenges are the main focus of this research.

The environmental concern and the design challenge along with personal interest in exploring the idea of buildings that go beyond the conventional design measures to improve the energy performance of the structure has encouraged the design of a sun-tracking façade system.

[1] http://architecture2030.org/

Conventional buildings are designed and built for various uses and reasons. What they all have in common is that they need to be stable, rigid and resistant to climatic and human forces and in compliance with certain building codes. However, climate, energy, information and human agents acting on buildings are in essence transient and constantly changing. Therefore, conventional buildings designed for a specific climatic condition cannot function sufficiently as that conditions change. A comprehensive understanding of the building's behavior exposed to these elements shows, to reduce the energy used to withstand a transient force, flexibility is more helpful than rigidity. This idea is the basis for responsive buildings as flexible entities constantly adapting to the changes in their environment.

Resolving the paradox of mutable external agents and the fixed structures is possible through a balanced approach that does not compromise any of the two. This design research tries to answer how this balanced solution is shaped through computer simulation of various design alternatives and building their physical mock ups for energy tests.

The reason behind choosing solar energy producing technology as the solution for design of energy efficient building envelope lies in the advantages of the solar energy itself and the fact that building envelopes are more than anything exposed to sun and wind, which make them the most efficient site for innovative high performance designs.

This design focuses on solar energy as a free source of energy readily available to everyone. It is "clean, silent and reliable, with very low maintenance costs" and produces no GHG emission while being produced. (Tudorache & Kreindler, 2010) This leads to minimum environmental impact which is mainly the impact from the production of the PV panels.

While cheaper products has become widely available in the market and has made home-scale solar energy a popular technology for individuals, the high upfront cost for large projects is still a disadvantage.

1.2. Research Question

How a computer controlled sun-tracking photovoltaic system can be integrated into a building envelope?

1.3. Methodology

This thesis studies the design of a high-performance sun-tracking system as an example of a combined passive and active solar façade system.

This design research attempts to answer how a computer controlled sun-tracking system can be integrated in the building envelope. Overcoming the challenges of merging design ideas with performance-driven priorities makes the larger part of this document. The current design is the result of an ongoing research on responsive façade systems. The design progress along with the pros and cons of each alternative are explained in chapter 4 and 5.

To better examine the performance of the adaptive building systems, a physical mock-up of the simulated façade system module is built. The geometry and mechanics of the responsive sun-tracking system forms the main part of the design procedure. The goal is to explore the potentials of integrating an interactive solar tracking system into the building envelope.

The thesis is focused on the conversion of incident solar rays' energy into electricity through automated adaptive systems. This electricity conversion process is called photo-voltaic or PV and as noted by Tudorache (Tudorache & Kreindler, 2010) is not a new technology. One reason behind this particular focus is the unique qualities of solar energy. It is "practically inexhaustible, and involves no polluting residue or greenhouse gases emissions." (Tudorache & Kreindler, 2010) The second reason is the need to improve the efficiency of ever growing PV technology to make it a more economic and viable choice for ordinary buildings and the fact that incorporating adaptive solar cells is an effective way to achieve more efficiency in solar gain and conversion. Further, despite the progress of the technology and efficiency of PV cells implementation on building surfaces, the aesthetic expression of photovoltaics is still cursory. The conventional PV cells are usually dark colored and assembled in a rectangular arrangement on metal panels, often hidden on the roofs. However, a variety of newer cells in the PV market, such as double sided, flexible, solar shingles (PV cells designed to look like conventional shingles), also known as building integrated photovoltaics (BIPV), make room for more creativity in PV cell integration. The architectural expression of a solar energy powered building certainly helps raising public awareness and encourages its adaptation in more buildings.

As previously mentioned, efficiency improvement is key in designing a new solution to integrate PV cells in this thesis. Tudorache has identified three different improvement solutions for PV efficiency: optimization of solar cell configuration and geometry, application of new material and technologies and use of solar tracking (Tudorache & Kreindler, 2010). This thesis design project develops upon the latter solution, the use of solar tracking. In an attempt to answer why adaptive façade system is used in this thesis, the solution is discussed in chapter 3.

The inevitable question, however, is why the automated adaptive system should be integrated in the building's façade. The building envelope is the immediate medium between the natural and the built environments and works as "the primary subsystem through which prevailing external condition can be influenced and regulated to meet the comfort requirements of the user inside the building" (Schittich, 2006, p. 29). This envelope is where the most prominent measures for improving the environmental performance of the building can be implemented.

The environmental conditions of the natural surroundings of the built environment are constantly changing. In order to control the environmental performance of the architecture, building systems should consider the natural conditions and adapt to them. Adapting the building, the environmental information and user demands shape the design decisions. For an architecture, to be regarded environmentally adaptive in various climates and weather conditions all the time, there are numerous factors that need to be considered, such as location, light, wind, humidity, etc. However, the more criteria the designer takes into consideration, the more complex the design and decision-making process becomes, so far as it becomes impossible to implement the project without computational tools.

Emerging high performing multi-functional building systems that are self-sufficient and capable of responding to various circumstances simultaneously use computation for higher efficiency and accuracy. These sophisticated building envelope systems are explained in chapter 2. Michael Fox, an expert in interactive architecture, believes an interactive building envelope as the environmental controlling layer can "dynamically mitigate conditions to take advantage of energy-conserving strategies" (Fox & Kemp, 2009, p. 58). In addition to the passive design strategies that enable the built environment adapt to its natural surroundings, "one great opportunity for interactive architecture is to examine passive sustainable systems coupled with automated kinetics and computer control to optimize their performance." (Fox & Kemp, 2009,

p. 113) These automated active strategies adds to the efficiency of the building envelope by maximizing the solar energy gain, converting solar energy to heat or electricity for local use, exploiting wind power, etc.

1.4. Design steps

Below are the questions that were considered throughout the design and implementation of this thesis. The questions help better understand the steps taken for this design.

- *What has been done before? What can be learned from the precedents and how the lessons from those can contribute to this research?* Precedents are explained where necessary through this document in chapter 2 and 3 to clarify the goals of this research.
- *What tools and techniques are useful?* Computer tools for design and simulation, energy analysis and computer control useful in designing a high performance responsive façade system are discussed in chapter 4.
- *How the sun-tracking system is automated?* An actual model of the responsive system requires precise collection and processing of the environmental information in order to get appropriate responses from the control system. Chapter 4 explains how in this method, the building senses the environmental changes with sensor devices – photo sensors in this design – gathering physical environment's data such as light, motion, sound, temperature, etc. This information is sent to a micro-controller that has a memory and a processing device programmed to translate the environmental stimulus into actions. *Arduino*, an inexpensive micro-controller readily available to designers and programmed by an open-source programming language and processing-based software, is used as the controller here. Users with minimum understanding of programming languages can use and customize the available codes for various functions in design. This controller can be connected to micro-servos as mechanic actuators that translate computer controller's orders into physical action.
- *What is the efficient form?* While this question does not have a definite answer because form design is subjective, this research, as it progresses, attempts to demonstrate why specific forms are ruled out. Precedent computation research and design progress are explained in chapter 4 and 5.

- *What are the technical challenges?* The challenges related to implementing automation equipment in an architectural design mock-up and learning to program the automated system are discussed in chapter 4 and the challenges to construct the computer-controlled physical model that can track the sun three dimensionally are explained in chapter 5. The physical mock-up of the computer simulated module is built to put the performance of this design to a real test. The mechanical specifications of the dynamic sun-tracking elements are designed based on the type of motions needed (axial or radial), the daylight demand inside the building, the size and scale of the module and the speed of the motion – a very slow movement in this case due to the slow change of solar stimulus. The responsive sun-tracking model must be able to move in at least two directions through the hours of the day to capture all natural light. Chapter 5 concludes with the potentials and limitations of integrating an adaptive solar system into the building envelope.
- *How is the environmental performance of the envelope affected?* In the final chapter the test measurements of the energy produced from the sun-tracking device explains the performance of the physical mock up and predicts the overall performance of a proposed sun-tracking envelope system.

2. High performance building envelopes: types and precedents

Before getting started on the design of a sun-tracking building envelope it is necessary to briefly discuss the emergence of sophisticated and environmentally responsive building envelope systems called high performance building envelopes, their distinct types, how they vary and the common terminologies used to explain them. Where needed to clarify the functionalities of each type of high performing façade system, relevant examples are used.

Katy Velikov and Geoffrey Thun from RVTR design/research group argue that the building envelope "as the building component most directly exposed to sun and wind, is the most effective site for innovations in energy savings and alternative energy generation." (Velikov & Thun, 2012, p. 75) Innovative performance-driven envelope designs that are trending in architecture today often include complex assemblies of innovative material, environmental feedback from sensors and kinetic automation through microprocessors and actuators. This trend in façade design as described by Velikov and Thun has shifted the designers' approach "from form to performance" and "from structure to envelope". (Velikov & Thun, 2012, p. 75)

As previously mentioned, the performance of building envelopes hugely relies on their response to their changing environment. More comprehensive understanding of the combination of forces affecting a building envelope requires designers to create more flexible and responsive solutions. These responsive solutions involving technologies such as microprocessors and actuators entail collaboration with other disciplines of mechanical and electrical engineering, computing, physical and social sciences. Therefore, design of high-performance building envelopes is a good example of interdisciplinary practice in architecture resulting in improved efficiency and performance in buildings.

Complex assemblies of building façade systems are sometimes referred to as building skins which can be a controversial term since it is borrowed from biology and is therefore more appropriate to describe organic systems. However, Michael Wigginton and Jude Harris authors of the book *Intelligent Skins,* go one step further, arguing that the term "skin" is not merely a metaphor in the building design. They believe "the building's envelope can be considered quite literally as a complex membrane capable of energy, material and information exchanges." (Velikov & Thun, 2012, p. 76) Ulrich Knaack in his *Facades* book calls buildings and their elements, which can adapt to changing climate conditions, intelligent. (Knaack, 2007, p. 85) This adaptation, he claims, can also be extended to responses to non-climatic changes in the surrounding environment such as motion, sound, etc. However, "since the term intelligent can be misleading when used in the context of buildings or facades," (Knaack, 2007, p. 85) it is suggested to use the term "adaptive" instead. "Responsive" and "interactive" are also interchangeably used where adaptive buildings or envelopes are discussed.

Katy Velikov and Geoffrey Thun have also pointed out the confusion over the common vocabulary used to develop emerging high-performance building envelopes in a book chapter titled *Responsive building Envelope: Characteristics and Evolving Paradigms*. They identify four distinct, and in some cases overlapping, categories of emerging building envelopes as smart, intelligent, interactive and responsive. (Velikov & Thun, 2012, p. 77)

What all four categories of these intricate systems have often in common are:

- Real-time environmental response,
- Advanced material,
- Automation,
- Embedded microprocessors, wireless sensors and actuators.

Intelligent building envelopes are quick to respond using sensors and actuators.

2.1. Smart

As discussed by Velikov and Thun and confirmed by Addington and Schodek, "smart materials" are systems that retain "embedded technological functions" as their intrinsic physical properties. (Velikov & Thun, 2012, p. 77) These internal properties can induce environmental responses through physical changes that happen at molecular level of such material.

Smart materials offer a variety of appealing advantages in design of high-performance building envelopes. The properties of material are intrinsic, so the physical change stimulates automatically. Not requiring an external energy source for actuating the environmental response is the most efficient way of running a high performance building envelope. When the material is exposed to the condition that induces property alterations, the change happens instantly. Smart materials respond to a combination of environmental conditions. The response is direct and often as expected. The predictable behavior of the material provides more opportunities for reliable design of high-performance envelopes.

One example of smart material beneficial to high-performing building envelope, especially for solar control is the thermotropic polymer in which the molecular phase changes when temperature passes a certain level. The temperature driven change between translucent to transparent makes it possible to pass daylight intelligently and avoid glare without manual control of the glazing. The studies conducted by Nitx and Harwig (Nitz & Hartwig, 2004) on the test models show a significant reduction in interior glare and overheating. Different configurations of the glazing have been examined to find a way not to compromise outside view, because thermo tropic layers become translucent and obstruct view for long hours in daytime. These layers, according to Nitz and Hartwig (Nitz & Hartwig, 2004, p. 581), have promising properties compared to other solar regulating devices that include:

- No active regulation necessary
- No additional maintenance
- Easily integrated into any glazing systems
- Cheap in mass production

Figure 1-Media-TIC building in Barcelona by Cloud 9 Architects. Source: http://www.ruiz-geli.com/

Many cases of smart materials' application in building envelopes are still very new and in research/development stages. However, there are few successful examples among the built projects such as the Media-TIC exhibition building in Barcelona designed by Cloud 9 architects and constructed in 2011. The south façade of this exhibition hall is covered with triangular ETFE cushions that inflate and deflate. ETFE cushions' "encased lamella fins whose pneumatic mechanisms are automatically activated by light sensors" regulate the amount of light infiltration. (Velikov & Thun, 2012, p. 80) Media-TIC reportedly achieved a 20 percent energy saving by using inflatable cushions in the south-west façade and a foggy combination of nitrogen and oil in vertical pillows of the south-east façade. (Bullivant, 2010)

Another practical smart envelope developed by Sachin Anshuman in 2006 is the pixelSkin02 project that uses Shape Memory Alloy (SMA) wires as a non-motorized technique for opening. "Each pixel-tile consists of four triangular panels actuated by 200mA SMA wires." (Brownell, Transmaterial 2: A Catalog of Materials That Redefine Our Physical Environment , 2008) The operable pixels that open and close with electricity current can provide a screen to display low-resolution videos while functioning as shading devices.

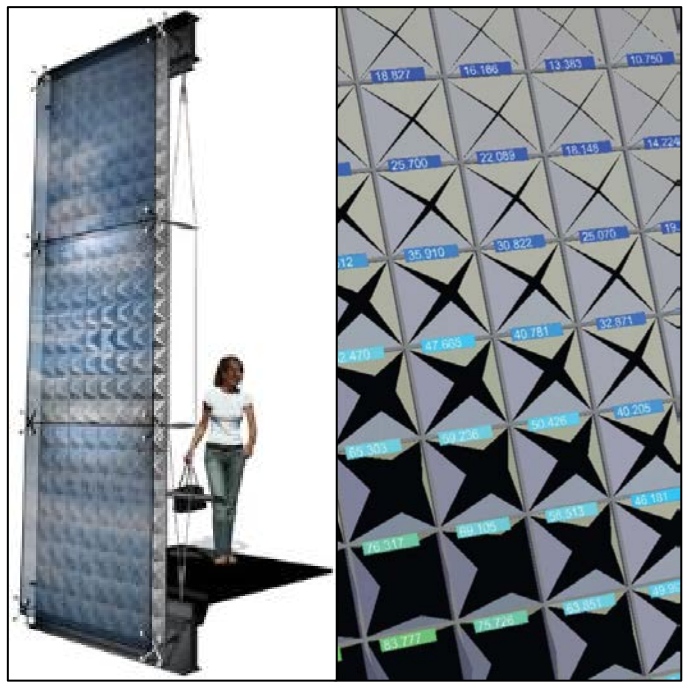


Figure 2 - PixelSkin02 computer generated models. On the left, pixels are installed as an interior shading screen. Source: (Fox & Kemp, 2009, p. 81). On the right different states of opening can be seen. Source: (Brownell, Transmaterial 2: A Catalog of Materials That Redefine Our Physical Environment , 2008)

2.2. Intelligent

Compared to smart façade systems, Velikov and Thun define intelligent envelopes as ones which incorporate computation, automated technologies, sensors, building control systems and adaptive elements rather than smart materials. Dynamic shading devices, energy conserving panels and louvers are among the adaptive elements used in intelligent building envelopes. Intelligent building systems also require a processor that receives sensors' data and a program to tell the mechanical systems or automated parts how to respond to environmental triggers. (Velikov & Thun, 2012, p. 80)

HelioTrace design is the example of an intelligent adaptive building envelope that improves the building's performance by providing an adaptive cover for the Center for Architecture in New York. To create the HelioTrace façade concept as an innovative curtain wall design, Adaptive Building Initiative (ABI) has teamed up with Skidmore, Owings, and Merrill. (HelioTrace, 2010) The aluminum perforated shading surfaces work in two separate layers in response to daily sun path. Each square shaped opening/window is fully covered with 4 vertical triangular folding shading surfaces. The shading surfaces that fold out horizontally are located at edges of each window.

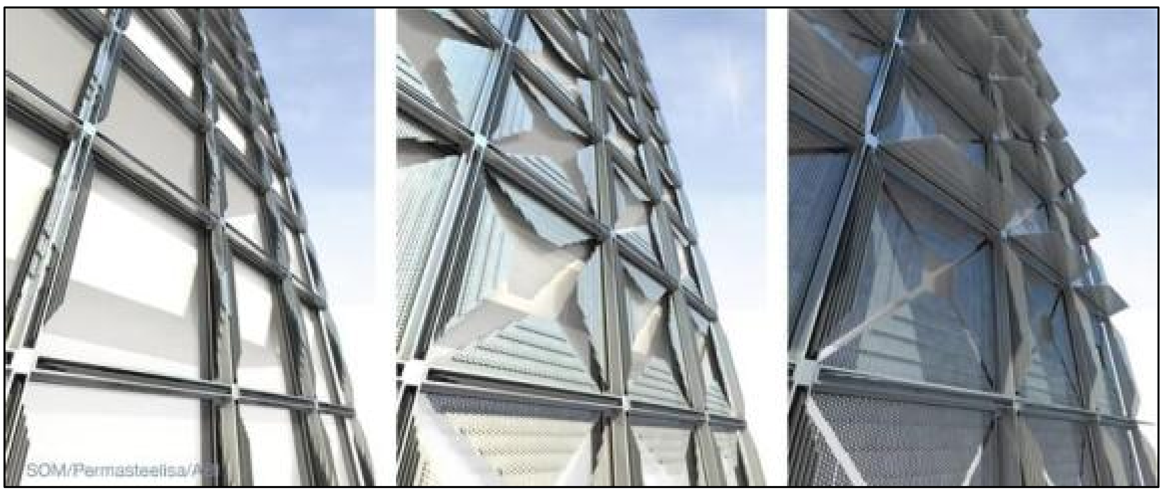


Figure 3- HelioTrace building envelope system in three stages of coverage, Source: (HelioTrace Façade System Featured in Popular Science's "Best of What's New", 2010)

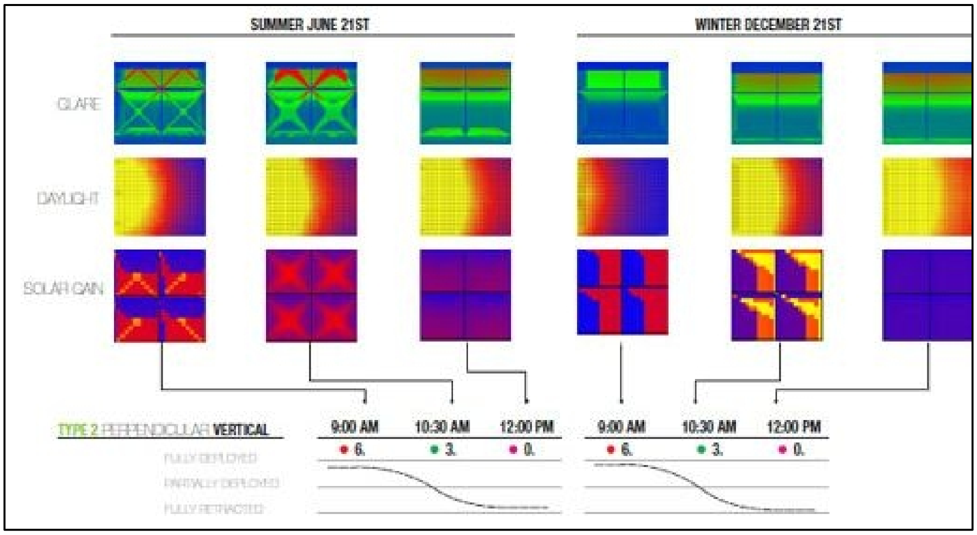


Figure 4 - Analysis of glare, daylight level and heat gain for HelioTrace design in warm (left) and cold season (right), source: (HelioTrace, 2010)

HelioTrace solar-responsive building enclosure prototype uses environmental inputs to inform a responsive kinetic curtain wall system when to fold/unfold. The analysis of the outcome indicates an increase in wall's performance in day lighting and glare, and shows an 81% reduction in solar heat gain. (HelioTrace, 2010)

The automated wood louvers of TU Darmstadt's 2007 Solar Decathlon House is a practical example of intelligent high-performance building envelopes that integrates smart materials in its automated sun shading elements. All folding solar shutters are covered with photovoltaic cells. Solar shutters block the sun radiation by rotating perpendicular to the radiation angle which is the most efficient orientation for the PV cells to generate maximum solar energy.

Figure 5- Intelligent façade of automated wood louvers with building integrated photovoltaics create a continuous façade for TU Darmstadt's 2007 Solar Decathlon House

2.3. Interactive

According to Velikov and Thun, interactive is the term mostly attributed to computerized artworks and installations rather than building elements and envelope systems. Nonetheless, an interactive building envelope would define façade systems that use the computer technology to engage public users, observers or certain occupants usually via sensors, digital display and automated parts. (Velikov & Thun, 2012, p. 86) Environmental performance of the envelope can be a secondary objective of the design or integrated in the response to the users' needs.

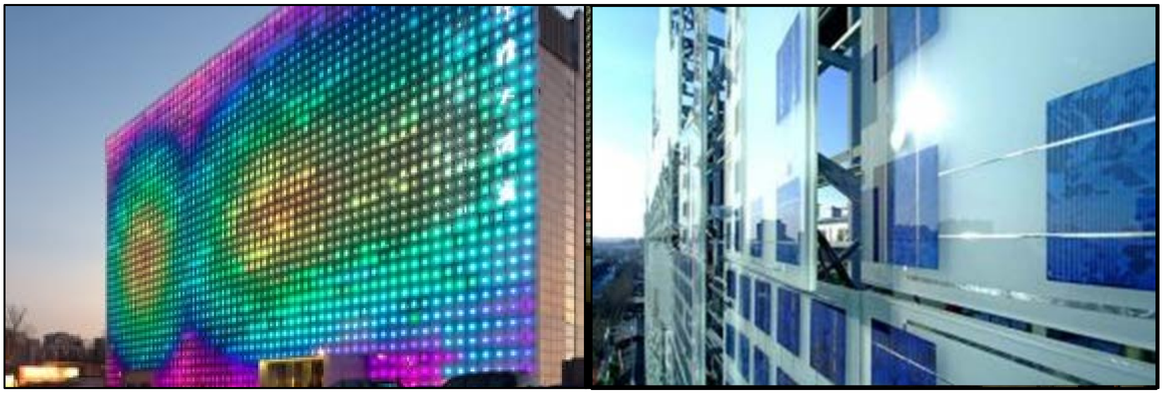


Figure 6 - GreenPIX, The Zero Energy Media Wall images showing the large LED display and detail of the integrated PV cells: (GreenPIX, 2009)

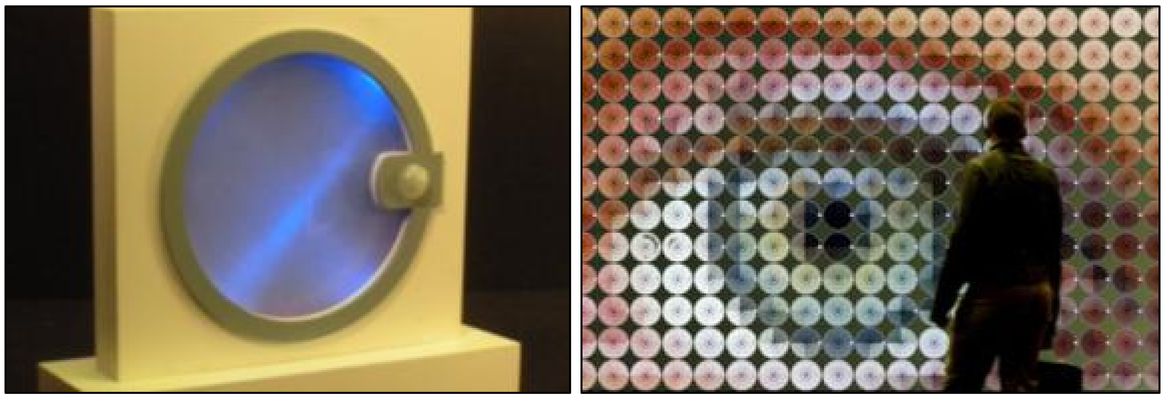
For example the GreenPix Zero Energy Media Wall installed on the Xicui entertainment complex in Beijing interacts with its context and users via a large-scale sustainable LED media display applied to the glass curtain wall. At a different scale the photovoltaic cells integrated in the curtain wall secure a high-performance envelope that "performs as a self-sufficient organic system, harvesting solar energy by day and using it to illuminate the screen after dark, mirroring a day's climatic cycle." (GreenPIX press release, 2009)

Prototype for an Adaptive Bloom project, on the other hand, is an example of an interactive surface that is not necessarily a performance-driven building element but more of an artwork with more emphasis on public interaction rather than functionality. The blooms respond, mimic and translate the movements of a dance performance. "The pieces are laser sintered prototypes activated by servo-control motors controlled via PC from a live camera feed." (Goodyre, 2010)

Figure 7 - A prototype for an Adaptive Bloom. Source: (Goodyre, 2010)

PixelSkin01 prototype is an interactive installation with capabilities to control daylight and view using microcomputers and sensors that enable the electro chromatic films to transform from transparent to translucent state. The envelope system designed by Sachin Anshuman is an interacting window. As the user approaches the surface, integrated sensors turn the pixels into the transparent state of the closest cluster of disks. This cluster will move with the user creating an interacting effect. (Brownell, PixelSkin01, 2009)

Figure 8 - PixelSkin01 prototype on the left, source: (Everett, 2009), Computer generated image of the PixelSkin01 wall on the right, source: (Anshuman, 2009)



2.4. Responsive

Although the term responsive can be synonymous with intelligent and interactive systems, responsive building envelopes usually define envelope systems that in addition to sensing, computation and automation have a more complicated responding system that “learns” and “readjusts” over time. “A truly responsive building envelope, therefore, not only includes mechanisms for inhabitant sensing and feedback, but is also committed to educating both the building and its occupants. […] In this way, both building and occupant are engaged in a continuous and evolving conversation.” (Velikov & Thun, 2012, p. 89)

3. Responsibilities of a Sun-tracking Façade System

Now that various categories of high-performance building envelopes are identified and the precedents have provided a research basis, it is useful to briefly break down the functionalities of high-performance building envelopes. Responsibilities of the proposed sun-tracking façade system are discussed at the end of this chapter.

The building envelope as a subsystem of the whole building consists of multiple layers of substance, element and structure that can perform a wide range of functions. By enclosing the structure, the façade system, regardless of being adaptive or not, divides and defines the interior and exterior perimeters of the building. The primary function of this defining layer is to protect the inside and the vulnerable from the outside and the unwanted, such as light, heat, air, and moisture. Meanwhile, to maintain a level of connection between inside and out, an abundance of physical, visual, thermal and acoustic connections between the interior and the exterior have to be balanced and maintained at desired level. To keep the equilibrium, the layer(s) of material and structure require enough stability, integrity and flexibility to balance the amount of air, heat and moisture that passes through the building envelope. These regulatory tasks are performed intrinsically when smart materials or passive strategies are in place. Adaptive envelopes, on the other hand, respond to the external conditions by active computation and automation. The proposed sun-tracking building envelope in particular is focused on protecting the interiors from sun heat through automatic shading and also capturing solar energy to supply the energy required for the automation.

3.1. Enclosing

The opening, relative to its opened or closed position, determines how the building envelope connects to and interacts with its surrounding environment and balances the infiltration of outside elements such as light, heat, sight, etc. Traditional buildings often have small openings. Christian Schittich argues “it would seem our ancestors had a true love of the dark, the mystic [in their buildings].” (Schittich, 2006, p. 10) The real reason behind the darkness of older buildings, however, was the constraints of construction that limited cutting large openings in the load bearing walls and roofs. Besides, glass was not as abundant as it is today and thus openings in general were not covered to avoid creating a “primary source of energy loss”. (Schittich, 2006, p. 10) Vast openings and lesser energy loss, today, is possible with advancements in production of transparent material, more structurally efficient substances and better insulating characteristics.

It is important to recognize that large openings, while providing convincing aesthetics and visual contact with the outside and the daylight, could be problematic due to overheating, increased cost of insulation and load bearing structures. It should also be noted that large panes of glass, while abundant, are not cheap. Therefore, the need for shading and proper material choice should not be overlooked. Responsiveness in control of building envelope’s opening enhances the efficiency of the system by adapting the size, position, orientation and material characteristics of openings of the envelope.

The reference point of responsive envelopes is often the operable lenses in L'Institut du Monde Arabe that was designed as a cultural center in Paris in 1988 by Jean Nouvel. Inspired by Arabic patterns, his idea was to incorporate numerous mechanically driven lenses to interactively respond to light. Being a very advanced implementation at the time, the dynamic modules turned out to be expensive to maintain, susceptible to erosion and noisy.

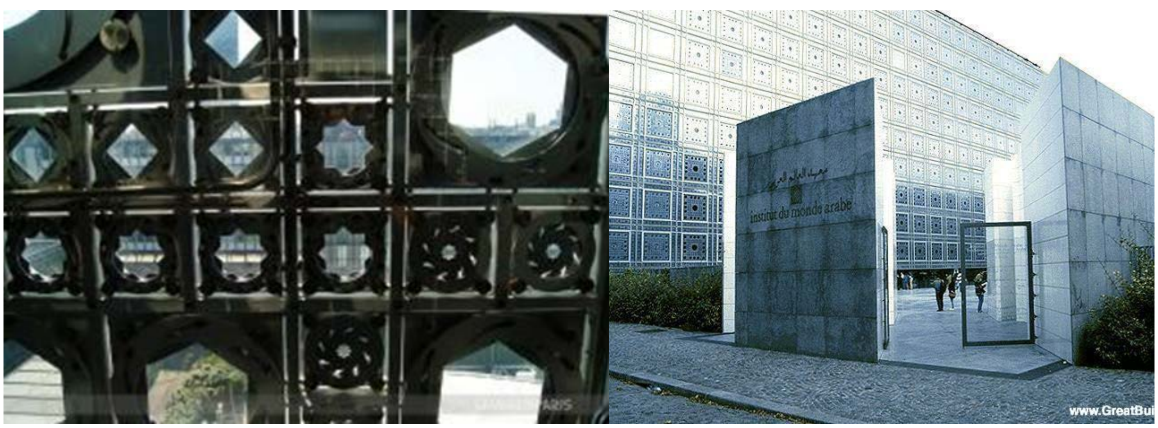


Figure 9- Left: Close view of the Institute du monde l'Arabe lenses, Source: (Prospero, 2011), right: Building entry and façade view. Source: http://www.greatbuildings.com/cgi-bin/gbi.cgi/L_Institut_du_Monde_Arabe.html/cid_3027883.jpg

More successful attempts have been made since L'Institut du Monde Arabe was constructed. They are mostly research prototypes with great potentials. ShapeShift concept for example, uses electro-active polymers (EAP) to change shape using electrical charge instead of mechanical actuators.

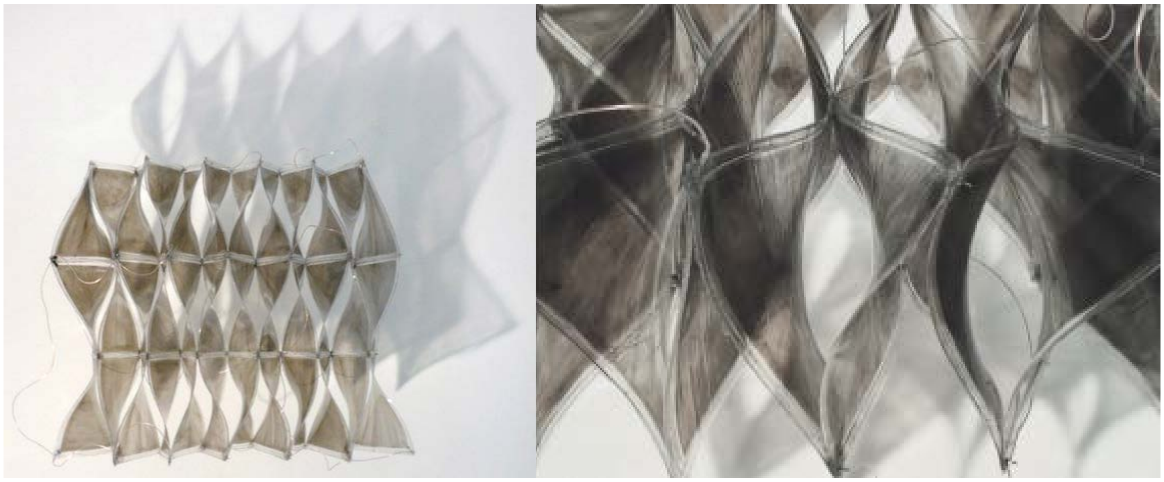


Figure 10- ShapeShift prototype installed in StarkArt exhibition in Zurich 2010, source: (ShapeShift, 2010)

These precedents and other built and imagined projects mentioned in chapter 2, indicate that it is possible to physically control the openings by various means such as rotating, folding, pushing, pulling, blowing air, expanding, and shrinking, of the operable elements. The adaptation of the size and form of the opening in high-performance building envelopes can couple with other functionalities such as daylight control and energy saving.

3.2. Regulating daylight, heat and air

The air flow, light infiltration or heat exchange is largely controlled by the building's envelope. "The building skin is the primary subsystem through which prevailing external condition can be influenced and regulated to meet the comfort requirements of the user inside the building." (Schittich, 2006, p. 29)

The building envelope can be completely shut to the external conditions. Traditional buildings used to work based on such system that provided air and moisture, cooled and heated the building entirely by mechanical HVAC systems. The importance of energy loss prevention today and the technologies available for controlling the speed, quality and moisture of the air turn the building envelopes into one of the most sensitive elements of buildings that regulate the balance of air between the inside and the outside more efficiently.

The performance-driven strategies that control the comforts level inside can be as simple as using certain material characteristics such as the insulation Argon gas used in double-glazed windows (Figure 11), or as avant-garde as the idea of inflatable façade elements mounted in airtight double-layered surfaces to improve the insulating properties of the building skin. The illustrated Balloon sun-shading mock-up (Figure 11) attempts to passively control the daylight infiltration by flexible balloons that inflate upon heating.

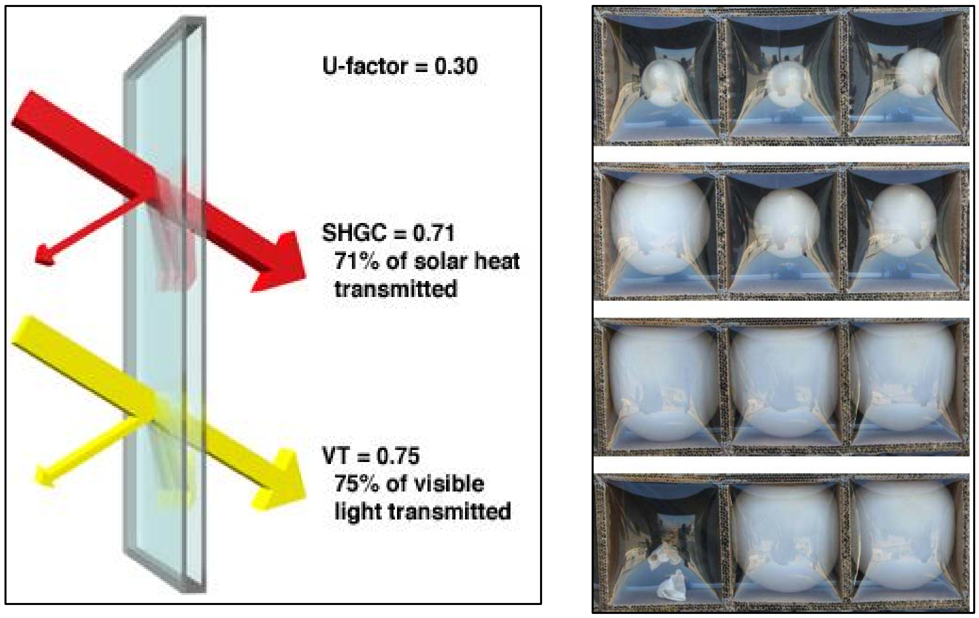


Figure 11- Left: Effect of argon gas fills on efficiency of a low E double glazed window, source: (Double Glazing, 1998-2012) Right: Balloon sun-shading model, imagined by Marcel Bilow, Tillmann Klein, source: (Knaack, Klein, & Bilow, Imagine 02 Deflateables, 2008)

The size, orientation and the structure of the opening and shading surfaces also influence the internal balance of light, glare and temperature. The structural layers of the envelope dictate how air, heat and moisture move around and penetrate the building.

The double-skin facade is the most common form of building envelope design in which the structural arrangement of the façade layers regulates the temperature of the air layer around the building. To control the quality of light, air, and moisture, actual filters can also be applied to building skin layers. The advantage of multi-layered building envelopes is that multiple layers with different functions and specifications can work together to contribute to a more optimized outcome. In addition, multi-layered structures create gaps in which numerous filtering measures are applied to guarantee better interior conditions in buildings. In combination with thermal mass layers and the greenhouse effect of the glazing, the gap between the double-skin façade layers create a proper area to store solar heat that can be reused at night. “Translucent façade components are increasingly popular for optimal daylight use; this function was provided even in the distant past by means of stretching animal skins and using thin alabaster and onyx slabs.”

(Schittich, 2006, p. 46) Diffusing light through a translucent material is possible in new architectural materials, such as PTFE membranes and switchable solar polymers as discussed in Chapter 2 under smart envelopes.

The proposed sun-tracking façade system is also designed as a second layer installed in front of the main curtain wall. The kinetic sun-tracking element of this system does not open the curtain wall to expose the interiors directly to the outside air. It rather rotates the shading panels to protect the interior spaces from the undesired sun radiation.

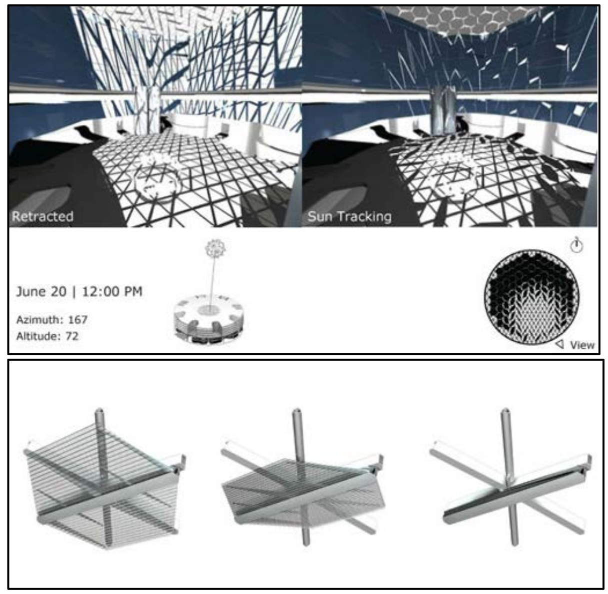


Figure 12 - Strata System for City of Justice campus, Madrid, Spain. Source: http://www.adaptivebuildings.com/city-of-justice.html

The adaptive envelopes regulate daylight, heat and air through similar strategies to conventional building envelopes. The difference is, in order to respond properly, the computer controlled façade systems require sensors and computer tools to translate the data received from the sensors of common environmental factors like air temperature or humidity.

One impressive example of an adaptive building envelope is the Strata system design for the City of Justice building in Madrid, Spain, designed by Forster and Partners. The adaptive shading units cover a central atrium to regulate the daylight infiltration and heat comfort. Each of 115 aluminum shading unit is operated individually using servo motors.


Figure 13 - Detail of automated windows in Stuckeman Family Building, source: author.

Although most high-performance building envelopes focus on daylight and heat control, inspiring examples of air and temperature controlling envelopes systems are also very effective in reducing building energy load. Penn State's LEED Gold rated School of Architecture building integrates a motorized ventilating envelope that provides fresh air into studio spaces and reduces cooling loads in warmer days. These energy-efficient windows rotate around a steel axis to open up for natural ventilation. (Sahler, 2008)

3.3. Energy conservation and energy production

Efficient passive design of the building envelope significantly decreases the energy loads of the building, and therefore, its carbon emission. For example, using thermal mass to store heat for cooler times, applying appropriate insulation in the wall layers, and shading the openings are among the methods used to reduce energy consumption in a building. In addition, active strategies for incorporating renewable energy resources, such as wind and solar in the building envelope, add to the energy efficiency of the building by storing and producing the energy.

We discussed in the chapter 2 how the building envelope is the most effective site for energy innovation in building. That is one reason why designers and engineers are especially focused on ways to implement collectors and convertors on the building surfaces for gathering the energy and converting it to electricity. In recent years, examples of wind turbines installed on building roofs or solar collector pipes mounted on building envelopes gained more popularity. However, these innovative energy conservation technologies might negatively impact the appearance of the building and the design of the envelope and its structure. To avoid this, designers integrate the technological additives into the building envelope in such a way that concurrently promote both the high performing design approaches and technical application of sustainable energy technologies.

However, the main challenge is to maintain the visual harmony, the material consistency and the energy collection function of the main façade system with an energy storing subsystem that simultaneously has to perform its traditional protective and definitive functions. For example, the computer generated illustrations of the *Solar Ivy* project on an existing building shows a beautiful arrangement of an advanced form of PV cell integration on the building envelopes developed by SMIT. (Figure 15) However, the design doesn't address the problem of PV cells shading on one another and, as a result, reducing the electricity current.

Figure 14- Solar Ivy design, a solar energy delivery device that draws inspiration from ivy growing on a building. Source: (The idea, 2011)

Solar technology, after being in use for about half a century and still a novelty in the building industry, is one of the most common energy producing technologies in conventional buildings. "Solar energy has only been directly used for heating for a few hundred years, and the technology of solar energy generation is a lot newer than that – it is only a few decades old." (Knaack, 2007, p. 85) This technology, however, requires major aesthetic improvements to be successfully integrated in delicate building elements. Photovoltaic panels, usually available in dark colors and rigid shapes are often concealed on the flat roofs of conventional buildings. The unpleasant appearance of the available photovoltaic cells impedes the idea of energy producing buildings.

The implementation of solar collectors and convertors in buildings, in recent decades, has led to a distinctive area called solar design. Solar radiation are captured and used as a promising energy source for buildings in two distinctive forms: direct (passive) and indirect (active). (Schittich, 2006, p. 47) The indirect form requires secondary technical measures such as absorbers, pumps, pipes or cells to absorb, store and distribute solar gain.

There are three main solar conservation strategies for indirect form: solar collectors, solar reflectors, and PV cells. These strategies can be integrated in the building design based on the desired use for the energy they produce. Solar thermal collector using hot water panels, for example, is very efficient for heating swimming pools while solar cells which convert solar radiation to electricity are capable of supplying electrical and thermal energy for residential and commercial uses.

"Solar radiation varies widely over a course of a day and a year, and is also strongly influenced by prevailing weather conditions." (Schittich, 2006, p. 47) The solar radiation influences the choice of energy conservation strategies. Fixed solar collectors have less efficiency compared to dynamic ones. Table 1 shows the performance data from solar collectors at different angles and orientations in winter and summer. Optimum angles are easily identified from this table. As shown, a dynamic collector capable of maintaining its optimum angle and orientation is more efficient than a fixed one. Studies also show that the angle of the collector is a more effective factor compared to the orientation of the panels. For example "in summer an angle of approx. 40 degrees results in slight radiation losses in comparison between south-east to south-west exposure." (Schittich, 2006, p. 49) In other words, a dynamic solar tracking device's performance is mostly affected by its vertical movement rather than its horizontal orientation adjustment. However, this does not mean two axis dynamism of a solar collector is less valuable.

Angle / Orientation	0°	30°	60°	90°
East	93 %	90 %	78 %	< 60 %
South-east	93 %	96 %	88 %	66 %
South	93 %	**100 %**	91 %	68 %
South-west	93 %	96 %	88 %	66 %
West	93 %	90 %	78 %	< 60 %

Table 1- Energy gain according to angle and orientation of collector in summer (April to Sept). Source: (Schittich, 2006, p. 49)

In addition to the choice of solar conservation strategy, the material characteristics of each collector or reflector influence the solar gain. Direct solar heat gain is achievable by exposing any surface equipped with solar collector to the sun. The darker the surface of the collector, the more energy is converted to electricity. Therefore, the conventional collectors in the market are usually darker in color. Further, the newer types with variable colors and transparencies are not as efficient and are not widely used.

Solar heat pipes and solar cells can directly turn solar energy into practical energy. Converting harvested energy into serviceable form of energy (electricity) in photovoltaic cells and some high-performance building envelopes resemble the photosynthesis, the biological process of converting light to energy in green plants.

Generating power from harvested energy entails certain conversion techniques and tools. Photovoltaic cells produce electricity through direct conversion of incident solar radiation in form of direct current (DC) electricity. DC output has various uses such as supplying DC loads, AC loads (after conversion), charging batteries and feeding the electrical grid with net-metering and inter-connection.

The Green Studio Handbook describes two basic types of solar cells:

- Thin film panels with lower efficiency, are generally cheaper and lose less power under high temperature conditions,
- Crystalline panels are more efficient and expensive (Kwok & Grondzik, 2007, p. 197);

Alison Kwok states that photovoltaic is the most common technology for on-site energy (electricity) production. (Kwok & Grondzik, 2007, p. 197) Similarly, in the building envelopes, photovoltaic cells, capable of directly transforming sun radiation into electricity, are becoming the common technology. However, mere installation of PV cells without considering the consequences on the structure of the façade, the visual impact and the effect on the interior spaces behind the envelope does not lead to a compelling envelope design. As an alternative, it is possible to integrate solar cells in the building envelope replacing the wall or roof material.

PV systems have a number of advantages including being silent, relatively easy to install, and architecturally concealable or prominently featured. These advantages make them favorable tools for on-site energy production. However, solar cells only generate electricity during daytime, resulting in variant energy production and unreliability. Therefore, it is necessary to consider the use of battery storage or net-metering if the installation is connected to the grid. (Kwok & Grondzik, 2007, p. 197)

The integration of solar design strategies in the building, despite its advantages, is challenging. The main challenge is the intermittent nature of the energy produced. Movements of the sun and the weather conditions change the amount of absorbable solar energy. To mitigate the swings in the amount of solar energy, each context and site should be carefully assessed to obtain a clear estimate of the solar resources and to understand the potentials and benefits that installing a solar system will bring to the building. Evaluating local climatic information, site characteristics and obstructions, building electrical loads and usage profile are initial perquisites of a PV installation in any capacity from industrial solar farm-size to a single family house.

To reduce the energy load in a building that is supplied by photovoltaic system, energy efficient design strategies such as daylight control and shading should also be in place. The combination of both strategies would result in a more cost-effective photovoltaic installation. According to Alison Kwok, “PV is rarely cost-effectively used to heat or cool a building.” (Kwok & Grondzik, 2007, p. 198)

Further, to maximize daily solar radiation reception and the energy output, PV arrays should be orientated and tilted towards the light source (the sun). Solar collectors are generally more efficient when positioned to true south in northern hemisphere and true north in southern hemisphere. Adapting the tilt and the orientation of the PV cells to the changing position of the sun in the sky, throughout different seasons and times of day, enhances the energy output. MACS lab, a full service environmental testing laboratory in California, reports that this enhancement in the total electricity output varies between 10 percent in winter to 40 percent in summer when compared to fixed installations. (Landau, 2001-2012)

Customarily, PV cells are fixed on the south-facing surface, usually on the roof at an optimum tilt depending on the altitude of the site location. More sophisticated installations with seasonal (4 times a year) or half year (twice a year) adjustments are also used. The most sophisticated approach is a system capable of tracking the sun all year round. While complicated to implement and expensive to build, operate and maintain, this system yields promising results. At 40 degree latitude, table 1 shows the effectiveness of two axes tracking method is about 25 percent more than seasonal adjustment methods and 30 percent higher than the fixed system.

Subsequently, the seasonal adjustments only improve the effectiveness of a fixed PV array about 5 percent.

Table 2 - The table shows the effect of adjusting the angle and orientation of the PV system, using a system at 40° latitude. Source: (Landau, 2001-2012)

	Fixed	Adj. 2 seasons	Adj. 4 seasons	2-axis tracker
% of optimum	71.1%	75.2%	75.7%	100%

Another design consideration in PV installations is the aesthetic integration of the technology. PV arrays can have minimal effects on the building since they are flat and often mounted on the roofs. However, there are aesthetic potentials in integrating the cells or arrays in the building envelope. In addition, the space availability in dense urban areas should be addressed before the design and output calculations. Although PV installations can be architecturally negligible "PV location will have an impact on landscaping, the appearance of the facade/roof, and perhaps security measures necessary to prevent theft of or vandalism to the array." (Kwok & Grondzik, 2007, p. 229)

Photovoltaic design as the main carrier of performance-based design depends on how the photovoltaic cells/panels affect the energy performance of the building. Only the innovative appearance or the integration methods of PVs that improve their performance have a chance to make their way into the market and appeal to the public. The newer PV cells should allow engineers and designers to stop hiding the energy producing elements of the building and instead accentuate the advantages of the integrated design and transfer the positive message of green energy production.

Designers are encouraged not to overlook the structural requirements of a building integrated PV system, but instead, calculate the additional loads of the cells and/or arrays on the vertical, inclined or horizontal surfaces. The load and the resulting momentum increase if the installation dynamically tracks the light source. The stability of the surface, on which the system is installed, should also be enough for human access for cleaning and maintenance checks of the PV cells.

On-site energy producing installations such as PV systems create possibilities for the long-term use of the energy in two main categories: stand-alone and grid-connected systems. Grid-connected systems require connection to the local utilities with net-metering equipment but do not require storage of the electricity, which saves considerable space by eliminating the batteries.

As suggested by Kwok, stand-alone systems, on the other hand, mostly involve battery-storage and may include use of dc equipment and appliances. “Some analysts suggest that without large quantities of cheap electrical energy storage, intermittent renewable energy sources like PV cannot make a major contribution. Whilst this would seem to be an exaggeration, at least for small to medium levels of ‘penetration’ of PV and other renewables into the system, it is certainly true that cheap storage in large amounts would make their integration easier.” (Boyle, 2004, p. 98)

Kwok suggests a simple formula to roughly estimate the area needed for the PV array with assumed 4% efficiency: *Area of PV array (sq. ft.) = desired power output (W)/3.3* (Kwok & Grondzik, 2007, p. 199) For example, to provide 1 kW of electricity for a single family house with 4% efficient PV arrays, (1000/3.3= 303 sq. ft. equal to 28 sq. m)) 303 sq. ft. of solar cells is needed. Clearly, using PV arrays with higher efficiency require smaller areas of solar collector. For example, for PVs with 16% efficient, only 75 sq. ft. space is needed.

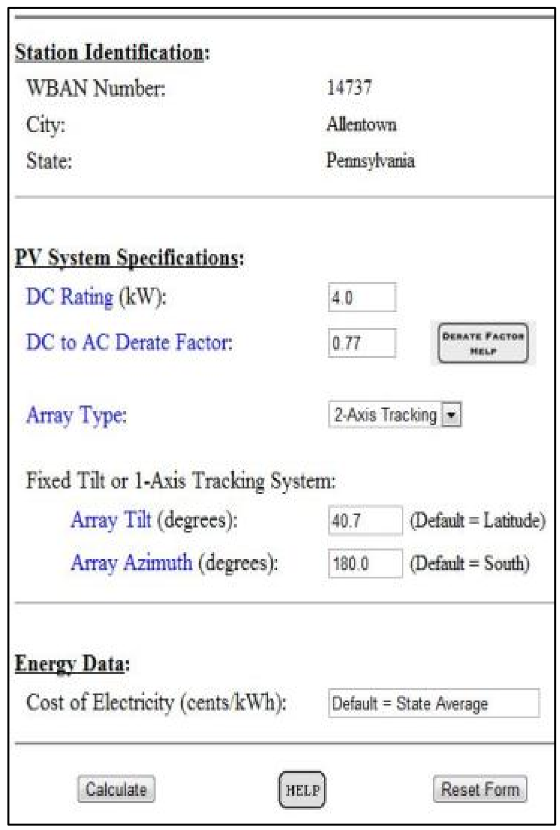


Figure 15 - Data from PVWATTS solar performance tool for Allentown, PA. Source: (PVWatts AC Energy and Cost Savings, 2009)

“Estimates on potential surfaces in Germany show that out of a total gross roof surface of 4345 million square meters, approximately 30% are suited for the integration of solar systems in or on the roof, depending on the orientation and shading.” (Schittich, 2006, p. 49) Based on this fact, Schittich concludes that roughly 400 million square meters of south-east to south-west facing facades are suitable for integrating solar systems. Since Germany’s longitude is almost the same as the north of Eastern United States, the abundance of available solar energy is also applicable to this thesis.

The energy produced by the building elements would often be used to supply the energy needs of the building itself. The energy surplus can also be fed into the grid. The buildings capable of generating their own energy are called zero-energy buildings. In this thesis, the study of a specific design of solar tracking modules for a building envelope will help the understanding of whether this implementation supplies enough energy for tracking the light source and whether there will be extra power generated for HVAC systems or household appliances consumption.

There are computer and online tools to easily estimate output of a PV array in specific locations. National Renewable Energy Laboratory provides an online performance calculator for grid-connected PV systems here: http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/.

For example, for Washington DC, Sterling VA station is selected to achieve the closest results for that location. Adjusting variables such as array type, tilt and azimuth affect the energy output. For this research, the PV output is calculated with the default tilt and azimuth for both fixed and two-axis array. The below figure –1-axis tracking on the right and the 2-axis tracking on the left – shows the annual solar radiation, energy output and the energy value. The generated AC energy shows a 27 percent improvement in the two-axis tracking array compared to the fixed array.

Table 3- Annual results from comparing fixed (right) and (left) two axis tracking arrays in PVWATTS online calculator. Source: (PVWatts AC Energy and Cost Savings, 2009)

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
Year	6.04	6435	514.80

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
Year	4.68	4928	394.24

3.4. Conclusion

All functionalities defined for high-performance building envelopes have one main goal: to regulate the energy input and output of the building and to balance the environmental impact of the building. There can be numerous other factors and roles conceivable for a building envelope, as the most important and effective subsystem of each building, which requires a separate extensive study. However, to accomplish a deeper understanding and a buildable physical model, the proposed design in this thesis focuses on a limited list of functionalities that are deemed as the most influential in designing a solar-tracking façade system:

- *Solar energy conservation and power generation*

  The spatial configuration of the integrated power generating cells should achieve maximum sun radiation exposure at the fixed position and improve at the dynamic state of the system. Choosing the most efficient solar energy collector and convertor also increase the absorption of the energy.

- *Dynamism of envelope elements*

  The solar-tracking system should continuously respond to the changing position of the sun. This is possible through computer control and mechanical automation. The arrangement of the kinetic parts and the sun-tracking system depends on the scale of the envelope system, the motion range, the motion speed, aesthetics and its secondary functionalities.

- *Providing visual contact to exterior*

  A major challenge for application of solar panels on building skins is maintaining the balance between open and closed areas. The reason is that most common types of solar panels are dark colored and will obstruct the view. Although transparent or tinted forms are also available, they have proven to be less efficient than solid forms. Additionally, in order to perform as expected, solar panels should not be shaded. The demand for providing shading to prevent overheating also adds to the complexity of visual contact design in sun-tracking façade systems.

- *Averting shading on solar panels*

  One important consideration in using PV cells in energy generating projects is to avoid the slightest shadow on the collector pane, as it will significantly decrease their performance. Therefore, in dynamic systems, designers should specifically ensure the elements do not drop shadow on light conserving panels.

4. Application of computer tools in façade system

In this chapter computation tools beneficial to design of a sun-tracking façade system are introduced and categorized under 3 categories of design and visualization, energy simulation and computer control. Under each segment the progress of computation research prior to the final design is discussed.

4.1. Introduction

Computers are an integral part of most new technologies and sophisticated systems. Building industry, in particular, is a major user of computer applications for modeling and presentation, simulating and manufacturing, and creating progressive ideas to shape the built environment. Michael Fox argues that "the future architecture will utilize unique and wholly unexplored methods and applications that address dynamic, flexible and constantly evolving activities." (Fox & Kemp, 2009, p. 12) This chapter, first, answers how and why computer tools are an initial part of the modeling, analysis and control of an adaptive building system. Second, it introduces the computer aided design tools and methods in architecture that are used in this thesis. And finally, the chapter covers the research steps carried out to study the computer-controlled sun-tracking façade system.

Computers' efficiency and accuracy in performing complex and time-consuming calculations are their unquestionable advantages. But what makes computers necessary in architectural modeling and simulation is their capability of showing us the uncertainties. Parametric design tools such as *Grasshopper* for *Rhinoceros* for example show us how the form changes instantly when a certain parameter of design alters. The resulting form of a certain parametric algorithm might even be different from what the designer imagined in the first place. The ability to simulate the unknown conditions that act on buildings over a period of time, such as climatic conditions, is also very useful for energy analysis in adaptive building elements. For example how much a shading device reduces the overheating in a building throughout a particular day is much more efficiently simulated and analyzed through computer simulation. Also many analyses require iterative studies of single or multiple conditions over time. This is possible quickly in computer aided design softwares without having to generate separate models for each repetition. Another advantage of computer modeling and simulation tools is the capability of comparing various alternatives simultaneously to choose the best option. Newer energy analysis tools such as *Sefaira* plug-in for *SketchUp* generates real-time feedback enabling the user to immediately realize the consequences of the changes made on the model. The ability to keep a history of changes in form of reports that include informative charts is also very helpful in early stages of design. The resulting analysis reports help designers communicate more effectively with their clients and present to them an evidence-based architectural concept. Designers that benefit from computational design and analysis tools are more likely to make better informed decision early in the design.

Computer control of adaptive building elements is another computational application in architecture that is necessary for a sun-tracking building envelope. Computer control here describes the automation of a kinetic element such as a servo motor. It automatically moves the element in response to a pre-determined program or processed information from a sensor. In both cases application of the computer is vital. However, one can argue that in the instance of tracking the sun, since the sun path is predictable throughout a year, programming and using sensors is not necessary. While this idea is tempting, the main reason behind the proposed design of the sun-tracking façade system is to consider all environmental factors and to be able to respond to each factor directly, including the unpredictable events. If sensors and microprocessors are not used, the system still can exactly follow the sun path, but it fails to react to other environmental changes such as presence of clouds and reflection of the sun on surrounding surfaces.

4.2. Design and visualization tools

Existing modeling and design Computer Aided Design (CAD) tools such as *AutoCAD* and *Rhinoceros* have little coding capabilities. This has proved to be a shortcoming when more freedom and randomness is desired in the creative design. Therefore, architects are more inclined to utilize applications that allow some degree of computer coding.

Constantly changing parameters that affect the building are better modeled in parametric design platforms. "Parametric design relies on control of 3D modeled components through modification of certain parameters of a building model. These modifications are driven by mathematical formulas, data values, numbers or specific computer algorithms rather than manual changes of the model properties." (Aksamija, Snapp, Hodge, & Tang, 2012)

Grasshopper is one of the parametric tools that is integrated in *Rhinoceros* as a plug-in and provides a user-friendly graphic interface and allows designers to incorporate an algorithmic logic in their designs. The program is in effect a series of formulas, imitating the programming functions in design-based platforms linked to modeling platforms such as Rhinoceros or SketchUp. The variables in the formula could be dimensions and angles shaping a surface or environmental data tilting a window shade.

Grasshopper in combination with Ecotect was first used for this proposed design in the responsive solar shading study in spring 2011.

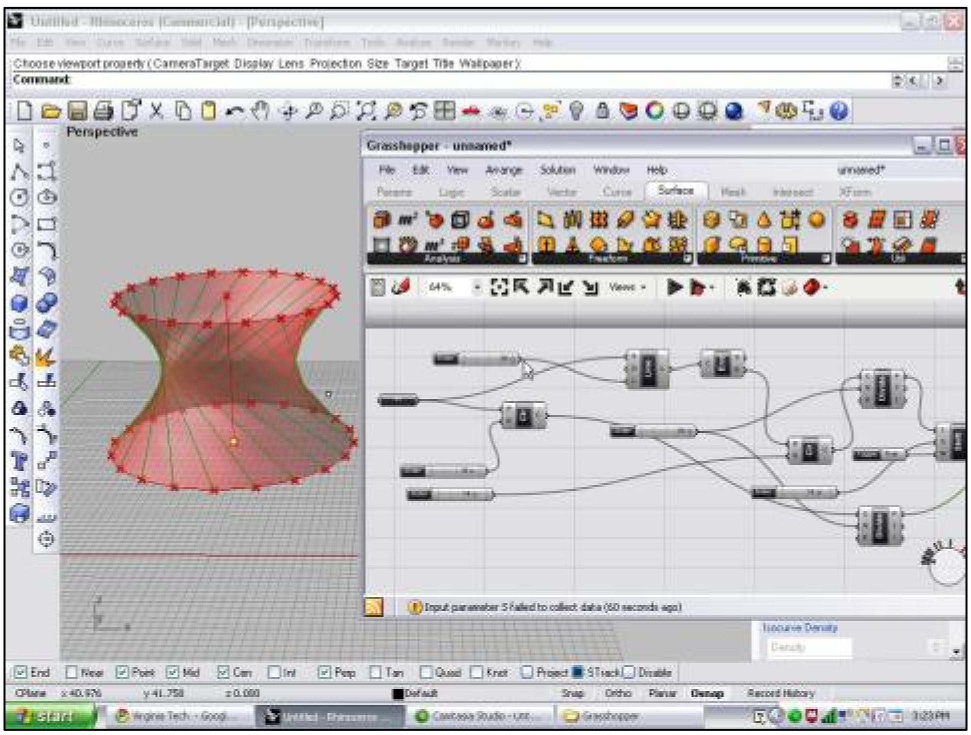


Figure 16 - Sample interface of Grasshopper program showing the algorithms and the Rhinoceros 3D platform. Source: http://www.designalyze.com/?paged=3

4.2.1. Individual Study: Parametric design of responsive solar shading

Adviser: David Celento, Spring 2011

This independent study was based on the research in kinetic architecture and the tools used for this purpose. Motion, liveliness, responsiveness, and energy efficiency are among the features the cutting edge architecture is seeking to achieve by using latest construction technology, computational processor, sensors and motors. This study was intended to foster skills needed for the forthcoming work on the graduate final design project on an environmentally responsive building envelope.

The design tried to capture the three most important aspects of responsive design including a new aesthetic criteria, energy efficiency and interaction between built and natural environment. The study also attempted to explore parametric design tools in order to determine the advantages of parametric design in studying real-time changes in building design, the significance of manufacturing tools and technologies in parametric design, the necessity of functionality and efficiency in complex form generation, and the effects of environmental data on building envelopes.

Figure 17 - New aesthetic effect of dynamic facade surfaces in texture, variety and motion effects. Source: left, Esplanade theatre: http://quintinlake.files.wordpress.com/2009/11/02-surface-and-texture_drawing-parallels_66-67.pdf, right: Flare Façade system: http://www.flare-facade.com/Flare_Webhead_L.html

The specific goals of the study were to use scripting software and electronic controllers in facade design, to integrate environmental data and parametric thinking in facade design, and to explore different geometries for efficient and aesthetically pleasant façade modules. (Figure 19)

Based on the set objectives, the project focused on developing the design proposal for blooming solar shading façade system in order to create a different aesthetic effect, while being environmentally smart and controllable.

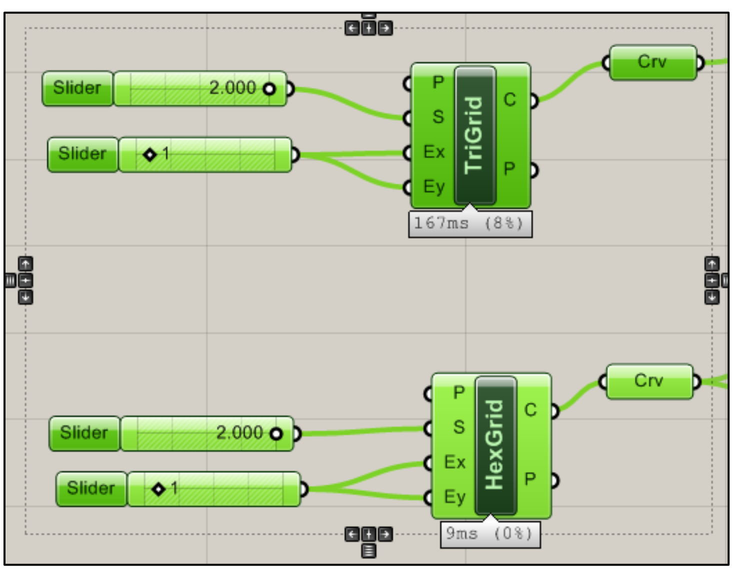
Having the idea of the blooming solar shading in mind, the sunscreen flaps resemble natural tissues that fold and unfold when exposed to light, heat or touch. (Figure 20) There is only one slight difference: the solar module blooms when electricity current is connected. In other words, plants' leaves unfold by their veins whereas this module's flaps open up with a shrinking wire.

Figure 18- Mimosa Pudica plant leaves before and after being touched in open and folded-in positions. source: http://simple.wikipedia.org/wiki/Mimosa

To generate a parametric shading design for a free formed building envelope that is environmentally adaptive and controllable, a parametric algorithm was written in *Rhinoceros' Grasshopper* plug-in to control the geometry of the surface, the module and the shading based on the angle of the sun in different times and climatic regions. This was accomplished by linking the *Grasshopper* algorithm to *Ecotect*, an energy tool, via *Geco* plug-in. The shaded area and optimum opening angles are also calculated.

Design process

1. The sample module follows a blooming hexagonal pattern. The design originated from a hexagonal grid with triangles dividing it. The number of edges and triangles inside in each N-gon can be changed based on the grid type.



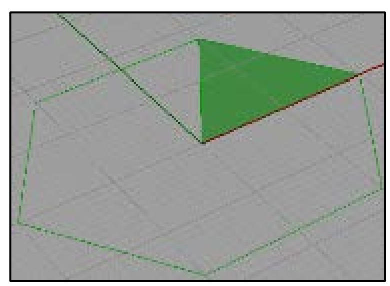


Figure 19- Design process algorithm and image of the first triangle. Source: the author.

2. The triangular flap is separated to be rotated around its appropriate axis and create the flap. The flap should be repeated N times to complete the N-gon. A slider defines the angle of opening manually.

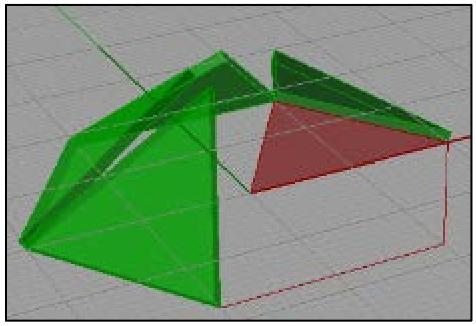


Figure 20 – Rotation of triangular flaps. Source: the author.

3. The surface can be modeled in the Rhino or be created from parametric edge lines in grasshopper. Once the surface is set, the module is mounted on top of it. The number of modules on the surface depends on the division parameters. They should be set based on the scale and dimension of the surface as well as the proportions of it.

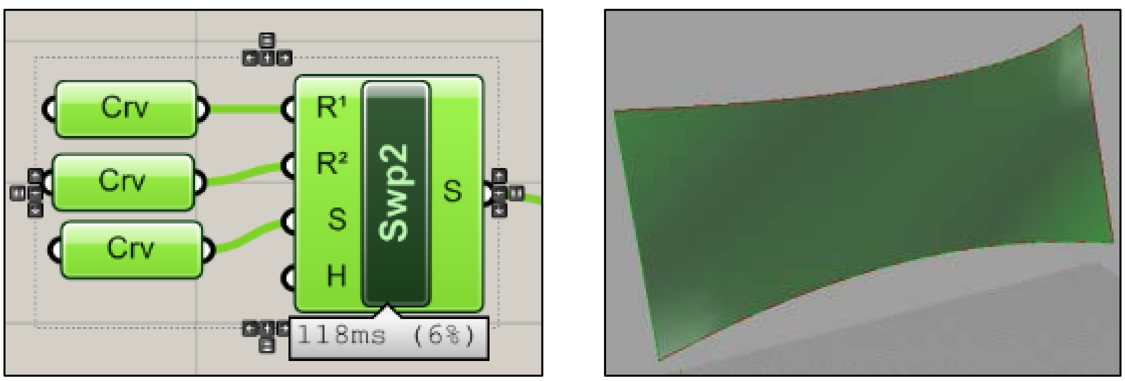


Figure 21 - Design process 04 algorithm of divided surface and the bounding box image. Source: the author.

4. The surface should be divided in desired Us and Vs and the module should be defined as a geometry object. A bounding box is needed around it to be mounted on the target boxes created on the divided surface. Bounding box can be scaled to determine the size of mounted geometry. To mount geometry on a surface that follows the parameters of the surface like curvature, dimensions and the sub surface boxes, the object should be morphed.

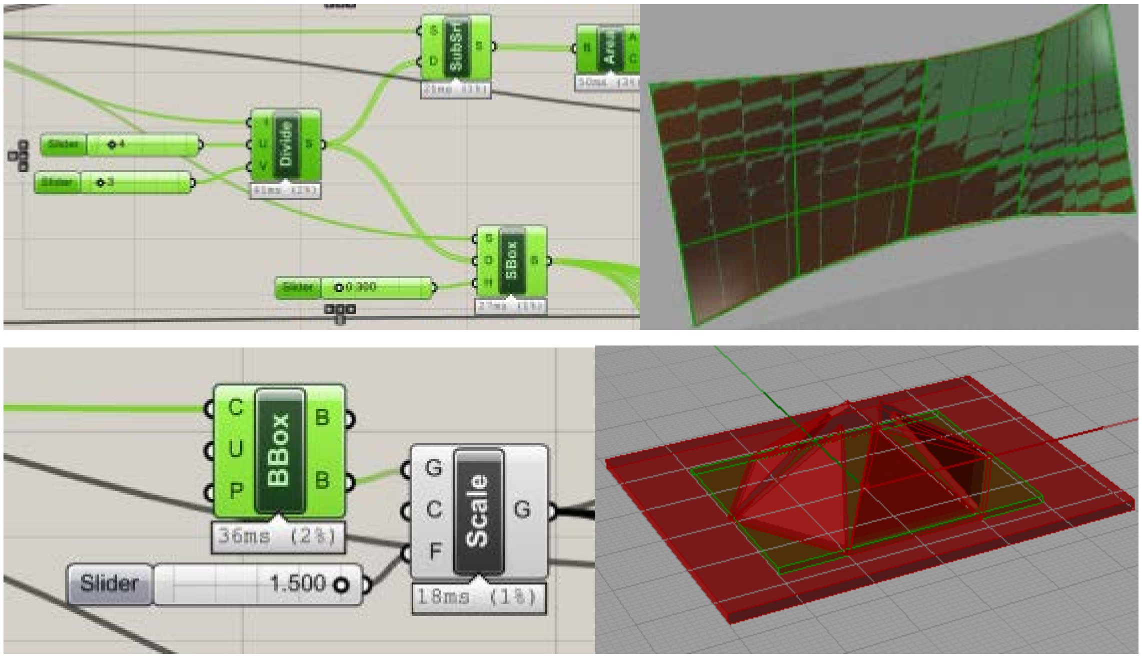
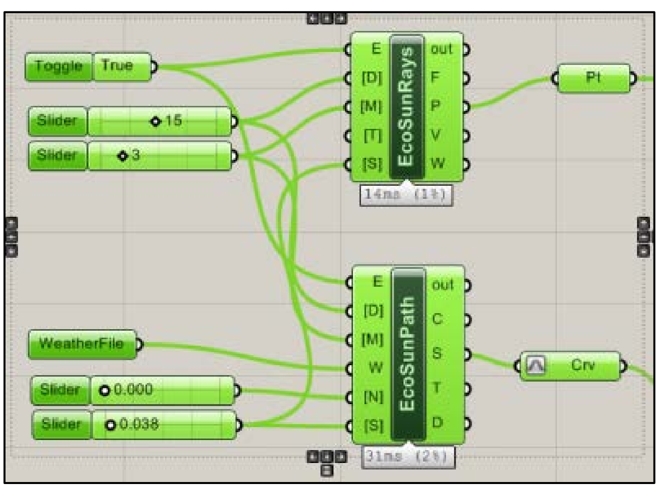


Figure 22 - Morphing algorithm and image of the operable openings

5. To add the day-light parameter, Geco should be used as the grasshopper Extra. Any time GH file containing Geco starts, Ecotect is launched to run the calculations. Weather file should be linked to Geco to provide the sun position and sunrays as geometric features. Here, the angle between the normal subsurface and the sun angle at any of the modules is evaluated and fed into the rotation angle of the module object.



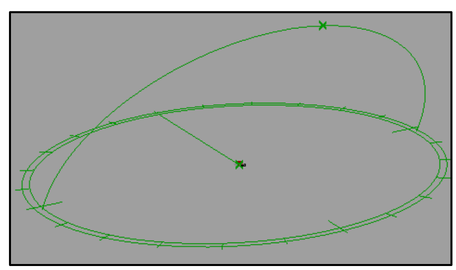


Figure 23 - Algorithm of the EcoSun path (left) and the image of the sun path (above)

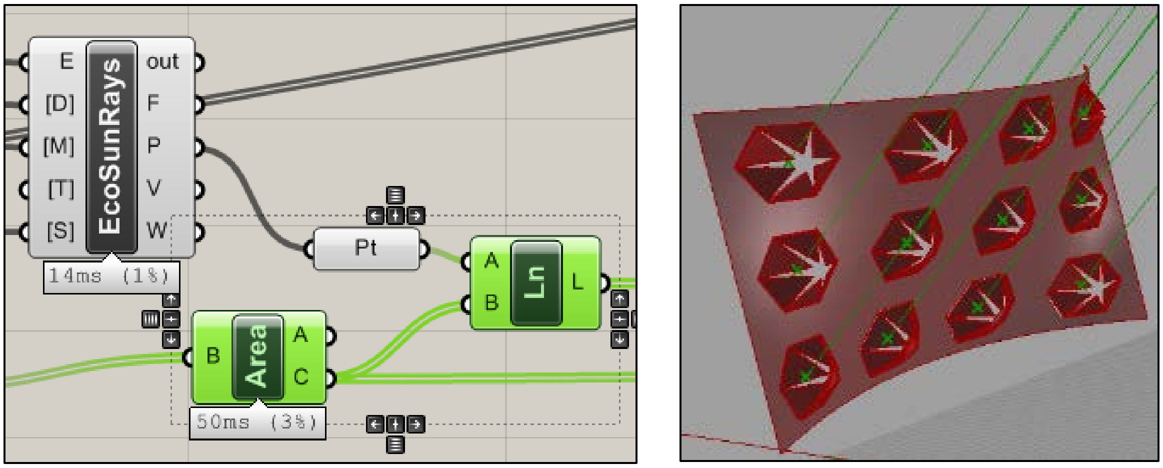


Figure 24 - Algorithm for creating the line between some position and the center point of each opening

6. The angle between sunray and the normal of surface at each center point can be evaluated and adjusted in order to produce suitable rotation angles for the flaps. Because the evaluation difference can be very small in the scale, it will not create appropriate opening.

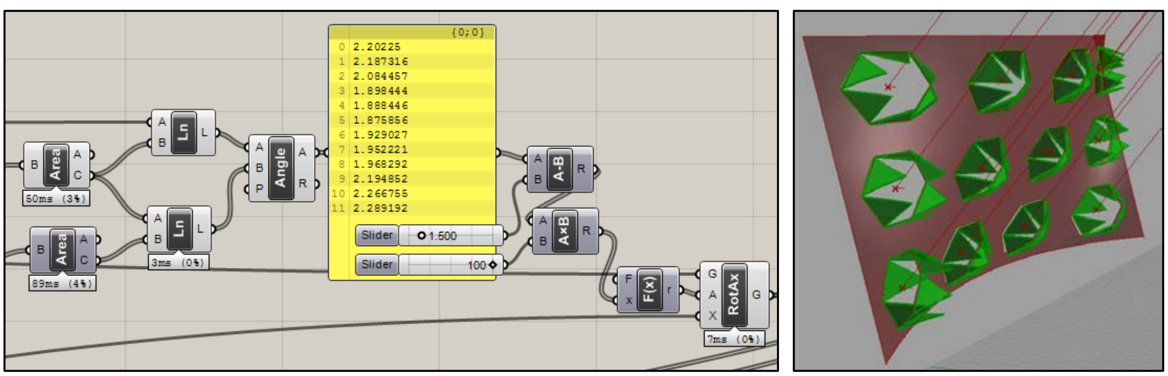


Figure 25 - Algorithm showing the functions that adjusts the rotation angle and the results in a list (left) and the final result (right). Source: the author

4.2.2. Façade Systems Course: Design of a smart façade system

Adviser: Ulrich Knaak, Spring 2011

The idea of a kinetic façade system evolved during the Façade Systems course in spring of 2011. The concept involved designing a creative façade system with chosen characteristics, which in this case were dynamism, shading and exploring new patterns.

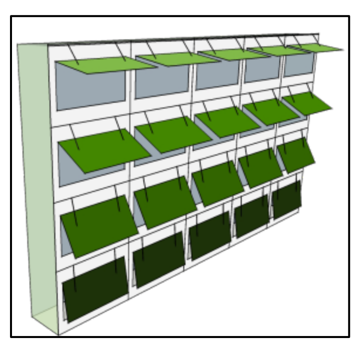


Figure 26 - Simple kinetic shading facade, source: the author

The design was significantly influenced by the adaptive behavior of the plants and the concept of a blooming flower. During the day, the blooming façade opens up to the light and the heat to capture more light and air and it closes down at night.

Figure 27 – Blooming flower the concept. Source: http://flowerpics.net/other-flowers/flowers-lily.html

The proposed modular system consisted of hexagonal blooming modules. Hexagonal pattern was chosen because it resembles the blooming flowers. This geometry of the design could be used in a variety of arrangements. Other potential patterns that were considered are also illustrated below:

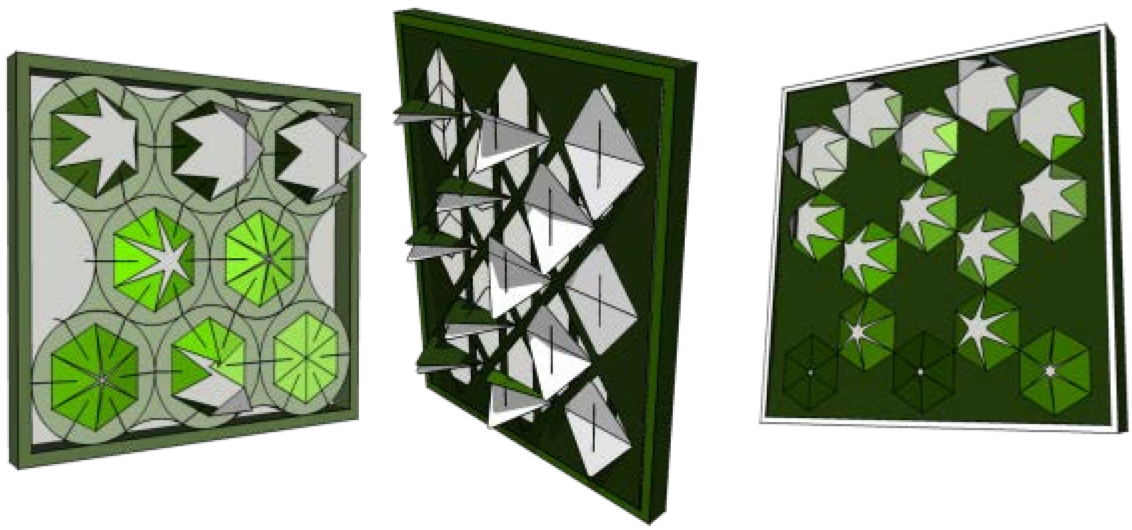


Figure 28 - Various possible patterns, by the author

More complex symbolic patterns were avoided because lack of linear segments makes it very difficult to include mechanical hinges in the design. To make it constructible, the patterns have to be modified and simplified. Irregular patterns such as Voronoi shapes are also potentially constructible in this design. In

Figure 29 - Mockup picture, taken by the author April 2011

that case however, the flaps have to be individually designed.

The idea was to create solar shading modules as a second layer of façade for buildings in the arid climate of Iran. This system is mountable on existing mullions of glazing or it can be built as a double layered façade. Arrangement of a group of similar operable shapes with different angles or amount of openings results in a wave-like effect through the façade and also creates a visual variety. Speed and smoothness of flap movements bring a variety of effects.

In the proposed design, two methods are used to operate the blooming panels. The first method is for users to manually open and close the flaps from inside in order to achieve the desired amount of shading using ropes that pull the panels outward. The second method involves Shape Memory Alloy (SMA) wires that are actuated by heat or electrical current.

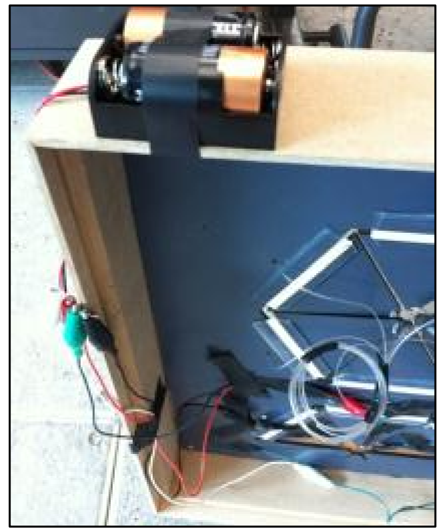


Figure 30 -Picture from Electric circuit and SMA wires taken by the author, April 2011

SMA, also known as smart metal, Nitinol, and Flexinol, is an alloy that “remembers” its original cold-forged shape and returns to the pre-formed shape by heating. This material is a light-weight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems.

In this design, PV cells can be used as panels to store energy. Light or heat sensors can also be integrated in the design to inform the building automation system when to change the orientation of the blooms based on the solar angle. The stored solar energy potentially runs the motor that opens the panels. As a more sophisticated alternative, Arduino, a micro-processor, processes environmental data from light sensors. The processed data, then, lead the simulated model of the façade system to effectively react to sun radiation and open/close appropriately.

The mock-up is made of Solid Acrylic sheets. The actual surface can be a translucent to diffuse and block sun light. The sheet is cut by laser cutter with an offset from the main shape to facilitate the movements of the panels. Continuous plastic hinges, known as piano hinge, are glued to the panels to make a spring loaded hinge while providing material consistency between actual material and a delicate joint. Fishing strings pull the panels in the manual system. In the automated version, SMA is used to actuate the solar place.

To create the necessary torque needed to open the panels and better hold the strings in place, acrylic holders were made (Figure 35 and Figure 34). The holders can be mounted on the main surface or on each flap. The whole surface can be mounted on vertical or horizontal surfaces as façade, roof or other claddings.

The final assembly performed as expected when connected to electrical current from a battery. SMA wires are nearly invisible and therefore provide a very delicate means of actuating small-sized panels. Advantages and disadvantages of this design on the path to design a sun-tracking façade system are listed below.

Pros:

- Appealing form that resembles blooming flowers and indicates growth and responsiveness to sun
- SMA wire actuates the system with no need for motor automation
- SMA wires are very sturdy while being thin and nearly invisible pulling elements

Cons:

- Wires close the flaps when more sun radiation is available which affects the interior conditions negatively and creates glare and overheating
- Not all flaps can hold a PV cell because some are not exposed to sun at certain hours during the day
- SMA wires cast a very narrow shadow on the proposed PV cells and cause disconnection

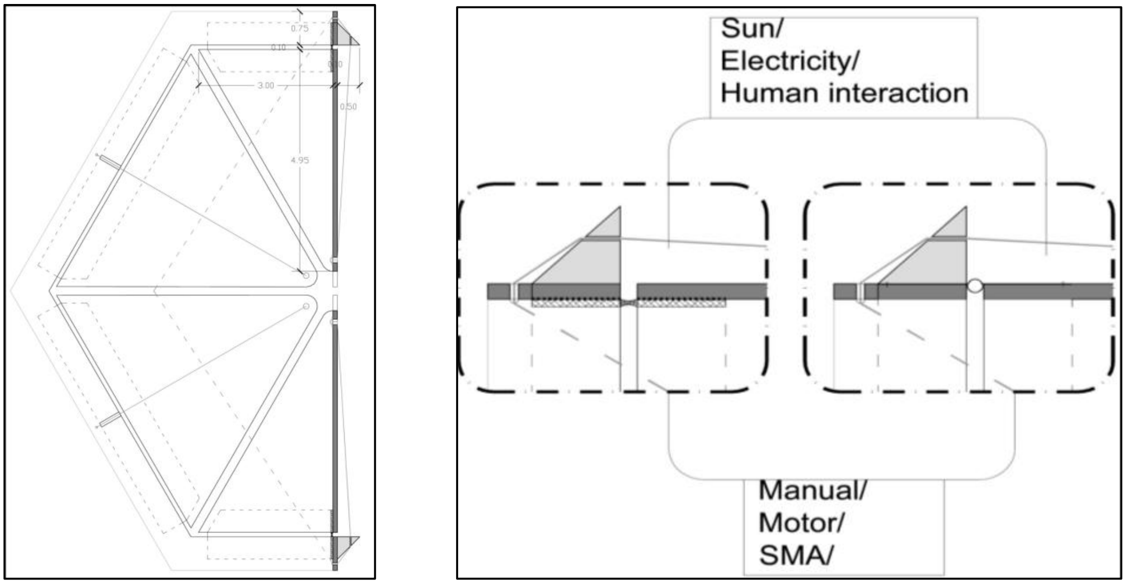


Figure 31- Plan drawing of the built mock up (left) and Section through two types of connections (right), one made with a continuous hinge and the other with a regular hinge. The wires can be pulled by various means. Source: the author

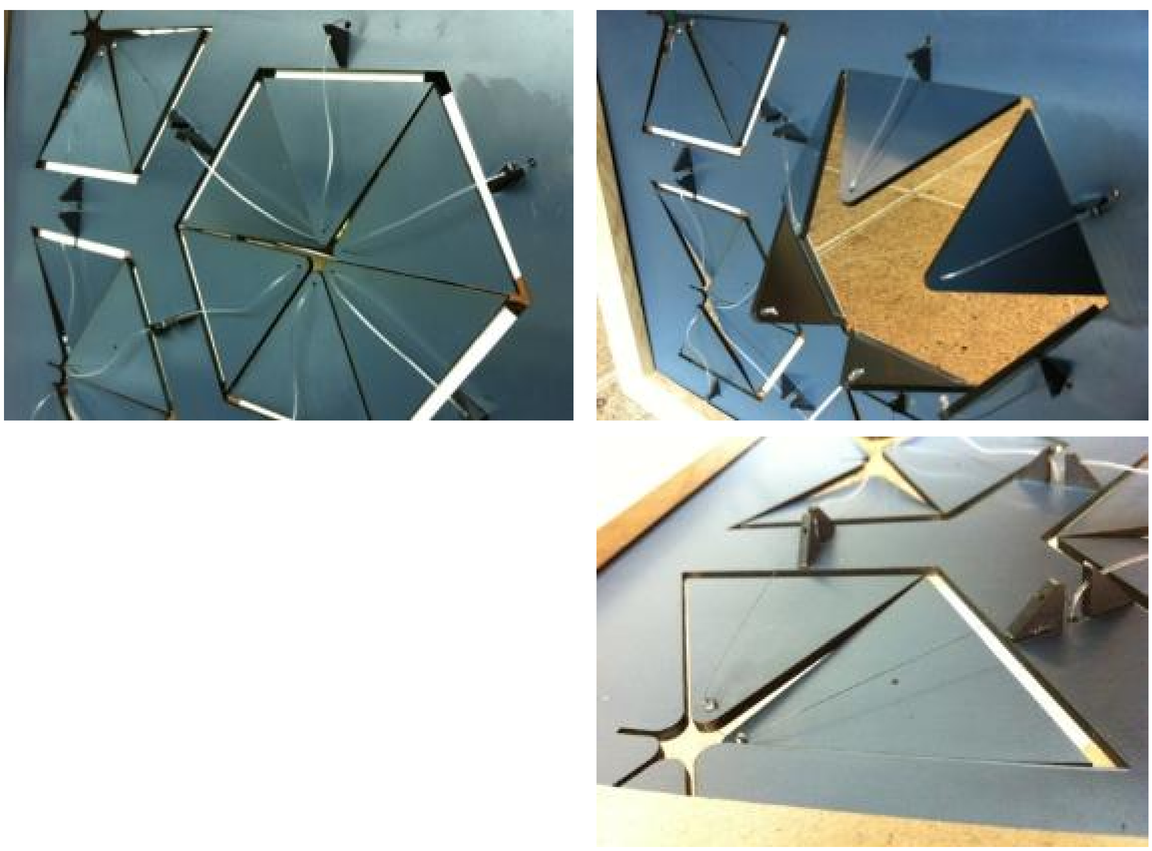


Figure 32- Mockup pictures showing the closed and open states. Source: the author, taken on April 2011

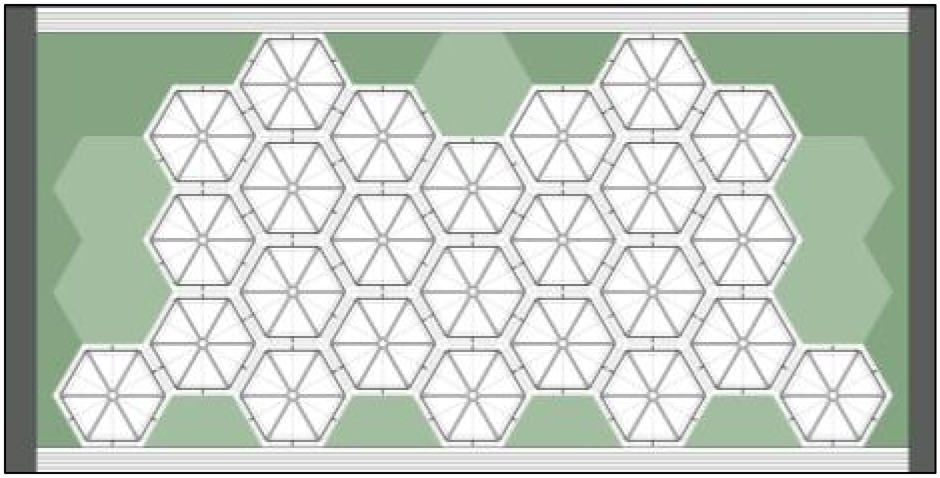


Figure 33 - Elevation view of modules on a wall. Source: the author

4.3. Energy simulation tools

In addition to modeling and visualization applications, energy tools have become a necessary device in the design process. One reason is that the environmental behavior of the building plays a significant role in its economic and ecological performance. Numerous energy tools have been developed in recent years that are connectable to the modeling applications. Sefaira joint with SketchUp and Revit, Revit Autodesk Vasari Project joint with Autodesk Revit Suite, Ecotect joint with a number of modeling applications and Solar Shoebox as an independent simulation application are among the most useful tools available to architects.

Same computer programs also facilitate the evaluation of the performance of building envelopes. Nevertheless, there are pitfalls. Computational tools are effective when used for creating more efficient products. "The goal of these design tools is to consider and integrate the prevailing climatic conditions in the façade concept, rather than to resist these conditions with technical options." (Knaack, 2007, p. 128)

Obtaining accurate estimates and a realistic image of the design as well as understanding how design decisions affect the built environment play a significant role in delivering an efficient end-product without wasting valuable time and resources. Having access to tools that enable designers to simulate their sustainable ideas in the early stages of design helps induce more informed decisions and avoid compromising the design in the development and construction stages.

The advantage of energy analysis tools for designers in simulating the unknown conditions and multiple design options was mentioned earlier in the introduction. Simulation of the environmental forces and their changes over time provide a real-time experience of what is likely to happen outside the building and in relation to it in a way that is not comparable to mere use of calculation sheets and design sketches.

Energy simulation tools used in this research include Geco, ecotect add-in for Grasshopper that was explained under chapter 4.2.1 and also Revit lighting study.

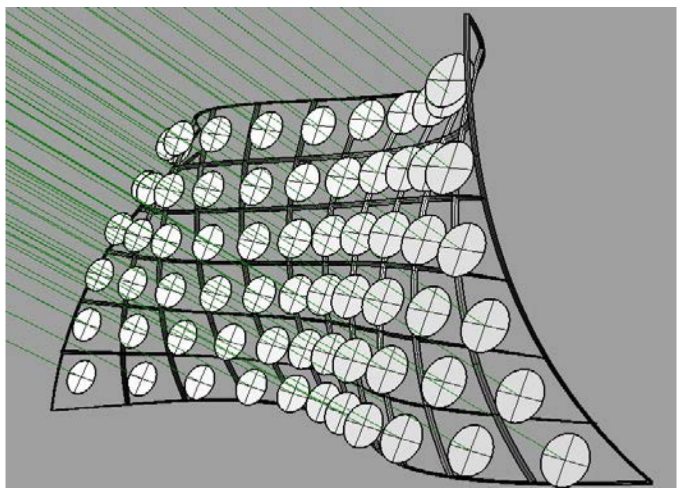


Figure 34- Geco provides climatic information such as sun ray angles for specific design location and time in Grasshopper modeling platform. Source: author

To avert shading on adjacent PV panels in a proposed sun-tracking façade comprised of a rows and columns of framed modules, a visual daylight/shading analysis is done in Revit. A sample rectangular wall assembly in rows and columns modeled in Autodesk Revit Architecture was studied in summer and winter solstice at different hours of the day. Panels are spaced by trial and error in this study until they are no longer shaded in summer solstice at 12 noon or winter solstice in the early morning and late afternoon hours.

The results show that for PV cells mounted on a circular flap in a x ft. by x ft. frame, to avoid casting shadow on adjacent PV panels, the next panel should be 3x away in vertical direction and 1.5x away in horizontal. 1.5x distance in horizontal direction is only acceptable if the sun energy intensity is assumed weak and negligible. Otherwise the horizontal panels also need to be spaced out about 3x which makes the final assembly very scarce and inefficient.

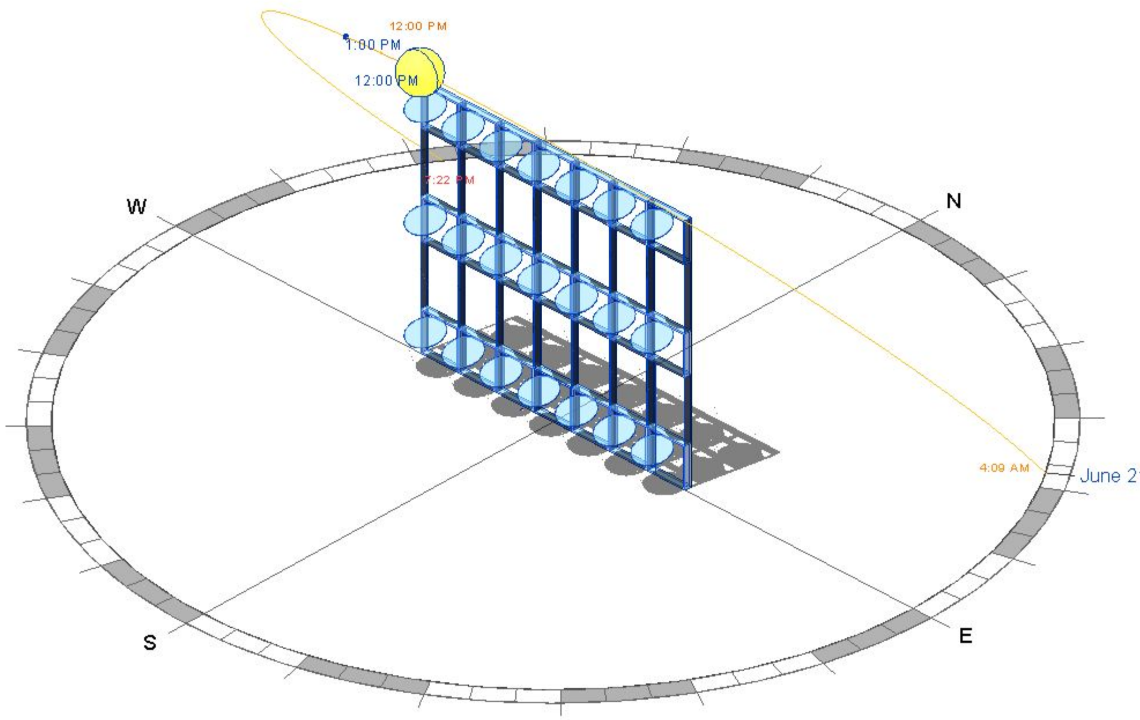


Figure 35- Revit shading study at Summer solstice at 12 noon. Source: author

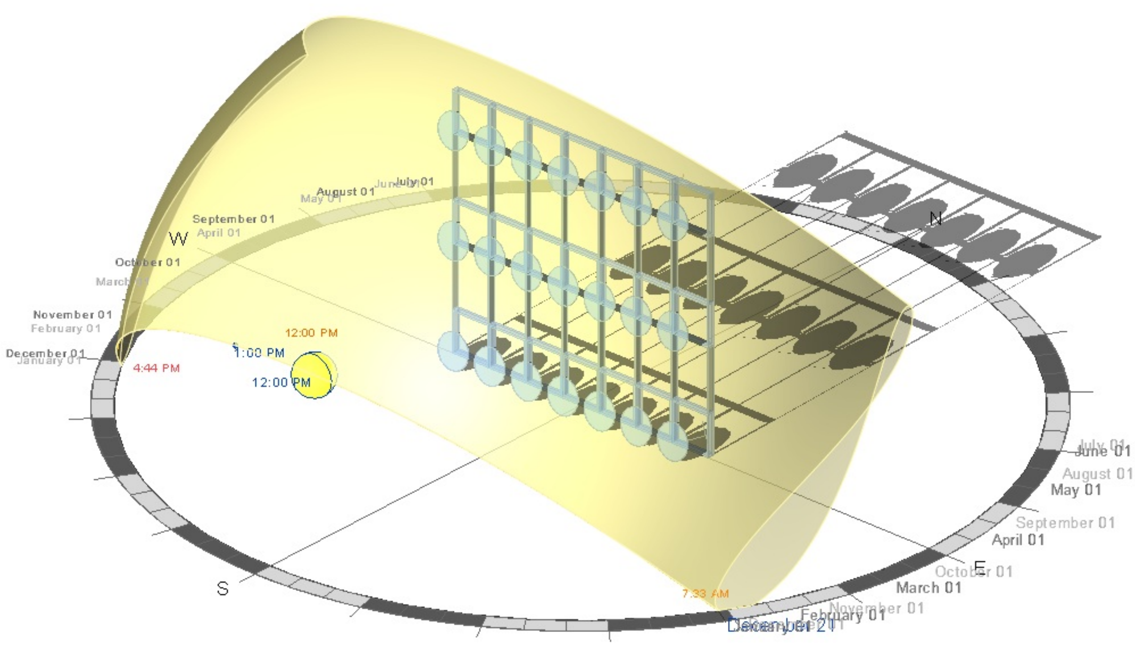


Figure 36- Revit shading study at winter solstice at 12 noon. Source: author

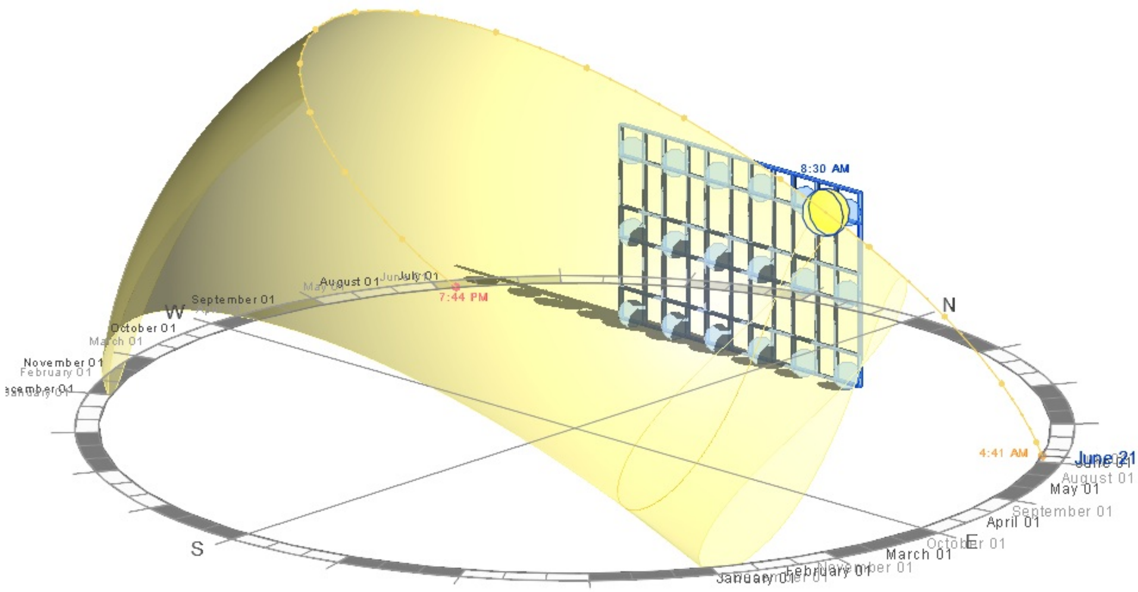


Figure 37-Revit shading study at summer solstice, 7:30 in the morning shows shadow cast. Source: the author

4.4. Computer control tools

Advantages of using computers for automation and programmed control, specifically for sun-tracking façade systems were discussed briefly in the introduction. Computer calculations are generally fast and reliable. Computers are capable of performing continuous calculations with minimized flaws. Using computers usually reduces the man-hours spent on a project and makes it more cost effective. Other means of computation in high-performance building envelopes has their own benefits. For instance, sensors are sensitive to any change in brightness in the environment instead of mere tracking of the sun so they provide a more accurate and efficient sun-tracking compared to programming the PV panel to track the annual sun path.

Architectural responsive systems are generally made of three main parts: sensors, actuators and controllers. The type of hardware chosen for a building envelope depends on the scale and demands of the systems. For example, the actuators or servos commonly used in architectural prototypes are usually similar to the conventional motors in hobby device developments.

A sensor translates analog environmental data into digital signals that are processed with controllers. An LDR photo sensor, for example, is a resistor that reacts to light radiation by changing the amount of resistance.

Micro controller acts as the brain responsible for processing the digital signals using its controller core, memory and programmable parts. The common electronic micro-controller used in architecture is Arduino Uno that will be discussed in the next section.

Actuator or motor controls the movements of dynamic elements of a machine. An actuator often uses electricity. It is similar to an arm muscle that controls the movements of hand using the energy obtained from body metabolism.

4.4.1. Physical computing project

Adviser: James Stone, Fall 2011

This independent study with James Stone in Visual Arts Department at Penn State provided solutions for computational control of the previously designed shading system. In this course, available hardware and tools that help multi-disciplinary digital designers to create interactive systems were studied. In this process an Arduino Uno board, sensors and micro servos were used to construct the mock up and program its automation.

Arduino Uno is a popular micro-controller used in multi-disciplinary robots and digital art/architecture. It has a single-board controller and its capacity could be enhanced with a secondary board. (Arduino, 2003) Multiple motors/servos could be connected together with an external battery. Ardunio connects to the computer with a USB cable.

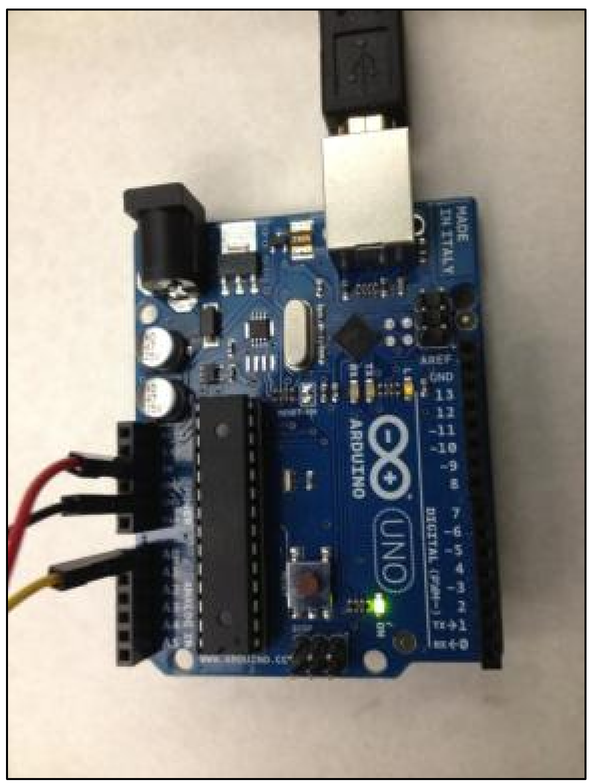


Figure 38- Arduino Uno board used in the mockup in this thesis.

Arduino has its own processing-based programming environment (Processing, 2003). Beginner designers have access to documentation and tutorials for working with this open-source tool and could learn how to program it with a basic knowledge.

The goal in this study was to give an

environmental input to the micro-controller, to manipulate the template code to create a visual version of input data and to program the servos to actuate the solar tracking device.

Very simple and inexpensive photo sensors were used to gather light input. The sensors were connected directly to the Arduino board. The Graph template code (Graph) was used to graph the resulting data. The visual results contribute to feedback and post occupancy management.

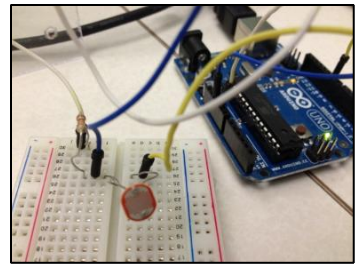


Figure 39 - A Photo resistor connected to the Arduino Uno to collect analog data (light).

Micro servo, the small version of the regular servo that works as the actuating part of a robotic system, consists of several gears and can be controlled via an electronic controller to rotate the gears. The moving parts of the robot system should be mounted on the servo. The template code was manipulated to create a visual slider and feedback graph to control the amount and speed of rotation.

To rotate the shading device, an arm was needed to pull the flap and push it back in place. The necessary rotation angle was 90 degrees. The servo had to be fixed on the main surface. An L shaped was built with one revolute joint and a revolving joint at the end. The whole arm was mounted on the servo. The revolving joints allowed easy movement of the flap.

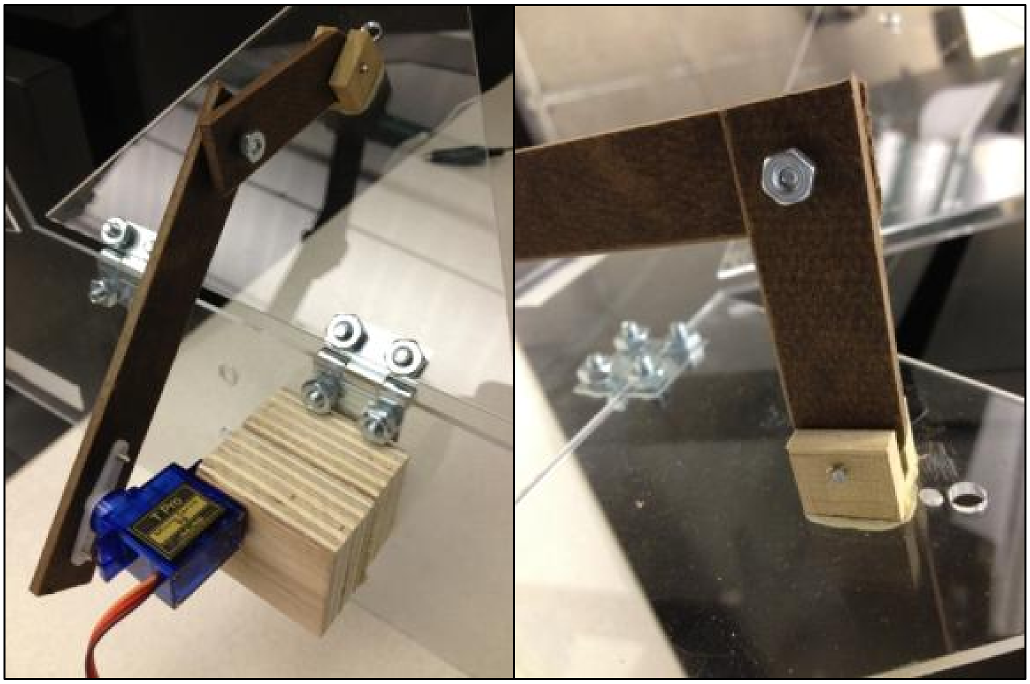


Figure 40 - Views of the automated arm in closed and open states of the module flap. The image shows the joints.

The computer code to program the sun-tracking computation using Ardunio Uno micro-processor was developed in this course via *Processing*. Although the final design was not shaped at this point the automation logics to track the bright spot was adequately developed.

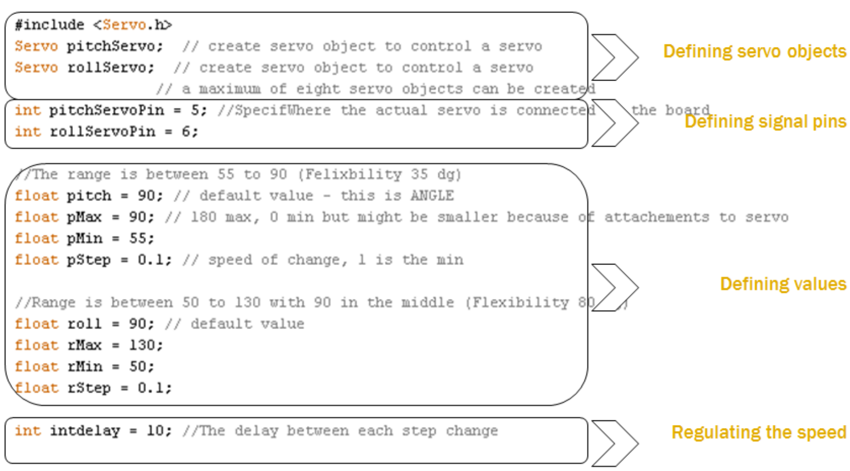


Figure 41- Arduino code that introduces servos to the microprocessor board, defines servos' rotation range and regulates their speed. Source: author

Each sun-tracking servo is introduced to the Arduino board as a pin number. The rotation range and default position is defined for each servo. A delay can be introduced to control the rotation speed of servos. Certain servos get damaged in unusually high speeds.

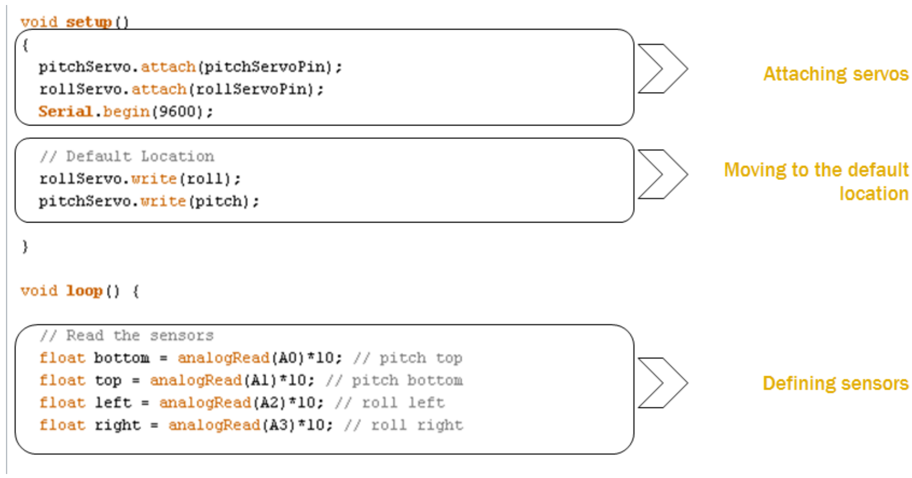


Figure 42- Arduino code moves the servo pins to their default location. Sensors are next introduced to Ardunio board. Source: board

Servos do not move until "write" function is added to the code. Next sensors are introduced to the Arduino board as individual names with separate analogue readings.

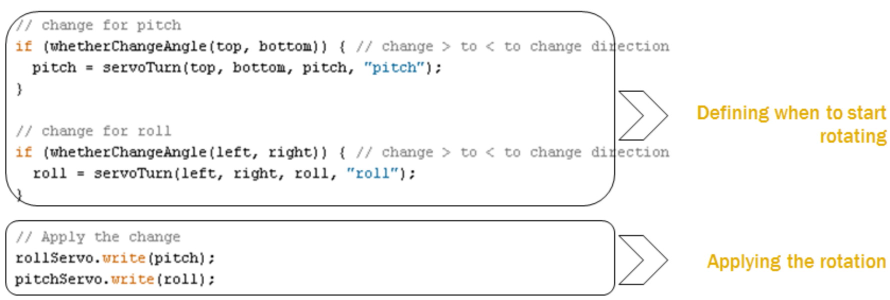


Figure 43- A loop is defines the logic of servo rotation based on sensor readings. Source: author

The loop defining the logic of servo rotation determines when the servos start rotating. For example whenever the readings from a pair of sensors is unequal to servo starts to roll.

```
float servoTurn(float read1, float read2, float angle, String type){
  if(type == "pitch"){
      if(read1 < read2){
        angle = increaseAngle(angle, pStep, pMax);
      }
      else
      {
        angle = decreaseAngle(angle, pStep, pMin);
      }
  }
  else if(type == "roll"){
      if(read1 > read2){
        angle = increaseAngle(angle, rStep, rMax);
      }
      else
      {
        angle = decreaseAngle(angle, rStep, rMin);
      }
  }

  return angle;
```

Continuous scanning of the sensors for continuous tracking

[when comparing data from each pair of sensors, at each True loop the servo tilts as much as the "step" value is]

```
boolean whetherChangeAngle(float read1, float read2) {
  float pitchAngleDiff; // the difference between readings of two resistors
  boolean result;

  pitchAngleDiff = read1 - read2;
  if(pitchAngleDiff != 0) {
    result = true;
  }
  else
  {
    result = false;
  }
  return result;
}
```

Defining when to stop

```
Serial.print(photo1);
Serial.print(", ");
Serial.print(photo2);
Serial.print(", ");
Serial.print(photo3);
Serial.print(", ");
Serial.println(photo4);
delay(10);
```

Writing the data from photo sensors in the serial monitor.

Figure 44-Next Arduino loop defines the angle of rotation and when the servo stops.

The angle of rotation for each servo is not defined as number. Rather, the servos continue to rotate until the reading from the pair of sensors is equal. This means the sun-tracking panel has reach a point where it is perpendicular to sun. Finally the sensors' readings are exported to a pop-up serial monitor.

4.4.2. Conclusion from computational tools research

The progress of research in computation of a sun-tracking façade system clarified the objectives of the final design project. The proposed design focused on a high-performance sun-tracking module that provides shading for the interior spaces behind the envelope. In the design development stage, Grasshopper was the primary modeling tool along with Geco plug-in to model the tracking. Revit shading studies was continuously used until the final design was shaped. Arduino board was integrated in the final mock-up. Integrating PV cells was the next step in the design development.

5. Design

Considering the conclusions from the design and research in previous chapters, this design thesis seeks to achieve the following goals:

- Explore the aesthetic of functional forms for the sun-tracking system to improve the visual aesthetics of an energy producing building envelope
- Integrate the energy conserving/producing technology in the adaptive envelope to increase its energy efficiency and solar gain.
- Integrate the energy conserving/producing system in a way that does not compromise the visual contact through the envelope openings.
- Resolve the issues with shading of the envelope elements on the solar energy storage elements.

5.1. Geometry exploration

5.1.1. Linear edged configurations

Following the hexagonal shading bloom described in section 4.2.2, four other configurations with similar mechanics of linear hinges at the edges are evaluated. The visual impact of the dynamic configurations is studied by making computer animations of the units. Screenshots of the animations are illustrated to better describe the potentials and shortcomings of each option.

One disadvantage of the hexagonal shape is the identical outline of all six flaps. For a solar tracking module, this outline is inefficient because it moves differently at various angles and orientations. The flaps also create obstructing shadings on one other and reduce the solar gain of the mounted PV cells.

Central axis linear configuration

In the first linear transformation alternative, each module consists of a single flat panel that operates by rotating around a central axis. The panels can have various shapes that can easily move inside the frame. Here the curved leaf form is illustrated. (Figure 48)

Pros:

- Simple and constructible form
- Simple automation with one axis rotation
- Automation can be expanded to rows or columns
- Appealing rhythmic effect while gradually opening, shading and closing the module at the same time from different viewpoints.
- Each flap faces the sun's horizontal orientation while fully shading the shape of the opening.
- Full visual contact at all hours

Cons:

- A percentage of each flap's area is shaded by the opening's frame and this reduces the energy generation potentials of the system.
- Requires double layered glazing because of full exposure
- Requires enough space for full rotation of flaps

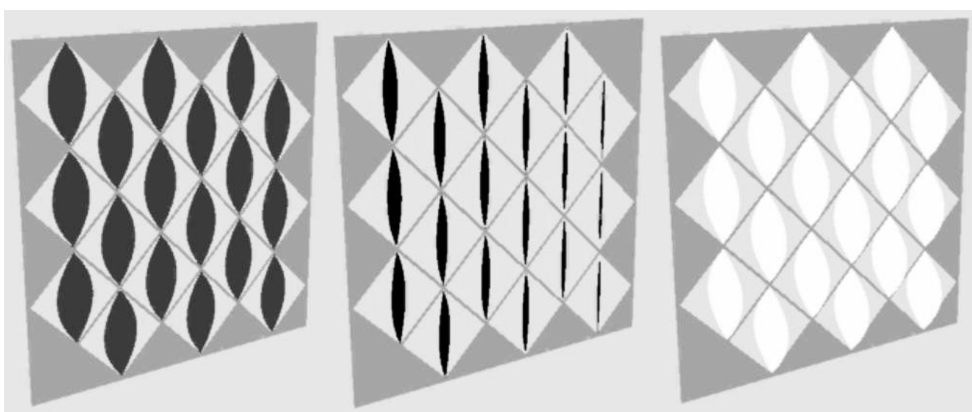


Figure 45 - Linear edge configuration no.1, computer model by the author

Central axis wing configuration

Each unit of the second linear transformation shape consists of two flaps that rotate 90 degrees outwards around one central hinge/axis. The flaps' opening resembles wings.

Pros:

- Simplicity and appeal of the form and that it resembles wing motions.
- Full visual contact at all hours. The openings face to the sides and provide a more panoramic view inside compared to the previous alternative.

- Simple construction and automation of one central axis
- Automation can be expanded to rows or columns

Cons:

- Solar collecting surfaces cannot be mounted without major radiation obstruction. At each hour only one set of the wings receive partial light because they are shaded by the other projected half. The other half are in full shade. If the energy generating PV cells are mounted on the front side of all wings, only half of them receive light. All wings can produce energy only if PV cells are mounted on both sides, which is very costly and inefficient.
- Requires double layered glazing because of full exposure
- Limited rotation and tracking capabilities. The flaps can only rotate in one direction and are less efficient compared to 2-axis rotating panels

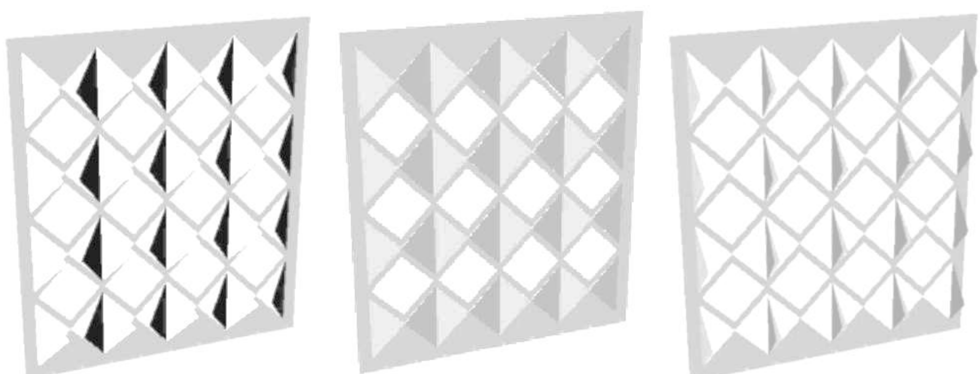


Figure 46 - Linear edge configuration no.2, computer model by the author

Edge axis linear configuration

To enhance the capabilities of the previous wing shaped outline, the coupled flaps are combined in a new cross arrangement. In this way each unit consists of four flaps.

Pros:

- Four flaps configuration improves the solar tracking capabilities of the system in vertical and horizontal directions.

Cons:

- Casting shadow over the adjacent elements is still an issue with this formation.

- Proximity of the dynamic flaps leaves little space for accommodating hinges, wirings and actuators.

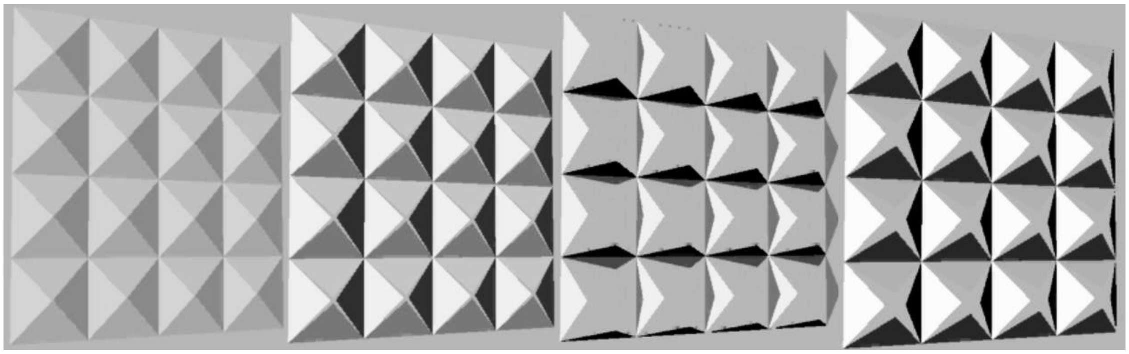


Figure 47 - Linear edge configuration no.3, computer model by the author

Triangular linear configuration

To reduce the overshadowing of the elements and also adding fixed surfaces to the curtain wall that house the actuating technology, a triangular configuration made of an equilateral triangle and an equilateral triangle cut into three isosceles triangles is designed.

Pros:

- Simple and appealing form
- More stable constructible configuration

Cons:

- Automation cannot be expanded to rows or columns
- This geometry while having less disadvantages compared with the previously mentioned options, was ruled out because diagonal flaps still shade on adjacent fixed triangles. This interrupts the PV cells from producing electricity.

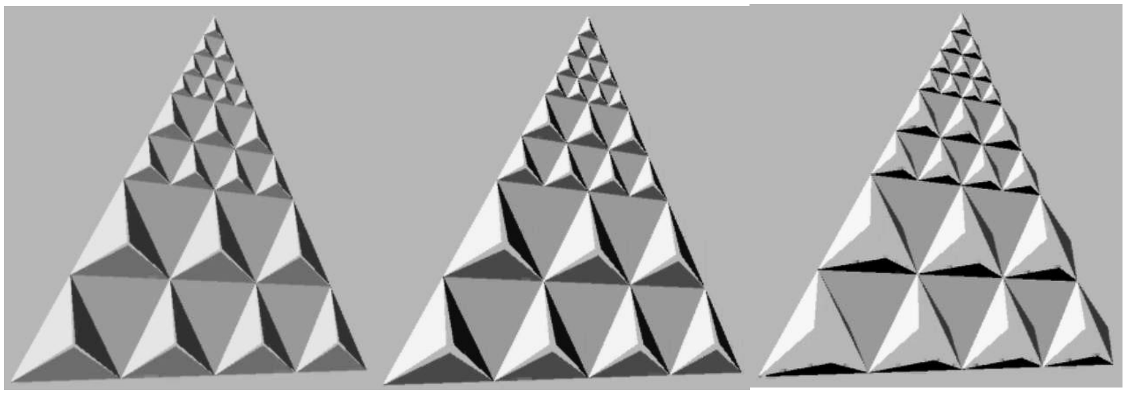


Figure 48 - Linear edge configuration no.4, computer model by the author

Besides in all of the mentioned configurations, except the first almond/leaf shaped flaps, visual contact between the inside and the exterior surroundings will be mostly blocked in the daytime when shading is necessary. Therefore, among the four configurations, the almond shaped structure is the best match to the design of a solar tracking module since the tracking surfaces pan from east to west and allow visual contact in opposite direction at all times.

5.1.2. Origami game configuration

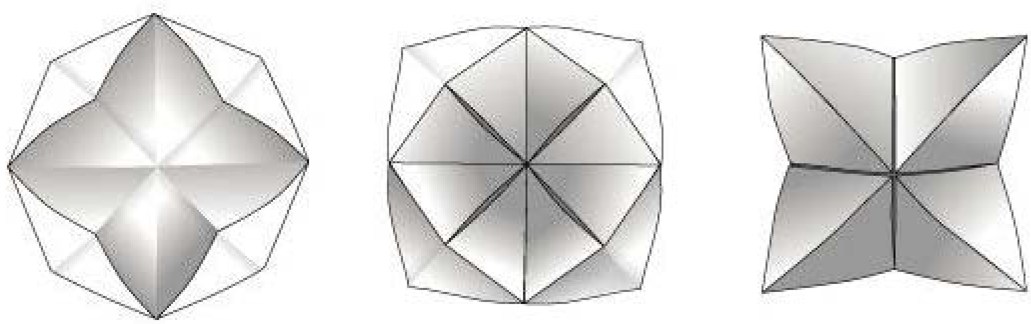


Figure 49 - Origami game or cootie catcher configuration view from below and top in open state. Source: (Make a cootie catcher, 2009)

The three dimensional geometric configuration of this particular origami was chosen to explore because of its relatively simple building process with thin, flexible material, its dominant geometric pattern, its variety of folding states and the potential that this outline offers for a system that needs to open, close and move three dimensionally.

The three dimensional square shape opens when its cone-shaped parts are pulled or pushed. The idea is to have the interior surfaces transparent or fully open and exterior ones solid, so that the whole system fully closes when light and air draft is not favorable. The cone-shaped parts are gradually pushed open in horizontal or vertical directions depending on the time of the day.

Pros:

- Appealing complex form. When automated to track the sun it resembles breathing
- Easy construction with flexible material
- Variety of folding states and wide range of 3 dimensional movement to track the sun
- Capable of providing solid and transparent opening on one module

Cons:

- Difficult construction and hinge mechanism with more durable material
- Difficult to expand the modules in rows and columns. Since the cone-shaped parts have linear motion, their non-linear edges is constantly moving and, therefore, connection to the adjacent unit's edges would not be possible with rigid materials.
- Multiple actuators (e.g. servos) are needed to control the movement of cones while each movement is dependent on the other three cones.
- Expensive actuators and hinges
- The structure holding the middle transparent panel causes visual obstruction

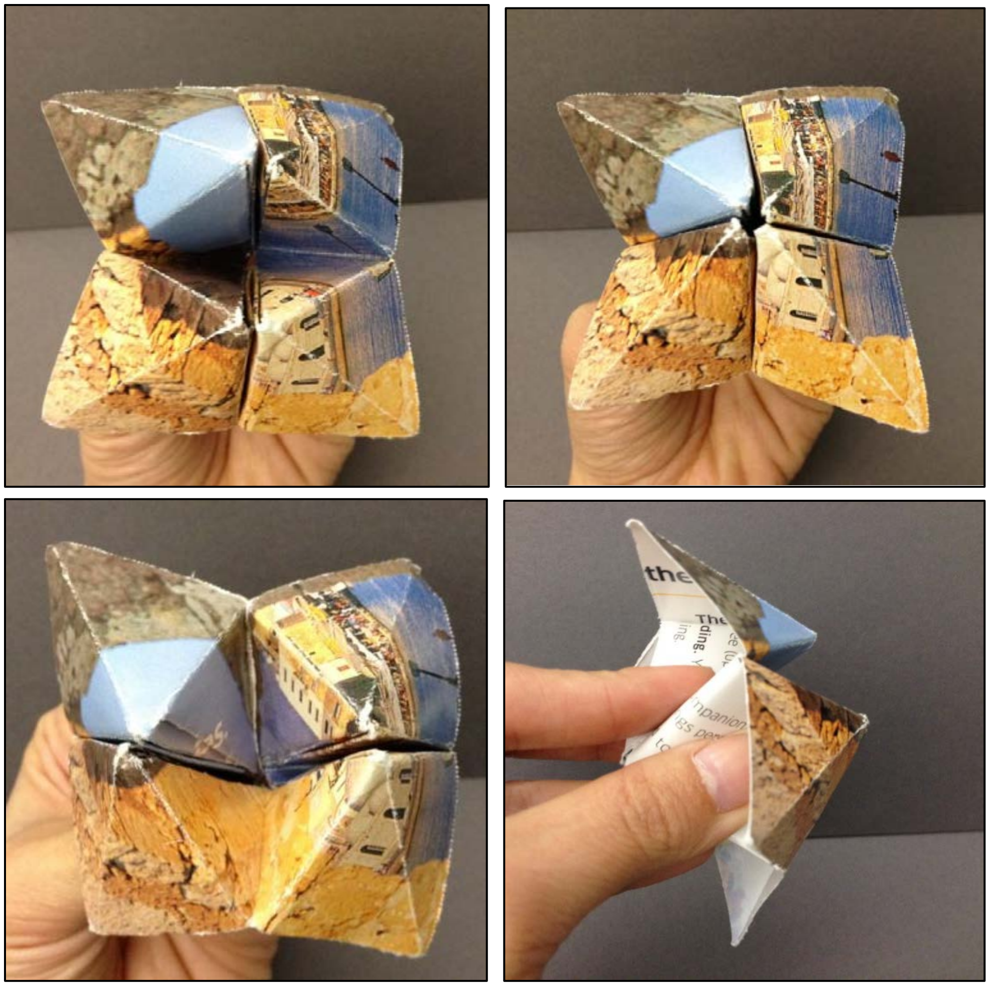


Figure 50 - Variant states of opening of the origami model, by the author

These limitations of the origami shape show inefficiency of the system in supplying electricity as a high performance environmentally responsive system. Complex kinetic designs are expensive and not easily replicable and built.

The study of three dimensional geometries with nonlinear edges and hinge mechanism was intended to seek more flexible tracking opportunities and to contribute to the shading and view functionalities of the responsive envelope. Therefore, other three dimensional configurations capable of implementing multiple functions of tracking, shading and maintaining visual contact were considered.

5.1.3. Floating cloud outline

To liberate the tracking surface from hinge mechanics and linear edges, the idea of floating sun-tracking panel on the cloud shaped membranes was explored. The floating circular surface holding the PV cell rotates in three dimensions in a window frame. To create a floating impression the remaining space between the solar surface and the window frame needs to be covered with a flexible material that holds its tight shape with the movements of the solar surface. Covering the central circle and the outer frame leaves no room for visual contact with the outside. Semi-transparent fabric or membrane is a good choice to create a diffuse light inside during day time while protecting the interior space from climatic elements. Semi-transparent material prevents overheating in hot weather. However, the visual contact to and from the interior space is completely blocked.

New material alternatives capable of switching behavior were briefly researched to find a balance between the opaque and transparent states of the envelope layer. Thermotropic layers discussed in chapter 2.1 provide excessive opportunities in combining phase changing substances with operable openings. But the potentials of such innovative material to create a balance between view and light control cannot fully benefit the floating design alternative.

One reason is that thermotropic materials are only used in flat panels and are not commercial in flexible shape yet. The electronic motors and accessories will be left visible and the complexity of fixing a membrane to the dynamic panel creates more difficulty.

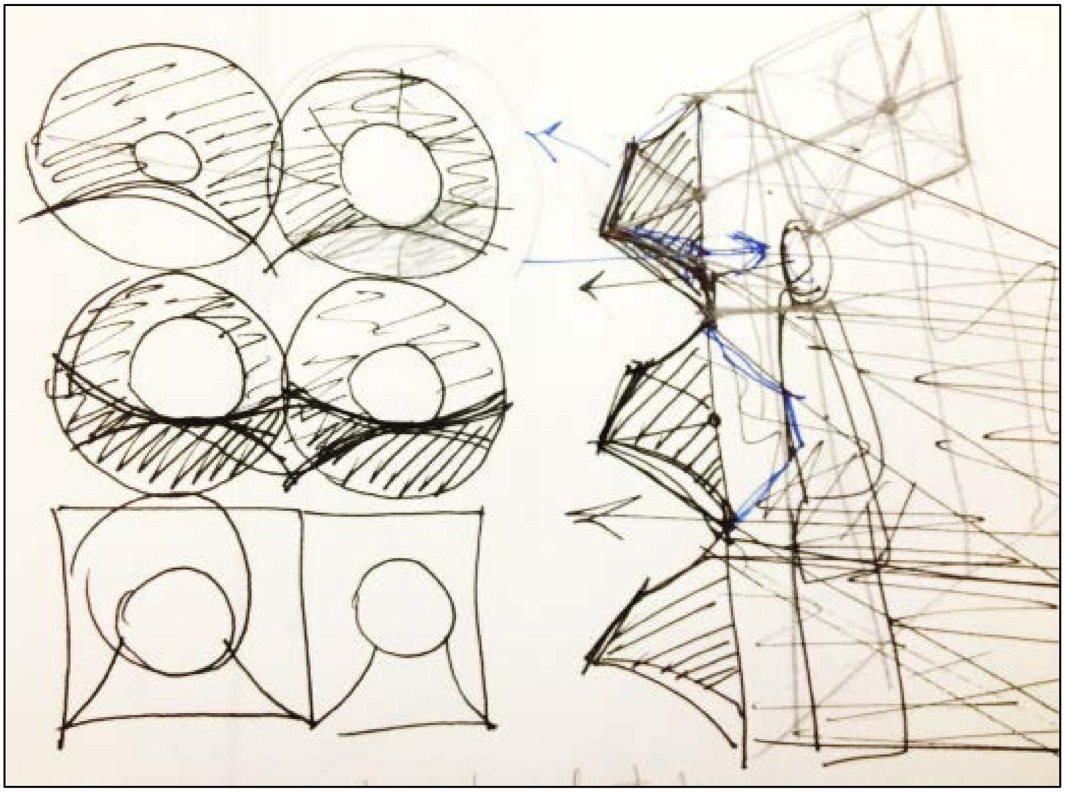


Figure 51 - Sketch of the floating panel idea with the motion tracking units facing inside.

The tracking modules, arranged in circles, form a cloudy envelope. The solar collector panel is integrated as the central tracking piece of the unit and semi-transparent membrane covers the remaining aspect of each frame. This configuration blocks the view in the whole wall assembly. One way to resolve this problem would be dividing the wall system into equal numbers of sun-tracking modules facing outwards while motion-tracking units face inward. Motion-tracking openings would, then, constantly face the inside and provide visual contact to the outside.

To study the floating panels, a parametric computer model was generated in Rhinoceros using Grasshopper plugin. The free form of the base surface is for visualization purposes only to show that the floating modules can potentially be mounted on any shape of building envelope.

In Grasshopper, one base surface is defined while a second one is set as the offset to the first. In the model, the base surface is made of rectangular frames, which are connected through a curved membrane to the circular frames of the second surface.

The rectangular frames are projected on any given surface with any network of curves. The circular openings are the elements that carry out the main function of the solar tracking. To orient the circular surfaces to the sun position, the line (vector) connecting the normal surface at each surface division to the sun should be identified so that each collector surface can be placed perpendicular to the line. Position of the sun is either formulated through VB scripting or using *Geco* plugin. Eco sun rays' input are the weather file, time of the day and time of the year and the output is the point representing the sun's position.

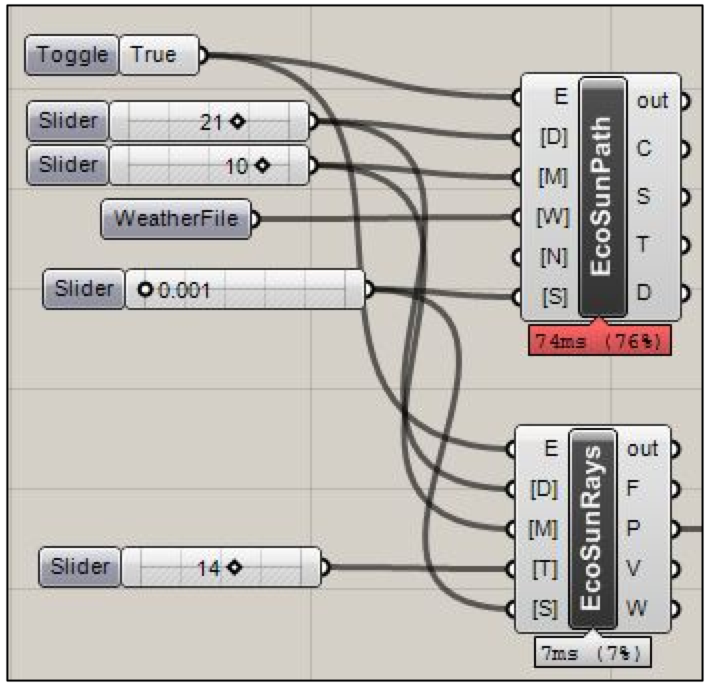


Figure 52- Geco sun position script, author

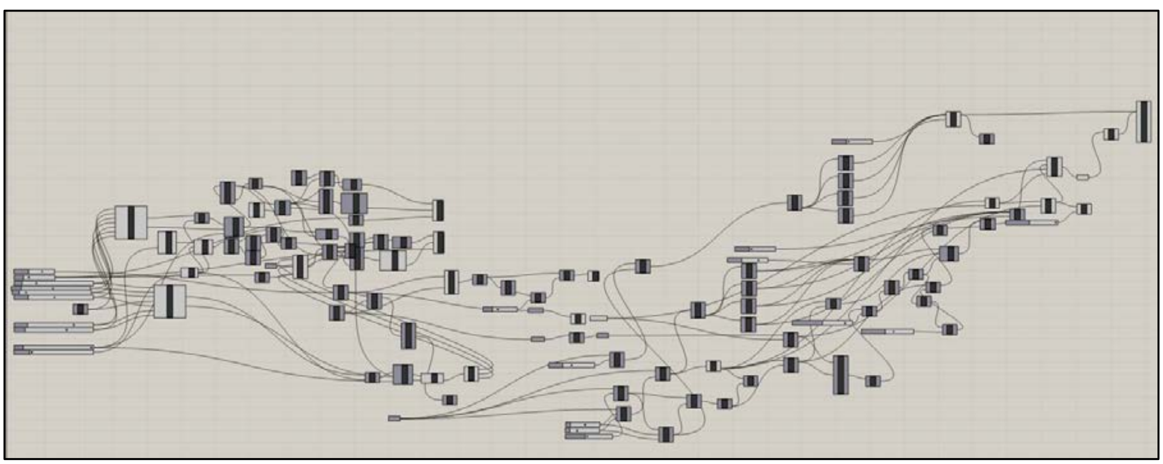


Figure 53 - Grasshopper code producing the sun tracking modules on any given surface. Source: the author

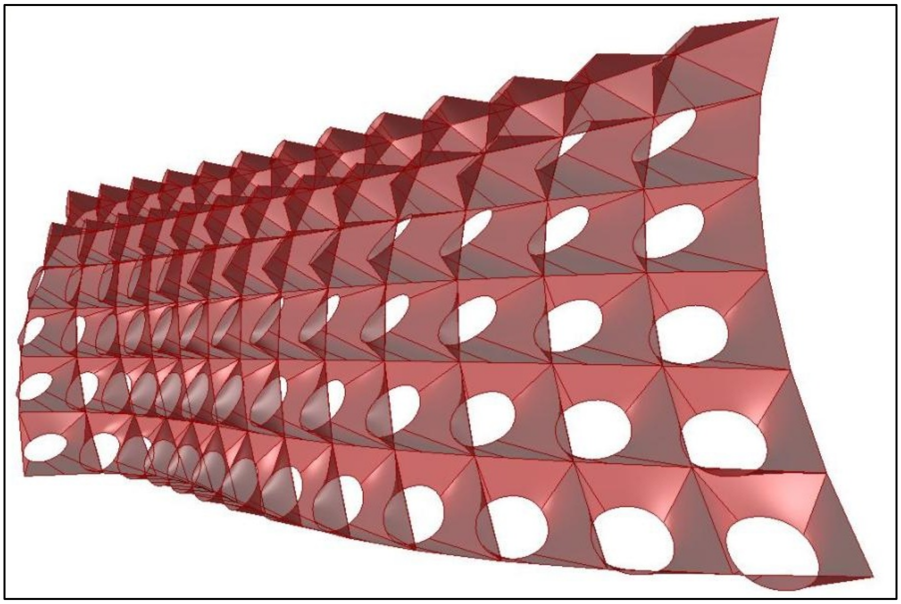


Figure 54 - Grasshopper generated 3D model of the floating panel solar tracking system. Source: author

The physical mockup of the floating panel was built to better study the potentials and shortcomings of the computer model. The physical model is made of a 15”x15” wooden (1/2” chipboard) frame enfolding the 10”x10” opening frame. The vertical framework is stabilized with two triangular foots. Four 7” long aluminium rods are fixed to the inside of the opening with steel galvanized hanger tapes and wood screws. Small scratches made on the rods help fitting and fixating the springs on the rods.

The wooden floating panel in the center has four “J”-shape lasercuts at the edges to accommodate the end rings of the springs. Plastic cords (used for lawn trimmers) are also knotted at this lasercut joints and then directed to the rollers (plastic rollers used in sliding doors) in the back of the frame.

The plastic cords are driven back to the front rollers to be aligned to the pulley mounted on the servo. Two sets of rollers and the pulley on the servo help smooth the movement of the cord in different directions. This way, a diagonaly held cord

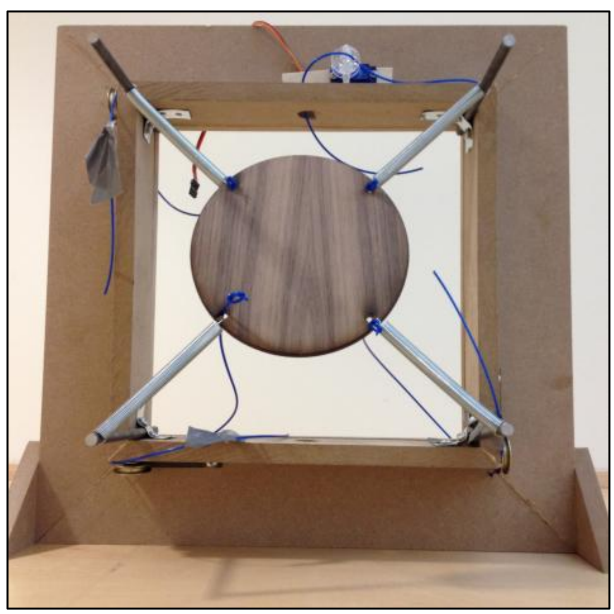


Figure 55- Front view of the spring model showing the panel held by four sets of rods and springs. Source: the author

smoothely pulls in a perpendicular plane in horizontal direction by a mini servo that has a low torque. The mechanism elminiates the need for regular sized servos and facilitates concealment of the mechanical parts.

The combination of the panel, rods, strings, cords, rollers and the servos are structured so that the panels can easily be oriented to each or a combination of directions (e.g. to top and to the west) by actuating the servos.

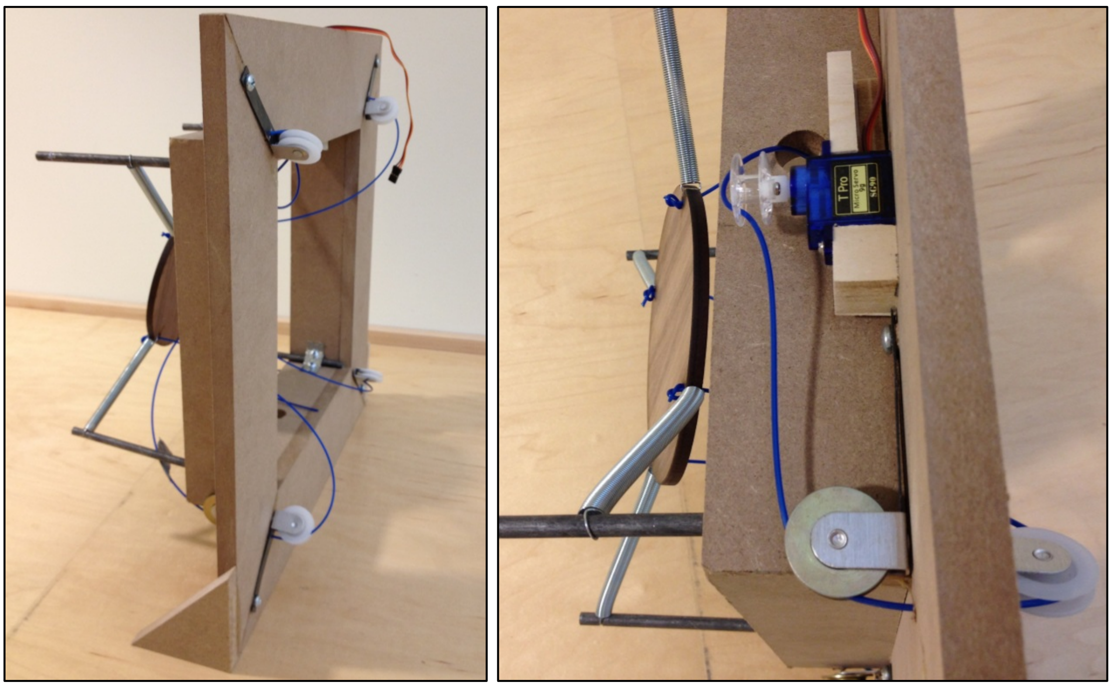


Figure 56 - Floating panel physical model shows the mechanical parts, rollers and the servos. Source: the author

Despite the potentials of this alternative in both concept and mock-up models, the system has a number of disadvantages, making it necessary to apply changes to the model in order to increase the efficiency and resolve the visual contact issue.

Pros

- Most appealing form for the sun-tracking building envelope. the proposed modules can cover any surface with any form
- This design alternative resolves the overshadowing issue with simply offsetting the panel to the outside using the rods. At extreme angles, the rods themselves can cast shadow on the panel but it can be avoided with careful adjustment of the rod height and the panel size. The minor shadings should be studied in an energy analysis tool.

Overall, the offsetting of the panel is a proper strategy that is maintained in the next models.

- Each individual module is flexible and efficient
- The floating movement can encourage public interaction and raise awareness about high-performance building envelopes
- Energy producing section is emphasized in the center of the shape
- Semi-transparent material can provide diffuse light

Cons

- Visual obstruction at all time, minimum visual contact: The study shows that the best place for the opening to provide the view is the bottom hemisphere. However, evaluating the physical mock-up indicates that creating openings below the solar tracking panel, even if it opens a large area of the membrane, would only provide a small opening that still obstructs the view.
- The spot which receives the maximum amount of solar radiation is also the best place for the opening. To prevent the cladding module from compromising the electricity production, the PV cells should be placed on the top part of solar tracking device and eligible openings should be identified by a shading study in the computer model.
- Complex construction of kinetic elements: The outcome from the physical model shows that the three dimensional motion is more complex and difficult to obtain. When a pulling force is applied to to the panel, it is not merely transmitted to the one direction, but it pulls the whole panel towards the force point. Therefore, it is not possible to create necessary angles needed for tracking the sun movement in horizontal and vertical directions.
- Complex automation: Programming more than one servo for rotation in one axis is complex and not efficient. More effective method should be developed.
- Visible mechanical elements and wiring decrease the quality of the view from inside of the building and affects the aesthetics of the adaptive envelope.

In conclusion, the physical assembly works well when manually manipulated. The panning range is around 110 degrees and tilting range is about 50 degrees upwards. An option to improve the pan and tilt function is incorporating linear actuators such as linear servos. Three linear servos can push and pull the surface and provide a wide range of motion three dimensionally.

However, researching linear servos for this purpose showed that the available products are pricey and only accessible in large scale.

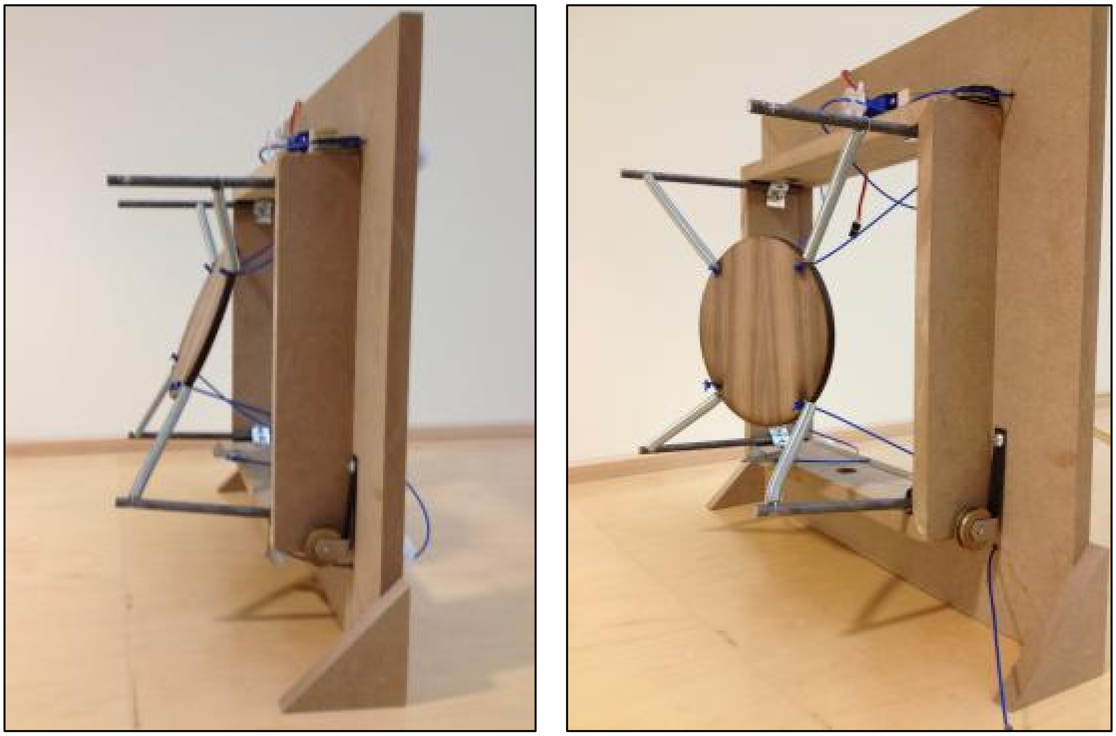


Figure 57 - Pictures of the spring held model showing different orientation of the panel.

5.1.4. Two axis rotating panel

To build a physical model with wider three dimensional rotation ranges, the rotation is broken into pan (horizontal) and tilt (vertical). Since complex three dimensional sphere joints cannot be replicated in this project, it is assumed that combining the rotation in two separate control systems would resolve the mechanical issues of previous trials.

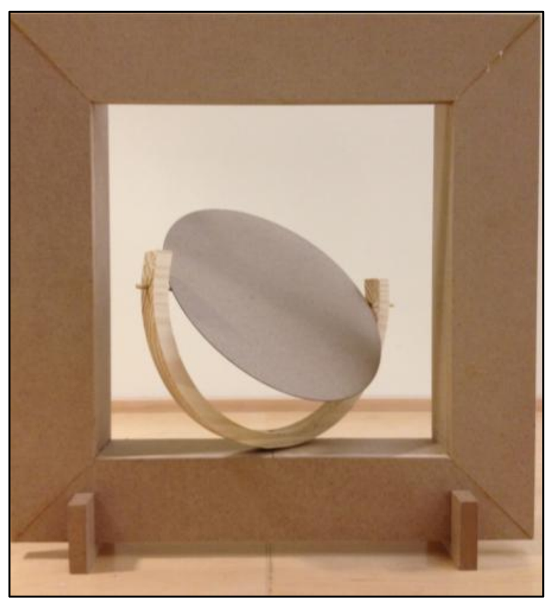


Figure 58- Picture of the circular panel with two axis rotation (Positioned for morning sun). Source: the

In the two-axis tracking panel design, the chipboard panel frame forming the opening is similar to the frame in the floating panel model. The complicated floating mechanism consists of rods, springs and cords and is replaced by a semicircular frame that is only connected to the frame at one point through a revolving shaft. The revolving shaft is controlled by a servo hidden beneath in the depth of the frame.

A thinner shaft is placed across the semicircular frame that holds the light weight panel. To motorize this rod the servo should be placed on the side of the semicircular frame and the rod should be connected to the servo axis through a pulley and band system. This would add an extra unsymmetrical weight to the frame. The visible motor on the frame also negatively affects the aesthetic of the model.

The preliminary model for the two axis tracking system shown in the picture below consisted of two circular frames two resemble the previous cloud shaped wall. The issues identified in this configuration were the stability and structure of the larger frame as the bearing system and also the overshadowing of both frames on the PV panel. Therefore in the second model the outer frame was changed back to rectangular and the inner frame was designed in semicircular shape to avoid overshadowing of the frame on the panel. However the similar problem persists with the larger rectangular frame of the opening.

In this design, if the remaining opening between the panel and the frame covers less than 1/3 of the larger frame's opening, the light infiltration control via membrane or other covering material is not essential. In other words, the shading of the 2/3 of the frame area with the PV panel will provide sufficient protection. Larger shadows in the afternoon improves the effectiveness of the shading by 60 percent (2/3 of the area is already shaded with the panel).

Figure 59 - Detail of the tilting panel.

Pros:

- The two axis rotation mechanism significantly improves the control of the Solar panel in a wide range of angles. This means the mechanism is completely responsive to the defined goal of the solar tracking module.

- The simplified mechanism also improves the visual contact with the surrounding environment through the uncovered gap between the panel and the frame. However, if the revolving shaft beneath the panel is not placed outside of the frame the shadow induced from the larger frame will affect the solar panel as illustrated in the images below.

Cons:

- Instability of the tilting servo because it is mounted on another kinetic element.
- The tilting servo is visually unavoidable because it is mounted on the horizontal axis

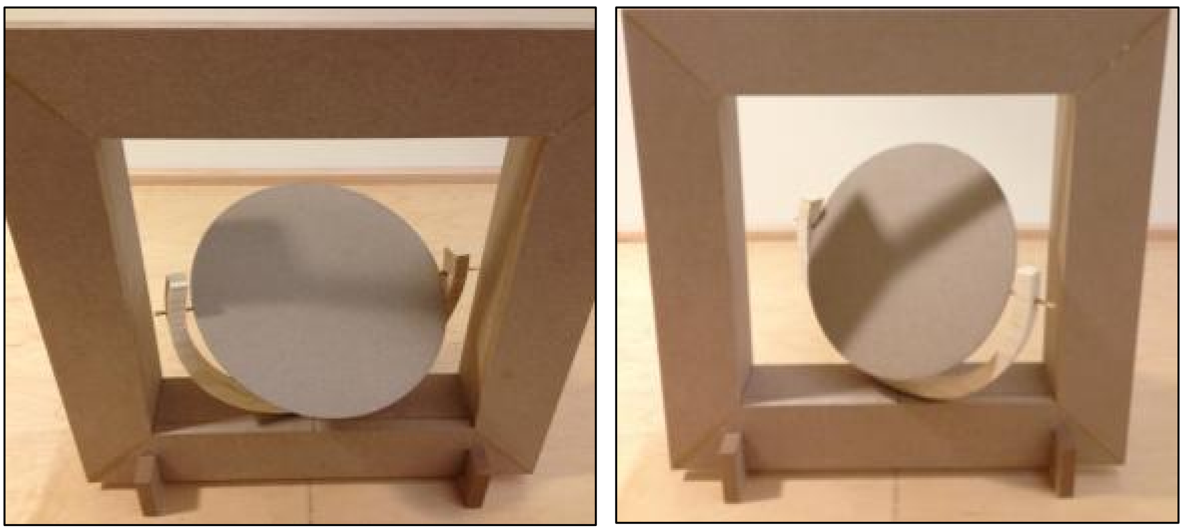


Figure 60 - Pictures of the rotating panel positioned at noon (left) and late afternoon (right)

5.1.5. Pan and Tilt with combined servos

Despite its advantages, the idea of dividing the rotation axes control, in the previous model, could cause various problems. For example, the second servo needed to be mounted on a kinetic part of the module (i.e. the semicircular frame) imposing an unsymmetrical momentum to the primary servo. Moreover, the visibility of the actuating element mounted on the dynamic frame could not be avoided and, therefore, negatively affected the design.

To resolve the visible actuator and the dynamic loads, the solution is to merge both rotating actuators and connect the tracking panel to one of them. This way, the rotation happens smoothly, the motors are placed in one unit and the tracking element is simplified to a single panel that is connected to one of the motors.

To implement this concept, a pan/tilt technology, usually used for controlling light weight cameras, was adopted. The pan/tilt kit consisting of a panning and a tilting panel accommodates two regular servos in one unit and is capable of rotating in two axes. The logic of the operation is not different from applying two separate servos. In both arrangements a complex of four photo resistor sensors provide light control data for the solar tracking system.

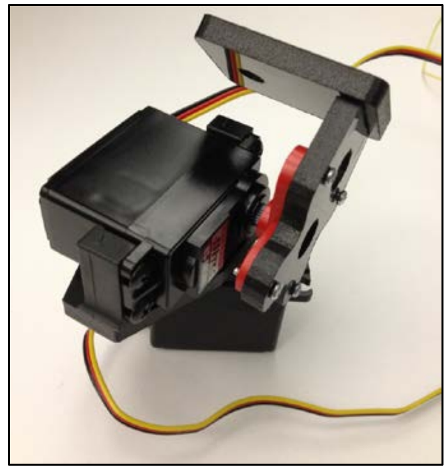


Figure 61- Pan and tilt module showing two servos merged in one unit. Source: the

Each pair of photocells collects information for one of the actuators. For example, two photocells are placed on east and west (if the PV cell is mounted on the south facing façade) edges of the PV cell. This pair is connected through two resistors to the Arduino board and to the panning servo that in this unit is located underneath.

The Arduino code is written based on data received from the sensors. If the sensor on the east end receives more light, it indicates more resistance. The code is outlined so that the data from the two sensors are compared. The difference between two resistances is calculated. Then the servo pans in the direction of the sensor with more light. The angle of rotation is in proportion to the amount of light radiated to the sensors.

The same process takes place in the other pair of photocells. The minimum, maximum and the default pan/tilt are identified by experimentation with the light and the specific unit of the servos. In this design, the panning servo is positioned at 90 degrees in the center and pans between zero and 180 degrees. The trials with artificial light (from flash light) result in a 150 degrees rotation from east to west. The tilting servo rotates 90 degrees only upwards since the sun position does not move below the horizon level.

The next step is to mount the PV cell on the pan/tilt unit and use the produced electricity to charge batteries or measure the electric current with ammeter. In the next section the electricity produced from the single PV cell in static and sun-tracking conditions will be compared. The result would show the efficiency percentage of the sun-tracking PV cell.

The following images produced by Grasshopper show a simple array of the solar tracking panels in winter solstice located in State College, Pennsylvania. The shading studies of the complete array are discussed in the conclusions.

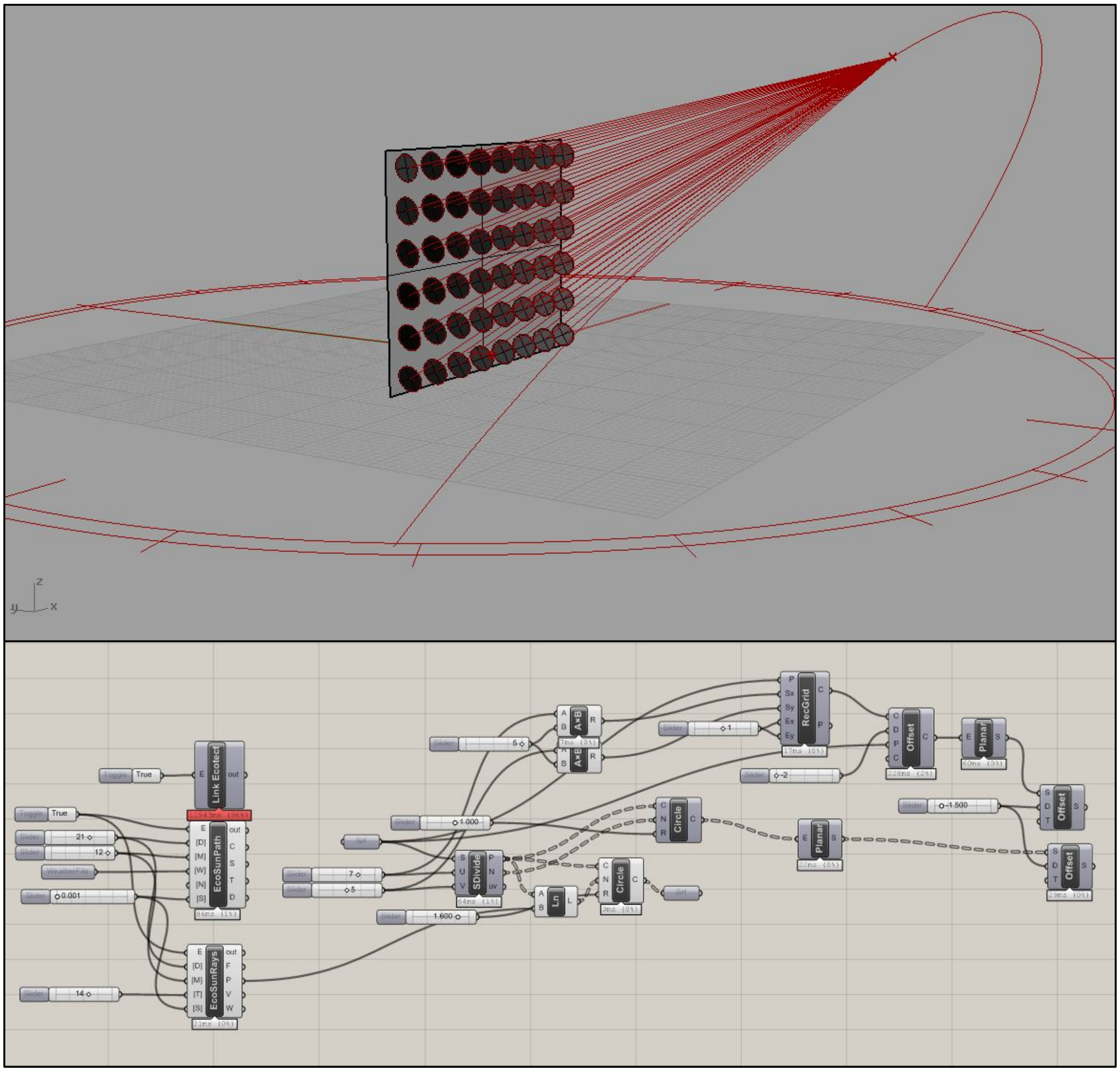


Figure 62- Grasshopper model of a sample array of the sun tracking panels in winter solstice located in State College, PA. Source: the author

5.2. Final Assembly

With the two axis sun-tracking module mechanics and strategies finalized, this section discusses the technical details of how each element fits in one module and make a functional sun-tracking device.

The PV cell is a monocrystalline 5x5 inch solar cell purchased on eBay with 2.6 W output. The PV cell is mounted on a circular panel and rotates by the servos. The panel is screwed to the tilting servo arm for stability during the rotations of the panel.

Four photo resistors, functioning as the sensors, are inserted into the circular panel on top, bottom, left and right corners. Each photo resistor has two pins that are connected to the Arduino board using jumper wires to transfer signals to the microprocessor. The pan/tilt servo combination is also screwed to the wooden frame. For minimal visibility of the wiring and the Arduino board, one servo is mounted below the frame and one on the side.

Adhesive copper flat wires are used to tab the photovoltaic cell. Each piece of copper wire is easily attached on the front and back of the cell to create positive and negative sides. Electrical leads are then directly connected to the copper wires transferring the electricity to the digital multimeter.

To read the produced amperage, the black cord is plugged in the COM terminal of the digital multimeter. When the other (red) cord is plugged in the mA terminal and the rotary switch is set on the A section, the amperage shows on the display in mA units.

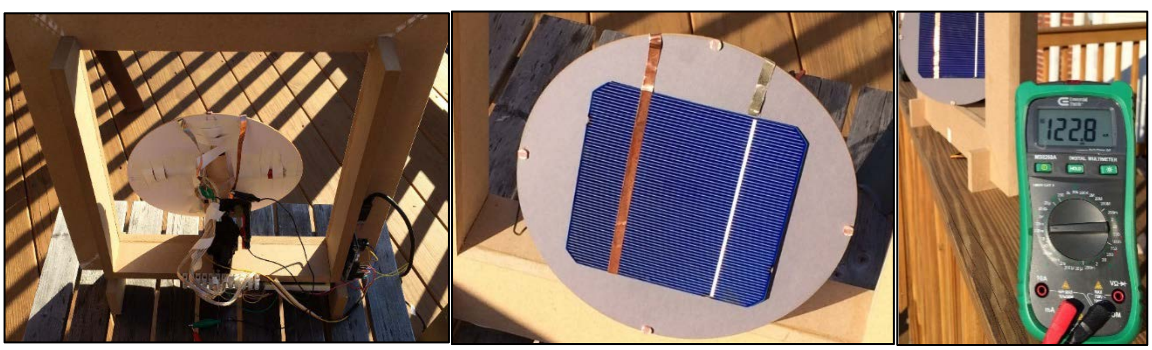


Figure 63 - PV panel's front and back setup. In the middle photo, 4 photo sensors and a tabbed PV cell using adhesive copper flat wires are visible. The digital multimeter used to measure the power output of the PV cell source is shown on the right photo: the author

Various ranges of milliamp (mA) readings are available on the rotary switch. For this photovoltaic cell, 200m scale yields readings with reasonable differences in photocurrent at the slightest rotations of the PV cell and changes in the radiation intensity.

The final assembly at large scale:

Figure 64- Schematic illustration of sun-tracking modules on Jean Nouvel's Arab world institute building in Paris. Image source: http://www.greatbuildings.com/cgi-bin/gbi.cgi/L_Institut_du_Monde_Arabe.html/cid_3027883.jpg , illustration by the author

Figure 67 is a simple illustration of the two axis sun-tracking modules. As shown in the figure, the modules can be easily expanded in rows and columns, as a second façade layer to rehabilitate an existing conventional building with limited intervention and change in the appearance. More complex distribution patterns and various sizes of the panels create more interesting and innovative building envelopes for new construction projects.

6. Conclusions

The performance of a sun-tracking envelope module is ultimately measured by the amount of photocurrent produced by the photovoltaic cell mounted on the system. To study the performance, a baseline is defined to compare against the sun-tracking results. This project defines two baselines to provide a better understanding of how and whether the computer controlled solar design is more efficient than conventional building envelopes. The first baseline is the power output from the solar panel in the default vertical position and the second baseline is the result of calculated tilting of the solar panel according to optimum south facing angle at each point in time.

For this experiment, latitude and longitude coordinates of Washington DC were used as input information. The data for the calculated baseline was retrieved from SunPosition, a tool that calculates the position of the sun by the hour on any given day throughout the year in any location. (Gonbeck, 2009) SunPosition is a product of Sustainable by Design, a solar engineering consulting firm in Seattle, WA that provides online green design tools. The date was set to January 30th when the test measurements were done. The exact position of the sun is shown below at each hour. The power intensity of the PV cell is at its maximum level when the sun radiation is perpendicular to the solar surface.

The optimum angle towards the sun was calculated from an array of altitudes and latitudes. For example, at the time of the experiment at 10 a.m. the altitude of the sun was 24.62, which gives the optimum vertical tilt of 24.62 towards the sun and 65.83 from the horizontal position. Similarly the azimuth of the sun was -37.35 (37.35 towards east from south Zero azimuth=0). At 4 pm the sun's altitude was 13.97 which created a lower tilt (13.97 degrees). The azimuth of 53.31 also created a 53.31 degrees tilt towards west. Subsequently, the amount of optimum pitch and tilt of the PV cell was easily recognized at each hour.[2]

```
SunPosition output complete

Latitude is 38.9 degrees north
Longitude is 77 degrees west
Time zone offset from GMT is -5 hours
```

[2] Similar other online tools for calculation of the sun position are also available. The Sun Position Calculator by pveducation.org calculates the position of the sun by hour and minute with an informative illustration of the sun position. http://pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator

Zero azimuth is south
Output angle units are degrees

date	time	altitude	azimuth	declination
Jan 30	07:00	-3.71	-70.38	-17.54
Jan 30	08:00	6.92	-60.80	-17.53
Jan 30	09:00	16.54	-49.98	-17.52
Jan 30	10:00	24.62	-37.35	-17.51
Jan 30	11:00	30.48	-22.62	-17.50
Jan 30	12:00	33.39	-06.10	-17.48
Jan 30	13:00	32.91	10.99	-17.47
Jan 30	14:00	29.10	27.09	-17.46
Jan 30	15:00	22.54	41.23	-17.45
Jan 30	16:00	13.97	53.31	-17.44
Jan 30	17:00	04.02	63.74	-17.43

This design project did not continuously measure the photocurrent, primarily because continuous data recording technologies for this type of measurement was not available. In addition, several tests showed that the difference between photocurrent measurements in one-hour periods was minimal in late January. At least two reasons might be attributed to this observation: first, length of direct sunshine is much shorter in the winter, and second, the conventional photocurrent measurements for individual purchase and off-the-shelf photo resistors have lower accuracy and efficiency. Therefore, to produce a proximate daily measurement the data was collected with 2 hour intervals on January 30th from 7:30 a.m. to 5:30 p.m. with two hour intervals, totaling 6 readings. (Actual sunrise time is 7:15 a.m. and sunset time is 17:27)

This design used retail off-the-shelf products in a non-industrial scale. Use of non-industrial tools and materials increases the margin of error and accuracy of the produced data. For example, the off-the-shelf photo resistors are not the most accurate light sensors. Nevertheless, they still work, are readily available and affordable for this design project and would demonstrate the objectives of the research.

The lack of efficiency and susceptibility to error in off-the-shelf products raises the question that whether a pre-set computer program populated with exact position of the sun should be used, allowing the design to exactly follow the movements of the sun at each moment. This scenario was ruled out in chapter 4 because sensors are capable of responding to change in light conditions but a programmed tracking is not.

To minimize the photocurrent loss in the measurement process, copper flat wires, a high efficiency tabbing option for conventional photovoltaic cells, were used. To create an electric circuit to use the electric charge from the photovoltaic cell and to measure the current, two threads of wire were used. One wire was connected to the top surface of the PV cells for transferring the positive current and the other was connected below the surface for capturing the negative current. Connecting these two flat wires as positive and negative diodes to a digital electrometer provided an easy way for reading the voltage and amperage of the photovoltaic cell at each moment.

Table below shows the readings for the two baselines and the tracking data throughout the day.

Table 4 - Power output measurement from the sun-tracking PV cell on January 30th 2014

Time of reading	**7:30**	**9:30**	**11:30**	**13:30**	**15:30**	**17:30**
Photocurrent at Vertical Position (mA)	73.5	130.4	139.2	143.9	124.8	86.6
Photocurrent at Calculated Optimum Tilt (mA)	82.6	133.3	159.1	147.9	125.9	116.4
Photocurrent at Optimum Tracked Position (mA)	88.1	139.8	150.7	158.8	129.5	119.7

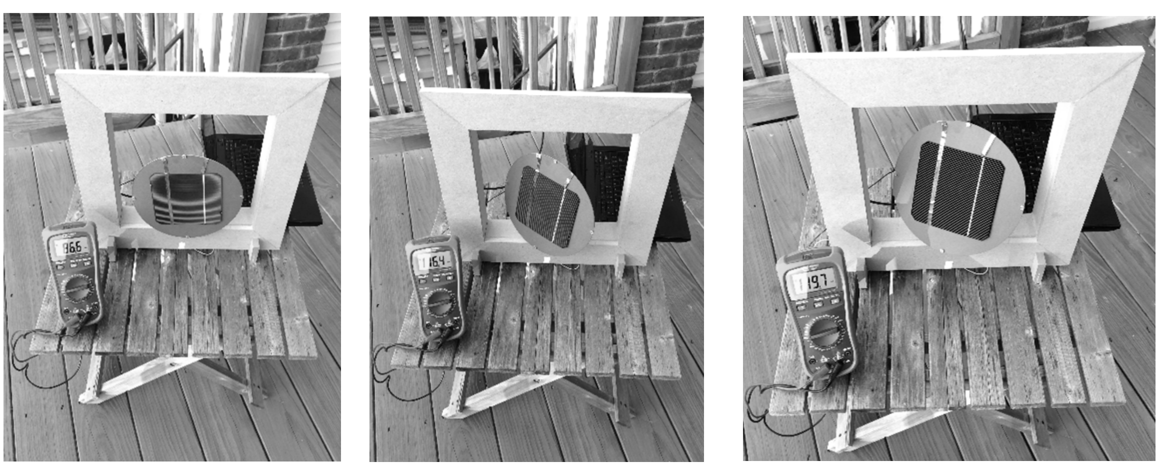


Figure 65 - Photo of the sun-tracking module at 5:15 p.m. on January 30th at three states from left to right: 1. vertical position facing south, 2. manual tilt to 1 degrees vertical and 67 degrees to west, 3. the tracked position. Source: the author.

Each time the digital multimeter was turned on or connected to the PV cell, the reading on the display fluctuated for few seconds. After waiting a few seconds, the reading at each position was recorded. In some cases the reading changed in the cold breeze and fluctuation continued for few more moments. The readings were all recorded with lowest possible changes in the recording condition to avoid errors due to secondary conditions.

7:30 am: The weather forecast showed a sunny day for January 30th 2014. Although 7:30 is past the 7:15 calculated sun-rise time, the sun had not risen enough yet to be visible in the horizon. The dusk light produced a 73.5 mA reading at vertical position. The reading increased to 82.6 when the panel was tilted 4 degrees vertically and about 75 degrees eastward (extracted from sun position tool). After running the Arduino code the sun-tracking system rotated towards the sun in a position that looked very close to the manual position. The display read 88.1 at this moment. The record difference was slight because the direct sun radiation was not a factor yet.

9:30 am: the sun had brightened the blue sky by this time. The sun was not visible yet because of the surrounding buildings and, therefore, there was no intense sun radiation and shadow in place. The reading showed a significant rise to 130.4, 133.3 and 139.8 in vertical, manual and the tracked position. Up to this point the highest output was read at the tracked position by the computer.

By 11:30 sun was high in the sky and shadows got sharp. The readings showed a change in the pattern. The manual tilt upwards results in higher reading (159.1) compared to the position that the sun-tracking module found optimum (150.7) and was considerably higher than the vertical position reading (139.2). The change in the pattern between the manual and tracked tilt i attributed to the possible inaccuracies of the photo resistors or the digital multimeter readings. The significant difference in output between the vertical and optimum position indicates when the sun is at a higher altitude the effect of adaptive building envelopes in energy conservation are more apparent.

At 1:30 pm the sky was sunny and the even higher results than the previous hours were shown on the display. The readings returned to the prevailing pattern of greater output at the tracked position at this measurement.

At 3:30 pm readings the sun radiation intensity, still quite high compared to previous readings, decreased. The output numbers decreased below the 9:30 am levels. The frame put shadows on parts of the panel but the light sensors were still under direct light.

At 5:15 pm. (minutes before the sunset) the sun was visible very close to the skyline and shadows got very light. The readings were lower because of the indirect light the PV cell received. The problem with the way the solar panel was installed inside the frame caused an over shadowing problem when the panel was tilted to about 65 degrees to the west. This issue was more apparent when the program ran the sun-tracking code and the readings on the computer display showed that at no point the right and left photo resistors showed equal resistance (which is when the program would stop the servos from turning).

Unequal resistance from the two photo resistors were a major problem throughout the study. This issue affects the reliability of the readings because it implies that the sun-tracking device was not stopped at the exact optimum position. It explains why one measurement showed better readings at the manual tilt.

Furthermore, the breeze caused fluctuation in the readings. Changing the elevation of the PV cell also changed the readings considerably, another indicator of errors in the readings. For example one reading at 5:30 in result of the computer sun-tracking showed an output of 119.7 mA. When the device was moved 3 feet higher the reading increased to 158.9.

The data gathering process was repeated on the next cloudy day with similar air temperatures at 3:30 pm, which showed very little change in the readings and the amount of solar panel tilt in computer tracked position. Knowing that in an overcast sky the position of the sun is not as clear as a sunny sky, this observation shows the total sun radiance and the resulting photocurrent are not significantly different.

It is further concluded the device is capable of locating the brightest spot in the surrounding environment rather than merely tracking the sun. This way the sun-tracking envelope retains its high performance throughout the year regardless of the weather and sky condition. Moreover other possible bright spots in the surrounding environment occasionally contribute to the energy producing function of the building envelope even at darker hours.

The physical model confirms the constructability of a sun-tracking device as discussed in previous chapters. The functionality of this physical model and the results of the current experiment confirm the expected premise that adaptive sun-tracking modules are more efficient in energy conservation than solar panels that are only tilted daily or seasonally. This model is clearly more efficient than fixed solar cells in vertical position. The added value of this research is in realizing that design criteria can couple with practical environmental performance in the building envelopes. For more reliable results the measurements should be repeated over a longer period of time to observe changes in the readings and the sun-tracking performance in other seasons.

6.1. Future research

This research is a proof that architectural designers can combine their aesthetic and performative concerns and it hopefully provides grounds for future designs to integrate performance enhancing technologies. Thus research offers opportunity for further question and future study on:

- The total power output by the sun-tracking PV cell versus the power consumed by the control system. This study should explore how economical and energy efficient it is to use computers and servo motors to run a sophisticated sun-tracking system.
- The effect of more sophisticated sensors on data readings.
- The effect of continuous data recording on the results rather than hourly samples of reading.
- How to protect the PV cells from dust and climatic elements and also keep birds from nesting in the frames.

Bibliography

Aksamija, A., Snapp, T., Hodge, M., & Tang, M. (2012, 9 27). *RE-SKINNING: PERFORMANCE-BASED DESIGN AND FABRICATION OF BUILDING FACADE COMPONENTS.* Retrieved February 9, 2013, from Perkins+Will: http://www.perkinswill.com/files/ID%203_PWRJ_Vol0401_02_Re-Skinning%20Performance-Based%20Design%20and%20Fabrication.pdf

Anshuman, S. (2009). *PixelSkin01*. Retrieved May 3, 2011, from Orangevoide: http://www.orangevoid.org.uk/

Arduino. (2003). Retrieved February 10, 2012, from Arduino: http://www.arduino.cc/

Boyle, G. (2004). *Renewable Energy.* New York: Oxford University Press in association with the Open University.

Brownell, B. (2008). *Transmaterial 2: A Catalog of Materials That Redefine Our Physical Environment .* New York: Princeton Architectural Press.

Brownell, B. (2009, August 14). *PixelSkin01*. Retrieved October 25, 2011, from Transmaterial: http://transmaterial.net/index.php/2009/08/14/pixelskin01/

Bullivant, L. (2010, 09). *ENRIC RUIZ GELI CLOUD 9 | MEDIA-TIC*. Retrieved February 12, 2014, from The Plan: http://theplan.it/J/index.php?option=com_content&view=article&id=1120%3Amedia-tic&catid=91%3Athe-plan-044-09-2010&Itemid=472&lang=en

Double Glazing. (1998-2012). Retrieved January 28, 2012, from Efficient Windows Collaborative: http://www.efficientwindows.org/glazing_.cfm?id=6

Drozdowski, Z. (2011). The Adaptive Building Initiative: The Functional Aesthetic of Adaptivity. *Architectural Design*, 118-123.

Everett, A. (2009, September 27). *Pixel Skin01 Smart wall*. Retrieved February 10, 2012, from SMART-WALL-EVERETT blog: http://smart-wall-everett-5334-5301-f09.blogspot.com/

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

Fuller, R. B. (1938). *Nine Chains to the Moon: An Adventure Story of Thought.* Philadelphia: Lippincott Williams & Wilkins.

Gonbeck, C. (2009). *Sun Position*. Retrieved January 30, 2014, from Sustainable by Design: http://www.susdesign.com/sunposition/index.php

Goodyre, J. (2010). *A Prototype for an Adaptive Bloom*. Retrieved April 19, 2012, from Constructing Realities: http://www.constructingrealities.com/?p=5

Graph. (n.d.). Retrieved February 12, 2012, from Arduino: http://arduino.cc/en/Tutorial/Graph

GreenPIX. (2009). Retrieved April 19, 2012, from GreenPIX: http://www.greenpix.org/

GreenPIX press release. (2009). Retrieved April 19, 2012, from GreenPIX: http://www.greenpix.org/press/PDF/Greenpix_press-release_EN.pdf

HelioTrace. (2010). Retrieved 4 10, 2012, from Adaptive Building Initiative: http://www.adaptivebuildings.com/heliotrace.html

HelioTrace Façade System Featured in Popular Science's "Best of What's New". (2010, December 3). Retrieved April 4, 2012, from SOM: http://www.som.com/content.cfm/heliotrace_facade_popular_science_best_of_whats_new

Issue 4/2009 Trends in window and façade construction. (2009, July 2). Retrieved January 25, 2012, from Tuer Tor Report: http://www.tuer-tor-report.com/index.php/news/248/324/Trends-in-window-and-facade-construction

Italy, San Paolo. (1999-2012). Retrieved January 30, 2012, from Travel Adventures: http://www.traveladventures.org/continents/europe/sanpaolo04.shtml

Knaack, U. (2007). *Facades: Principles of Construction.* Basel: Birkhäuser.

Knaack, U., Klein, T., & Bilow, M. (2008). *Imagine 02 Deflateables.* Rotterdam: 010 Publishers.

Knight, T. (2000, Spetember 14). *Shape Grammarin education and practice*. Retrieved December 5, 2011, from MIT: http://www.mit.edu/~tknight/IJDC/

Krauel, J. (2010). *Contemporary digital architecture : design & techniques.* Barcelona: Links.

Kwok, A., & Grondzik, W. T. (2007). *The Green Studio Handbook: Environmental Strategies for Schematic Design.* Burlington, MA: Architectural Press.

Landau, C. R. (2001-2012). *Optimum Tilt of Solar Panels*. Retrieved April 20, 2012, from MACS Lab, Inc.: http://www.macslab.com/optsolar.html

Nitz, P., & Hartwig, H. (2004). Solar control with thermotropic layers. *Elsevier*, 573-582.

Pawlyn, M. (2011). *Biomimicry in Architecture.* RIBA.

Processing. (2003). Retrieved February 10, 2012, from Processin: http://processing.org/

PVWatts AC Energy and Cost Savings. (2009). Retrieved April 21, 2012, from NREL Renewable Resource Data Center : http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/US/code/pvwattsv1.cgi

Sahler, J. (2008, August 27). *Penn State's LEED Gold School of Architecture*. Retrieved April 16, 2012, from Inhabitat: http://inhabitat.com/penn-state-school-of-architecture-leed-gold/

Schittich, C. (2006). *in Detail Building Skins.* (C. Schittich, Ed.) Munchen, Germany: Birkhauser.

Schmidt, N. (2010, December 13). *Dynamic façade – Kiefer technic showroom by Ernst Giselbrecht + Partner*. Retrieved March 5, 2012, from daily Tonic: http://www.dailytonic.com/dynamic-facade-kiefer-technic-showroom-by-ernst-giselbrecht-partner-at/

ShapeShift. (2010). Retrieved February 12, 2013, from ShapeShift: http://www.caad-eap.blogspot.com/

Strategies for Design Schools. (2011). Retrieved February 3, 2012, from Architecture2030: http://architecture2030.org/action/design_schools

The idea. (2011). Retrieved March 2, 2012, from Solar Ivy: http://solarivy.com/the_idea

Tudorache, T., & Kreindler, L. (2010). Design of a solar tracker system for PV power plants. *Acta Polytechnica Hungarica*, 23-39.

USGBC. (2003, October). *California Report on Green Building Costs and Benefits*. Retrieved November 21, 2011, from U.S. Green Building Council: https://www.usgbc.org/docs/resources/CA_report_GBbenefits.pdf

Velikov, K., & Thun, G. (2012). Responsive Building Envelopes: Characteristics and Evolving Paradigms. In F. Trubiano, *Design and Construction of High-Performance Homes: Building Envelopes, Renewable Energies and Integrated Practice* (pp. 75-92). Routledge.