Folding Fan Façade: Designing an Actuated Adaptive Façade System for Fine-Grain Daylight Control

by

June Kim

Submitted to the Department of Architecture in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Architecture Studies

at the Massachusetts Institute of Technology

June 2018

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Abstract:

In architecture, natural light is one of the main factors to consider when designing a building or a room. A building has to be designed in such a way to allow the right amount of natural light in which influences the building occupants' visual and thermal comfort level. Curtains, blinds, shades, or shutters are the most common static shading methods currently used to regulate the amount of sunlight coming into a room.

However, traditional blinds or shades cannot be customized with respect to fine-grain localized control, which can result in suboptimal indoor lighting levels when the blinds or shades are down. While static window treatments are practical low-cost options, they cannot offer the level of adjustment that dynamic shadings can provide. Majority of the time, occupants of a room have the freedom to adjust the shades; however, the shades are often left in one position since occupants are not willing to constantly adjust the shutters every time the outside environmental conditions change.

Unlike traditional blinds, adaptive façades are designed to automatically adjust positions depending on the environmental changes or have the ability to be fine-grain controlled by the occupant. Because of the ability to respond to fluctuating weather conditions, adaptive façades can provide optimal indoor day lit space.

The purpose of this thesis is to design and build a proof-of-concept prototype of a folding fan-shaped actuated adaptive facade system. Because of the scope of this thesis, the prototype is designed to fit in one of the windows at McCormick Hall instead of a full scale building façade. There are 13 fan-shaped shades units that can be individually controlled to reduce direct sunlight coming into the indoor space. The results demonstrate that this technology can be designed and built with a modest budget and commonly available tools to achieve high quality results for customized daylight control.

Thesis Supervisor: Caitlin Mueller
Title: Assistant Professor of Architecture and Civil and Environmental Engineering
Acknowledgements

I would like to express my sincere gratitude to:

Assistant Professor Caitlin Mueller, for her endless support and mentorship as my thesis advisor. Caitlin not only helped me with my thesis but also helped me through tough times throughout the semester.

Technical Instructor Chris Dewart, for his expertise in woodworking and the dedication to help projects come to life.

ProjX program, for the generous $500 funding and for helpful ProjX mentors.

Jim Bales, Ed Moriarty, and the Edgerton staff, for helping me understand electrical engineering concepts, being a bounce board for ideas, and for lending me various equipment.

Instructor Cherie Abbanat and Administrator of Academic Programs Renee Caso, for always checking in on me and being concerned about my well-being.

Isaac Yeshak Fenta, Mathew Lau, and Shane Colton for answering many of my panicked late-night questions about Arduinos and circuits.

SMArchS BT Awino, SMArchS BT Yijiang Huang, and MArch Anran Li, for technical support in DIVA daylight simulator, circuits, and Firefly.

Tarfah Alrashed and Al-Muataz Khalil, for helping me with coding, listening to my rants, and giving me that one cup of hot chocolate.

Last but not least, my boyfriend Jose Peña, for endless support, dealing with my tantrums, and endless boba runs.
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1. Introduction

1.1 Why is natural light important in architecture?
Today’s rapidly changing climate caused by increase in greenhouse gases is a critical environmental issue that has to be addressed. In terms of architecture, a building’s energy consumption influences the amount of greenhouse gases released into the atmosphere. Artificial lighting and HVAC (heating, ventilation and air conditioning) system are few factors that increases the building’s energy consumption. The building’s occupants rely on artificial lighting and HVAC system for visual and thermal comfort levels in the indoor space. However, the use of artificial lighting and HVAC system can be lowered by the use of natural lighting.

Too much daylight causes visual difficulties from glare. In such a case, occupants rely on blinds or shades to prevent too much daylight from entering the room. Because traditional blinds or shades cannot be localized, this can result in suboptimal indoor lighting levels when they are in use, which results in occupants using artificial lights to provide the necessary lighting even during the daytime.

Amount of daylight coming into an indoor space not only influences the visual comfort level but the thermal comfort level as well. An indoor space can get overheated if there is too much sunlight, whereas too little sunlight would result in a cold indoor environment. However, there are more nuances when it comes to the relationship between thermal comfort level and daylight level. For example, the positions of the sun are similar around April and September as shown in the northern hemisphere analemma (figure 1.1). Analemma is a diagram showing the changes of the sun position in the sky over the course of a year when viewed at the same time of day from the same fixed location on Earth. Even though the sun position is similar during April and September, April tends to be colder compared to September as the season changes. More sunlight in an indoor space is desirable during April for warmth and vice versa for September. Thus the thermal comfort level of an indoor space is influenced both by the position of the sun and the season. If natural lighting can be controlled in such a way to provide optimal indoor lighting throughout the daytime, the use of artificial lights and HVAC can be reduced.
36.6.2 Analenuna

Analenna curve drawn in northern hemisphere using camera with solar filter lens

Figure 1.1. Solar analemma diagram for northern hemisphere sky. Image from Smithsonian article written by Mohi Kumar.

1.2 How can natural lighting be controlled?

According to Christoph Reinhart in his Daylighting Handbook: Fundamentals Designing with the Sun Vol.1, a day lit space is “primarily lit with natural light and combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling...” Static window treatments such as curtains, blinds, shades, or shutters are the most common practical low-cost methods currently used to regulate the amount of sunlight coming into a room. However, the static window treatments can only provide binary lighting control; either the blinds are up to let the direct natural light in or down to let no natural light in. Because of such binary nature of static window treatments, the shades are often left in one position even if the indoor space does not have optimal lighting level. Occupants are not willing to constantly adjust the shutters every time the outside environmental conditions change. Instead, occupants rely on artificial lights to achieve the necessary lighting level.

Unlike traditional blinds, adaptive façades are designed to automatically adjust positions depending on the environmental changes. Environmental changes include the shifting sun position, weather/sky conditions (such as overcast sky), and nearby objects casting shadows. Because of the ability to automatically respond to fluctuating sun positions, adaptive façades can provide optimal indoor day lit space without having to rely on occupant behavior which
would decrease the use of artificial lights and potentially the use of HVAC systems to help reduce the overall energy consumption of the building.

However, adaptive façades aren't always more energy efficient than static shading systems. If the overall dynamic shading system takes up more energy to operate than the energy that would be used in artificial lighting and heating/cooling systems, then obviously it's not a better solution. Also, "it is important to note that results of façade studies ... highly depend on climate, façade orientation and programmatic use." (Reinhart 2014) Depending on the climate of the site location, adaptive façades may not be necessary. For example, if a building is in an environment where the climate is mostly consistent, such as sites near the equator, then there will not be much change in the sun position throughout the year. Thus there is no need for an adaptive façade as the traditional blinds would be sufficient enough. On the other hand, sites at highly varying climates, such as Boston, could benefit from adaptive façades as they are more prone to changes in sun positions given that the façade does not require more energy to operate. As shown in figure 1.2a and 1.2b, the shadows of the house correspond to the direction of sunlight. The diagrams for figure 1.2a and 1.2b show how the sun position changes drastically through the day and throughout the year.

**Figure 1.2a.** 3D analemma diagram of the sun in Boston, MA. Sun (orange dot) on the left is at June 21\(^{st}\) 9am, and on the right is at 5pm. This diagram shows the changes in the sunlight direction throughout the day. The figure-8 analemma represents the position of the sun throughout the year, whereas the arcs that connect the different figure-8s represent the sun position throughout the day.
Figure 1.2b. 3D analemma diagram of the sun in Boston, MA. Sun (orange dot) on top is at June 21\textsuperscript{st} noon (summer solstice), casting the shorter shadow. Sun on the bottom is at December 21\textsuperscript{st} noon (winter solstice), casting the longer shadow.

1.3 Thesis scope

The goal of this thesis is to design and fabricate a fan-shaped actuated adaptive facade that uses a daylight simulator to respond to changes in sun position. Specifically, this Folding Fan Façade is designed so that it would fit into one of the south-east facing windows on the 7\textsuperscript{th} floor of McCormick Hall at MIT. The location was chosen based on the ease of access since I live in McCormick Hall. Also due to logistical constraints, the façade is the size of a window instead of the entire building envelope. However, the façade can easily be scaled up by either tessellating the fan units or by increasing the size of each rotating fans. Additionally, the façade would ideally be affordable and easily replicated by anyone with access to a maker space with laser cutter and CNC milling machine.
2. Literature Review and Precedent Studies

2.1 Photometry and Lighting Quality

Photometry is the science of measuring visible electromagnetic radiation in the form of light in terms of its perceived brightness to human daytime vision. Luminous flux, luminous intensity, luminance, and illuminance are the “four commonly used photometric quantities to describe the light within space.” (Reinhart 2014) Luminous flux and luminous intensity describe the visible radiation emitted from a light source. Whereas luminance and illuminance describe the lighting incident on work surface or the human eye. Figure 2.1 illustrates a simple diagram to help understand the definition of each photometric quantity. Please refer to Appendix A for more detailed information on luminous flux, luminous intensity and luminance.

![Diagram of photometric quantities](image)

*Figure 2.1. Four photometric quantities (luminous flux, luminous intensity, luminance, and illuminance) characterizing how a space is perceived. Image from “Contrast Sensitivity and Measuring Methods” article on Optometry Zone.*

Illuminance, the most commonly used photometric quantity to describe the light in spaces, is a measure of the total amount of light (luminous flux) falling on a surface. The unit for illuminance is lux or lumens per unit area.

\[
\text{Illuminance} \ [\text{lux or lumen/m}^2] = \frac{\text{Luminous Flux} \ [\text{lumen}]}{\text{Area} \ [\text{m}^2]}
\]
Illuminance can be measured using a sensor called an illuminance meter. There are even free phone app illuminance meters that use the phone’s camera as a sensor. Illuminance will be the primary way to describe light in this thesis.

So what is considered an “optimal” day lit indoor space? Unfortunately, lighting quality is “something perceptual and somewhat subjective” and “an individual’s notion of what constitutes ‘good lighting’ or a ‘well-day lit space’ is personal and evolves over extended periods of time and within a cultural context.” (Reinhart 2014). In the “Recommended Light Levels (Illuminance) for Outdoor and Indoor Venues” by the National Optical Astronomy Observatory, sunlight is approximately 100,000 lux, full daylight is 10,000 lux, and overcast day is 1,000 lux. The recommended indoor light levels are 250 to 500 lux for office space, classrooms and libraries. In the “LUX LEVELS GUIDE DOMESTIC APPLICATIONS” by Beacon Lighting Commercial, the recommended indoor lux values are 100-200 lux for general bedroom use and 300-400 lux for doing tasks in the bedroom. Also for home office, 100-400 lux is recommended for general use and 300-400 lux for task use.

2.2 Daylighting Performance Metrics

“Annual Daylighting Performance Metrics Explained” article from archlighting.com thoroughly explained the standardize daylighting performance metrics for different types of indoor spaces from the Illuminating Engineering Society’s (IES) published testing and calculation guide called Lighting Measurement 83 (LM-83). LM-83 came from a six-year long research effort by the IES Daylight Metrics Committee, led by the energy efficiency consultant Heschong Mahone Group. Research for LM-83 was done through surveys asking about “[the human subjects’] visual preferences and comfort levels in more than 60 spaces across three building types (classrooms, offices, and other) and several climate zones. The two daylight performance metrics listed in LM-83 are Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

Spatial Daylight Autonomy (sDa) examines if a space gets enough daylight during standard operating hours of 8am to 6pm on an annual basis. Apparently the calculation for sDA value involves an assumption that the acceptable daylighting threshold is 300 lux for at least half of the analysis hours. The values range from 0 to 100% of the space’s floor area. 75% means that the daylighting in the space is “preferred” by occupants and would be a comfortable space to work without the use of artificial lights. 55 to 74% is “normally accepted” by occupants. Regularly occupied spaces, such as an office or a classroom, should have the sDA values of 75% or higher. For spaces where only some daylight is important has to have at least 55% sDA values.

Another metric that LM-83 use is the Annual Sunlight Exposure (ASE). ASE is meant to complement sDA to indicate excessive solar heat gain and glare in a space. ASE is calculated using an hourly horizontal illuminance grids and the values range from 0 to 100% as well. An assumed lux value of 1,000 was used for sunlight. This value is much lower than what the lux value of direct sunlight because the 1,000 lux value considers secondary bounce-off surfaces, which has lower lux value than direct sunlight. The ASE value of 100% means that the entire floor area of the space has 1,000 lux or more for at least 250 hours per year. LM-83
recommends that a space should not have ASE values exceeding 10% since that would indicate visual discomfort for the occupants. Therefore, architects and light designers are recommended to aim for low ASE values to reduce potential glare and thermal stress, and high sDA values to provide enough daylight.

2.3 Precedents

- Al Bahr Towers:

The Al Bahr towers in Abu Dhabi were designed by AHR. It has a building envelope comprised of series of environmentally responsive kinetic shadings. The envelope is inspired from “natural adaptive systems like leaves, flowers, and skin spikes that open and close in response to the environment – in particular, to the sun.” (Fox 2016) and mashrabiya screens, a type of wooden lattice shading used in traditional Islamic architecture. The interactive envelope is comprised of automated shading components that open and close via the centrally located linear actuators. The actuators are linked to a control system following the sun’s path to “better distribute natural diffused light, optimize the use of artificial lighting through dimmers linked to sensors, and reduce air-cooling loads, ultimately helping to reduce overall energy consumption.” Each of the dynamic mashrabiya unit is a Y shaped structure that has six triangular panels. When the unit is fully unfolded, each of the triangular panels lay flat and form a larger triangular panel. When the unit is at its fully folded position, the center of the overall triangular panel is raised and six triangular panels sits perpendicular to the Y-shaped frame.

![Figure 2.2. Al Bahr Towers in Abu Dhabi, United Arab Emirates designed by AHR architects. On the right, façade mechanism demonstrated with diagrams and prototypes. Source: ahr-global.com/Al-Bahr-Towers](image-url)
HygroScope and HygroSkin:

HygroScope installation and HygroSkin pavilion are designed by Achim Menges with Steffen Reichert and Oliver David Kreig. Hygroscopy is a natural phenomenon when objects absorb moisture from their environment. HygroSkin: Meteorosensitive Pavilion was commissioned by the FRAC Centre Orleans for its permanent collection and HygroScope: Meteorosensitive Morphology installation is part of a permanent exhibition in Centre Pompidou, Paris. Both projects use hygroscopic components that change in shape depending on the relative humidity in the air. The designers were inspired by how conifer cone scales move in response to humidity since the scale’s materiality allows it to change shape. The scale movement is done by a passive system that is completely “independent from a plant’s metabolic trigger mechanism.” (Fox 2016) When wood absorbs or desorbs water, the water molecules bond to or release from the wood cell tissue micro fibers which in turn causes expansion or shrinkage. Examples of such movements are shown in figure 2.3.

*Figure 2.3. Different conifer cone shapes (left) and HygroSkin/HygroScope scales (right) depending on the environment’s relative humidity. Image from contemporist.com/hygroskin-meteorosensitive-pavilion-by-achim-menges/*.

Much like a conifer cone, the thin triangular scales in HygroSkin and HygroScope uses the inherent dimensional change in wood to produce adaptive shape change. This hygroscopic mechanism requires no energy or metabolic process to run since it is entirely dependent on the
The actual movement of the paper thin triangular wooden scales can be controlled by changing the material specific parameters listed below:

1. The fiber directionality
2. The layout of the natural and synthetic composite
3. The length-width-thickness ratio
4. The element geometry
5. The humidity control during the production process

According to Fox in his article on Interactive Architecture: Adaptive World, the HygroSkin’s/HygroScope’s wooden scales displayed a “linear dependency between the degree of relative humidity and the degree of openness” in a controlled laboratory setting. However, when HygroSkin pavilion was installed in an outdoor environment, the scales behaved in unexpected ways. Since the scales were exposed to other ambient climate variables besides relative humidity, such as temperature and heat radiation, the scales’ movements became unpredictable. The technology involved in creating HygroSkin or HygroScope is beyond what I can do for my thesis, but the overall design and passive movement method makes these notable precedent projects. It would be interesting to find a different method to recreate the opening and closing of the HygroSkin/HygroScope scales.

Figure 2.4. HygroSkin pavilion installed in an outdoor space. Image source: designboom.com/architecture/achim-menges-developes-hygroskin-and-hygroscope-biomimetic-meteorosensitive-pavilions-4-14-2014/.
Figure 2.5. The HygroScope installation under two different relative humidity conditions. The scales are closed in a dry environment (left) and opened in a humid environment (right). Image source: designboom.com/architecture/achim-menges-developes-hygroskin-and-hygroscope-biomimetic-meteorosensitive-pavilions-4-14-2014/.

- Shady: A Truss Climbing Window Shade

The Rus Robotics Laboratory at MIT CSAIL (Computer Science and Artificial Intelligence Laboratory) developed a robot that climbs the window’s muntins to block direct sunlight. They decided to build Shady because their lab in the Stata building has large wall-window with no shades to block sunlight. Because a lot of their desks are next to the window, they had difficulty working or seeing their computer screens due to the sunlight glare inhibiting their field of view. The lab members didn’t want to use traditional static shades because the shades would “block the whole window, detracting from the view” so they “decided to build a robot which can climb on the window’s aluminum muntins.” The robot can be positioned on the window to provide “localized sunshade and will be able to dynamically track the sun throughout the day”. Shady in action can be seen in figure 2.6.
Figure 2.6. Shady the robot in action. (Top row) Shady rotating and gripping the window’s aluminum muntins to move about. (Bottom row) Shady positioned at a location on the window with strong sunlight glare and deploying a fan-like surface to block the light. Images captured from youtube.com/watch?v=xDw0C52X9Mw.

As shown in figure 2.7, the earlier prototype of Shady uses a Chinese hand fan as a shade. In the later version of the robot (as seen in figure 2.8), the fan-shaped surface can be deployed into a full circle using a spring loaded mechanism. From the image of the CAD model, it is unclear what actuation mechanism is used to deploy the fan.

Figure 2.7. Prototype of the four degree of freedom Shady robot with hand fan used as shade. Image source: groups.csail.mit.edu/drl/Shady/shady.htm
Figure 2.8. CAD representation of Shady, a truss climbing robot with a deployable sun-shade as an example application. Image source: groups.csail.mit.edu/drl/wiki/index.php?title=Shady.

- Arab World Institute (Institut du Monde Arabe)

Arab World Institute (or referred to as IMA) in Paris, France houses one of the most well-known adaptive façades in modern architecture. This building was designed by architect Jean Nouvel in collaboration with Architecture-Studio, Pierre Soria and Gilbert Lezenes in 1987. Created as a destination devoted to the relationship of the Arab culture with France, the south facing façade is a modern interpretation of mashrabiya, similar to that of the Al Bahr Towers’ façade. The IMA façade is “the advanced responsive metallic brise soleil” and was well received for “its originality and its reinforcement of an archetypal element of Arabic architecture.” (Winstanley 2011)

As seen in figure 2.9 and 2.10, Jean Nouvel’s façade is comprised of series of camera shutter like mechanical apertures that can control how much light comes into the building. 240 mashrabiya shutters are all linked to a central computer that is set to perform a maximum of 18 movements a day. There are also photoelectric cells and mobile apertures that detect the amount of sunlight in order to control natural light. The façade mechanisms are in between two layers of glass. (Jones 2012) Unfortunately, the mechanism stopped working because some of the pieces were damaged and blocked the multiple apertures. According to the IMA website, there is currently an effort to renovate the project to fix the façade mechanism and potentially add LEDs for dynamic lighting display.
Figure 2.9. View of the IMA south facing façade from the inside. Image source: aedesign.wordpress.com/2009/08/29/arab-world-institute-paris-france/

Figure 2.10. Camera shutter like aperture of the IMA façade imarabe.org/en/architecture.
- Snapping Façades

Designed by Dioinno Architecture PLLC, Snapping Façades uses the elastic instability of materials to actuate their mechanism. The project is currently still in progress and has not been built. According to Dioinno Architecture, the façade uses a “snapping-induced motion” to open and close the fan-like shading and explored the idea of using the unstable movement associated with “weakening-induced bands tied within the elastic threshold which produce ‘snap’ deformation with minimal stimulus.” Normally, unstable movement is considered undesirable, however, in this project, the unstable elastic material allows them to move the fan-like shading without having continuous energy consuming mechanical actuators to operate. As seen in figure 2.11, a small rotational stimulus is enough to start the snapping motion which then carries out the rest of the deployment motion, using the embedded energy within the materials. Unlike the Al Bahr Towers and IMA façades, this project does not require complicated maintenance.

Figure 2.11. Demonstration of the Snapping Façade’s snapping motion. Image source: dioinno.com/Snapping-Facade.
Figure 2.12. Rendered image of how the Snapping Façade would be used in an indoor setting. Image source: bustler.net/news/tags/competition/326/5363/investigating-architecture-that-reacts-in-the-2016-laka-competition-the-winning-entries/competition-news.

2.4 Current Challenges

Despite the broad interest in adaptive façades in recent decades, there are still some remaining open issues to be addressed before this technology can be widespread. As shown in the list of precedents, the adaptive façades are either in development at high-tech laboratories in controlled settings or can only be built with extraordinary large budget. Also some adaptive cannot provide fine-grain daylight control as the actuated parts are linked together.
3. Methodology

3.1 Design Goals

To overcome the current downfalls of existing adaptive facades, this thesis aims to develop an adaptive façade system that meets the following goals:

1. Repeating small units that can be individually controlled
2. Using overall low cost materials and readily available parts
3. Easily replicable by anyone with access to a maker space
4. Using daylight simulation to determine each units’ position

3.2 Initial Ideas

- Idea #1: SMA (Shape Memory Alloy) Wires

Shape Memory Alloy (SMA) wires are metals that can change shape to its “memorized” form or contract in length when heated. For example, a stretched out SMA spring would return to its original spring shape when it is heated. One of the pre-trained form of SMA wires, called muscle wire, is commercially available. Because SMA wires are silent, lightweight and flexible, it can potentially replace traditional actuators such as servos and solenoids.

The project in the article Animating Paper using Shape Memory Alloys by Jie Qi and Leah Buechley from MIT Media Lab group “High-Low Tech” uses SMA wires to animate paper figures, such as making paper crane wings to flap as shown in figure 3.1. The article contains a link to a step-by-step tutorial on how to make one of their flapping paper cranes (http://highlowtech.org/?p=1448).

Figure 3.1. Paper crane with SMA wires sewn into its wings. As the SMA wires contract, the wings curl up, creating a flapping motion. Project designed by Jie Qi.
To recreate the flapping paper crane project designed by Jie Qi, I followed the tutorial as best as I can except for the SMA wire diameter. In the tutorial, they used 0.006” diameter wires, but the 0.006” diameter wires were out of stock on their manufacturer website. Instead I bought a 0.008” diameter wires as a substitute. My attempts at recreating the tutorial did not work out. There was no movement or contraction in the SMA wires. I thought this could be because the wire got burned out from soldering. One of the issues of using SMA wires, as Jie Qi stated in her MAKE magazine article, is that the wire can burn out and stop contracting if too much current or heat flows into the wire. Thus the wires could have overheated during the soldering process.

Instead, I used folded copper tapes as the medium to forgo the soldering process. However, even with eliminating the soldering process, the wire did not contract. It is likely that the wire did not contract because of the difference in the wire diameter. SMA wires have consistent resistance per length and the optimum current is usually provided in the manufacturer’s technical data sheet. Based on the technical data sheet from the SMA wire manufacturer shown in figure 3.2, wires with diameter of 0.006” have a resistance of 1.3 Ohms/inch, whereas wires with diameter of 0.008” have a resistance of 0.8”.

\[ \text{Voltage} = \text{Current} \times \text{Resistance} \]

Using the Ohm’s law shown above, the length of the wire necessary can be calculated to maintain the right amount of current based on the power supply or vice versa. Wires with diameter of 0.008” and length of 6.5” would have a resistance of 5.2 Ohms. Since there are two crane wings each with the 6.5” length of SMA wire connected in series, the total resistance of the circuit would be 10.4 Ohms, thus the circuit would need 870 milliamps. However, 9V batteries can provide between 400 to 600 milliamps, which is an insufficient amount of current for the SMA wire to contract. Even if I provided the right amount of current and voltage, these experiments showed that SMA wires are difficult to work with. Therefore, SMA wires are unreliable method for this thesis.

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<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
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<td>0.5</td>
<td>930</td>
<td>1000</td>
<td>1</td>
<td>5.5</td>
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<tr>
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<td>0.33</td>
<td>1250</td>
<td>1750</td>
<td>1</td>
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<tr>
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<td>13.0</td>
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<tr>
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<td>3562</td>
<td>4000</td>
<td>1</td>
<td>17.0</td>
<td>14.0</td>
</tr>
</tbody>
</table>

*Approximate* Current at Room Temperature (mA) and Contraction* Time (seconds) are based on manufacturer’s specifications.

**Off Time LT=70°C Wire** and **Off Time HT=90°C Wire** are based on manufacturer’s specifications.

Figure 3.2. SMA wire (muscle wire or flexinol wire) technical data sheet from https://www.robotshop.com/media/files/pdf/flexinol-technical-data.pdf.
- Idea #2: Thread and Fabric

Idea #2 was inspired by the curling motion similar to that of HygroScope. The curling motion can be mimicked by running a regular sewing thread through fabric. When the thread is pulled, the total length of the thread running through the fabric contracts, resulting in the fabric to curl. As seen in figure 3.3, I tried 5 different methods. The first attempt on the far left of figure 3.3 has no frame and results in an accordion fold when the thread is pulled. The second attempt has a 1/16” card stock frame with the paper grain perpendicular to the longer edge of the fabric. This resulted in a curling motion but required some force to maintain the curled state. Third attempt has the card stock frame similar to the second attempt, but the paper grain is parallel to the longer edge of the fabric. Because the grain direction is parallel along the longer edge, the card stock had significant resistant and did not curl. The fourth attempt has a steel wire running along the edge of the fabric and did not curl at all. The last attempt has a thin plastic sheet along the edge of the fabric and resulted in the easiest curling motion as seen in figure 3.4. Even though the thin plastic sheet curled easily with minimal force applied, I decided not to pursue this idea because managing multiple threads at the correct tension would be difficult.

Figure 3.3. Thread and fabric idea.

Figure 3.4. Curling attempt number 5 by pulling the thread.
- **Idea #3: Umbrella**

This idea came to me when my umbrella was upturned in a storm. As seen in figure 3.5, four "fingers" of the umbrella shape is attached to a central location, connected by a thread. When the thread is pulled, the fingers pivot and resume an upturned umbrella shape. I did not pursue this idea because it relied on gravity for the upturned umbrella shape to fold back to its original position.

![Figure 3.5](image)

*Figure 3.5. Idea #3 mimicking an upturned umbrella shape. Left side image is when the umbrella is stationary. Right side image is when the central thread is pulled along the direction of the arrow, "upturning" the umbrella shape.*

- **Idea #4: Folding Fan**

Similar to Shady, this idea was inspired from an Asian folding fan similar to the one seen in figure 3.6. The fingers or the wooden strips of the fan are connected either by paper or fabric so that rotating one finger would result in the rest following along. However, unlike Shady, I explored havings multiple fans connected in the center because that would reduce the rotational angle necessary for the fans to cover a full circle. The first prototype of the folding fan idea can be seen in figure 3.7. I decided to proceed with the folding fan idea because of its simplistic rotational actuation motion.
3.3 Iterative Prototypes

- First Iteration

As seen in figure 3.7, the first prototype of the Folding Fan Façade was made of two card stock cross shapes joined in the center using a paper fasenter. The fingers of the cross shapes were connected by a piece of paper fin folded in an accordion fold. There weren't any other fingers supporting the paper fin besides the two fingers from the cross shapes, so the fin sagged when the cross shapes were aligned. I also tested two different methods of attaching the fin to the fingers: the fin sitting flat against the fingers and the fin sitting perpendicular to the fingers. The fin sitting perpendicular to the fingers resulted in complication as the fins would block the fingers from stacking neatly on top of one another.
- Second Iteration

For the second iteration prototype, I focused on the overall shape of the fan unit. Instead of having a cross shape that would require four fins, I used a Y shape that would only require three fins as shown in figure 3.8. By using the Y shape fingers, I was able to make the overall frame into a hexagon. I chose to use hexagonal frame because hexagons tessellate easily into a honeycomb pattern. Also I used muslin instead of paper for the fins, 1/16” museum board for the fingers and a bent wire for the center pivot axle. I used a spray on starch to stiffen the muslin fabric and ironed it to have folded panels. I added a second Y shape finger so that the fins would have more support and guide when they are being folded. However, I realized that the fins would still not stack neatly when the fingers were aligned.

Figure 3.8. Second iteration prototype made with muslin for fins, museum board for fingers and frame, and wire for the center pivot.

After analyzing a traditional folding fan, I realized that the fins have to have odd number of folding panels and every other panel needs to be supported by a finger. When the fan is folded, the panel that does not have a supporting finger flips over, or the normal vector to the surface points in the opposite direction. As seen in the illustration in figure 3.9, the shaded panel represents the panel that gets flipped over. Because the direction of the panel changes, it cannot have a finger glued to the panel. Therefore, there needs to be an alternating fin panels that have a finger support and panels that does not in order for the fan to properly close. Additionally, the first and the last panel has to be supported by a finger so that there aren’t any unsupported fin panels on the outer edges of the fan.
Thrid Iteration

With the second iteration in mind, the third iteration prototype had odd number of panels on the fins as well as more number of Y shape fingers for support. There were total of seven panels on each of the fins and two Y shape fingers between the main outer finger and the frame. With these changes, the fan was able to fold nicely as the fin panels stacked on top of each other as seen in figure 3.10a.

Figure 3.10a. Third iteration prototype with odd number of fin panels and more in between supporting fingers. When the fan is folded, the fin panels stack neatly on top of each other.
Figure 3.10b. Third iteration prototype when it is fully deployed. The fins had different laser cut perforation to test varying dashed line width.

Also for the third iteration prototype, I tested out different perforation dashed line width that divided the fins into panels. The fins were laser cut as well as the perforations. There wasn’t a significant difference between the varying perforation dashed line width in terms of folding performance. However, the longer perforation dashed lines were more visible than the shorter lines causing unwanted distractions. Thus, I decided to keep the shorter perforation dashed lines to have a cleaner and less distracting fins.

- Forth Iteration

For the forth iteration prototypes, I explored different types of fabric and materials for the fins. Except for the first iteration prototype, the previous prototypes used thin muslin fabric for the fins. I made three prototypes to test out different types of materials: thicker muslin fabric and two sheets of Mylar with different thicknesses.

One of the prototypes’ fins were made with thicker muslin than the muslin used in previous iterations. This resulted in stiffer fins; however, I still applied spray-on starch to add even more rigidity. However, because the muslin is thicker and coarser, the laser cut edges frayed when it came in contact with the starch. To prevent fraying, a layer of Tacky Glue was added to the edges. The thicker muslin fins provided more structural integrity to the fins and also caused the folding fans to “snap” into place as if it was spring loaded. The snapping phenomenon may be due to the stiffness of the material.
I wanted to try even more rigid material than the thick muslin, so I tried using 0.003” and 0.005” thick Mylar sheets. However, neither of the Mylar sheets were flexible enough to flip over (as mentioned in figure 3.9), making it impossible for the fan to close. This defeats the purpose of the fan shape, so the idea of using Mylar or other plastic sheets for the fin was abandoned.
- Fifth Iteration

For the fifth iteration prototype, I focused on actuating the fan. Before I actuated the fan, I wanted to make a prototype that would be as close to the dimensions of the final prototype. In order to estimate the necessary dimensions, I measured the size of the window that the fan façade would fit into. The window was roughly 39" by 60". Based on that measurement, I laid out a series of hexagons in a honeycomb manner as seen in figure 3.13.

![Figure 3.13. Rough estimate on the layout of the hexagons for a window of 39" x 60" (3'3" x 5')](image)

From the rough estimate layout, I extracted one unit as seen in figure 3.14 to test out the actuation method. I used a standard servo to actuate the prototype simply because I had the servo on hand. The servo horn was attached to the front most finger since only rotating the front most finger would result in the fan deploying as the different sheets of fingers are connected by the fabric fins.
In the sixth iteration prototype, I refined the design of the fifth iteration prototype. In order to have larger open surface areas, the hexagons were scaled up until the distance between the two hexagons would be just enough for the fingers to not touch each other. Also the sharp corners and the center of the hexagon were rounded out as seen in figure 3.15 so that the materials would not easily break off.

The center of the hexagon was turned into a curved triangular shape to keep the symmetry of the design. Also the minimum distance between the outer edge of the triangular shape and the rectangular hole where the servo sits had to be at least 0.25" wide so that the sheet material for the façade wouldn’t break off during CNC milling. However, I was able to make the
rectangular hole smaller by using a micro servo instead of a standard servo. A standard servo can generate around 3.2 kg-cm of torque at 5V. Because the fingers and fins are made of light materials, not a lot of force is required to rotate them. 3.2 kg-cm of torque is more than what is necessary, so a micro servo that can generate 1.6 kg-cm of torque at 5V is powerful enough to rotate the fans. A micro servo is much smaller than a standard servo, so the center of the hexagon can be reduced to allow a larger opening area.

**Figure 3.15** Sixth Iteration prototype layout. The corners of the hexagon and the center of the hexagon are rounded out.

The fins of the fan were modified so that the overall shape of the fan would create a circle slightly bigger than the hexagon below as shown in Figure 3.16. This decision was made because the angled fins would easily get stuck underneath the corners of the hexagon openings. Also the contrast of circular shape to hexagonal shape is aesthetically pleasing. The order of assembly for a single fan unit is shown in figure 3.17 and 3.18. The fins are attached to the fingers and the façade front surface in a cascading manner as shown in figure 3.20.
Figure 3.16. Single fan unit of the façade. Top: When the fan is closed. Bottom: When the fan is opened. This particular version is light sensor triggered.
Figure 3.17. Exploded view of one fan unit. Screws used for assembly are included in the Servo package.
Figure 3.18. Assembled view of one fan unit. Cylindrical holes are for the screws.

Figure 3.19. Photo of a micro-servo (Tower Pro SG92R) affixed to the back side of the façade surface with screws that were included in the servo packaging.
Figure 3.20. Locations where the fin is glued to the fingers and the façade surface. Repeat this for the rest of the fins.

- Final Iteration

The main goal of the final iteration was to create the overall façade surface and assemble the fans onto the surface. Because there are a lot of imperfections in the window construction, I had to take multiple measurements of the window. I measured the window in five different spots for each width and height to get the smallest measurement as shown in figure 3.21. The smallest distance would be the measurement for the façade surface because the façade would not fit if the façade surface is larger than the smallest window distance measured. Thus the measurements for the façade has to be 38.88” by 59.88”. The depth of the façade was chosen as 4” because of the depth of the windowsill.
Figure 3.21. Varying dimensions of the window opening.

With these measurements, I rescaled the hexagon openings so that the smallest width on the sheet would be no less than .25". I chose .25" thick marine grade Meranti plywood as my façade surface material because of its durability, affordability and good quality. The plywood comes in 4' by 8' size sheet which was then CNC milled as shown in figure 3.22. Then the leftover plywood piece was cut down into 4" wide strips to form the sides of the façade. The sides were glued on to the surface instead of using nails or stables because the plywood is thin and the nails or stables would protrude out if they stray from the center. The gluing process can be seen in figure 3.23. Once the overall façade was assembled, it was placed in the window to see if it would fit. The façade easily slid into the window opening as shown in figure 3.24. Once the body of the façade was assembled, I cut out the open areas of the hexagons and sanded down the jagged edges. 1/16" thick white museum boards were laser cut to make the fingers as seen in figure 3.25.
Figure 3.22. Façade front face surface cut on a CNC mill. The hexagonal openings were still attached to the plywood by a very thin layer. This was done so that pieces of the plywood would not move around during the cutting process. The pieces can be easily removed with a knife.

Figure 3.23. The 4" wide strips cut down to the width and height of the front face surface of the façade are being glued down.
Figure 3.24. Assembled Façade body fit into the window.

Figure 3.25. Laser cutting the fingers.
The fins were laser cut out of white cotton canvas fabric. Lines were perforated on the fins to help with folding at proper locations. Once the fabric was cut, the fins were treated with spray on starch, then folded and ironed to make the creases, and lastly the outer edges were glued to prevent fraying. After all the necessary parts were cut, I assembled the façade as described earlier in figure 3.17, 3.18 and 3.20.

Figure 3.26. Fins in three different states. Left: laser cut fins with no treatments. Center: starched, folded and creased with ironing. Right: Tacky glue applied to the outer perimeter of the fins to prevent fraying.
Figure 3.27a. Folding Fan Façade assembly process. Fingers and servos added. A cross of two strips of scrap wood was temporarily added to the back of the façade to help prevent warping. This can be taken off for when the façade is fitted into the window.

Figure 3.27b. Folding Fan Façade assembly process. Fins being added to the fingers.
3.4 Electrical Connections

- Circuit Schematic diagram

Figure 3.28 Circuit Schematic diagram with Arduino MEGA microcontroller, 13 micro-servos, and an external power supply.
- Circuit Specifications

One of the most important parts of the circuit is to figure out the servo connections and the type of external power supply. Each servo needs 5V to operate, meaning that the servos need to be connected in parallel. Since I’m using micro-servos, they draw about .5Amps each, resulting in a total of 6.5Amps for 13 servos. Therefore, I had to buy an external power supply or power adapter that can generate 5V and over 6.5Amps. I used Alitove 5v 10Amp AC to DC power supply adapter converter charger.

The power supply adapter should not connect directly to the Arduino MEGA microcontroller since Arduino boards are generally designed to handle only up to .8Amps. Instead, the servos need to be directly connected to the power supply adapter while only having ground connected to the microcontroller. Each servo connects to a digital output pin of the microcontroller to receive signals. The microcontroller is then powered by connecting to a computer using a USB wire.

3.5 Software Use and Programming Logic

Using Rhino, I created a 3D model of the McCormick Hall and the correct position of the chosen window on the building. DIVA (a Rhino Grasshopper plug-in) was used to simulate the sun path, which then simulated the illuminance of the vertical window surface at a given time. Then I used Firefly (another Rhino Grasshopper plug-in) as a bridge between Rhino Grasshopper and the Arduino microcontroller. By using Firefly, the microcontroller can receive signals real-time over the USB connection.

DIVA plug-in takes in inputs of location, date, time, and sky condition to simulate the sun path and the level of illuminance on a surface. Normally, horizontal surfaces are used to determine illuminance for the floor area of the indoor space. However, because the façade sits on a vertical plane, vertical surface was used as the illuminance grid surface. The illuminance value on a vertical surface is much higher than what would be for a horizontal surface because vertical surfaces get direct sunlight which can be over 100,000 lux, whereas horizontal surfaces are influenced more by secondary bounce-off light.

Using the vertical surface this resulted in a lux levels that ranged from 0 to greater than 10,000 lux. Therefore, I had to estimate what that would translate to on a horizontal surface and set an arbitrary limit to when the fans should be deployed. When the illuminance level was lower than 4,000 lux, the fans would be closed to let light in. When the illuminance level was between 4,000 lux and 8,000 lux, the fans would be open half way to let some amount of light in. If the illuminance level was greater than 8,000 lux, the fans would open fully to block the direct sunlight. This cut off thresholds can be adjusted based on individual preference. The overall logic behind the Grasshopper code is shown in figure 3.30.
Figure 3.29. Overall representation of connections between computer software (Rhino, Grasshopper, DIVA, Firefly) and hardware (Arduino MEGA, 13 servos, power supply).
Figure 3.30. Logic behind the sunlight simulation and how to determine which fans open when and to what position.
4. Results

4.1 Folding Fan Façade

Figure 4.1a. Folding Fan Façade fitted into the window. Finished result of the final iteration prototype.
4.2 Time lapse

I filmed the façade in action on 5/13/18 in Boston with a window facing south-east. It was recorded from 5:30am to 3:30pm. The left side of figure 4.2 shows the DIVA generated illuminance grid representing the amount of light coming through the window. The color changes from blue, yellow, and red to represent the increasing levels of illuminance. The positions of the fans were updated every 10 minutes.
Figure 4.2a. Time lapse of the façade in action. Left grid represents the amount of light coming into the window simulated using DIVA. 5:30am on 5/13/18 in Boston facing south-east.

Figure 4.2b. 6:30am on 5/13/18 in Boston facing south-east.
Figure 4.2c. 8:30am on 5/13/18 in Boston facing south-east

Figure 4.2d. 10:10am on 5/13/18 in Boston facing south-east
Figure 4.2e. 12:30pm on 5/13/18 in Boston facing south-east

Figure 4.2b. 3pm on 5/13/18 in Boston facing south-east
4.3 Rough Calculations

One of the main concerns about designing an adaptive façade is the amount of energy that is required to operate the façade. For the Folding Fan Façade, each of the thirteen servos requires .5Amps and 5V to operate. Using the equation shown below, the façade uses a total of 32.5W at its peak energy use. The lowest standard incandescent light bulbs use 40W.

\[ \text{Power [Watt]} = \text{Voltage} \times \text{Current} \]

Although it may not seem like a big difference in wattage, light bulbs are kept on over a long period of time, whereas the façade only needs short amount of power every few minutes to operate all of the servos at once. If the façade requires about 30 seconds to change the fan positions every 10 minutes for 12 hours, then the total amount of operating time for the façade in a day is 0.6 hours or 36 minutes. Using Boston’s average cost for electricity (22.5 cents per kilowatt hour), the façade operation would cost $0.004 for a day with 12 hours of daylight. On the other hand, if a 40W incandescent light bulb is on for 12 hours, it would cost $0.11.

\[ \text{Total hours} = \frac{30 \text{ seconds}}{10 \text{ minutes}} \times 12 \text{ hours} \]

These numbers are a very rough estimates and can be different depending on the situation, but this shows how the façade could lower the amount of energy use.
5. Conclusion

5.1 Summary of Contributions:

The ultimate goal of this research is to design and prototype a working adaptive façade. The façade prototype is a proof of concept of a larger idea that can be pursued beyond the scope of this thesis. The Folding Fan Façade is designed and created with low cost materials, costing less than $400 to make. This accessibility allows anyone with access to a maker space can create their own façade.

5.2 Potential Impact

Though this thesis has focused on creating a window size façade to demonstrate the concept of the Folding Fan Façade, this design can be easily scaled up or down to fit into any window size as seen in figure 5.1. This façade could potentially help reduce the amount of energy consumed in a building by help reducing the use of artificial lights during day time.

Figure 5.1. Conceptual drawing of Folding Fan Façades fitted into office window wall setting.
5.3 Future Work:

There are several ways to optimize and improve the Folding Fan Façade in the future. These include, among many others:

1. Currently, there is no mechanism to cut off power between the times when the façade changes in position. For example, if the façade position is updated every 10 minutes, there is no need to have power running through the façade during the 10 minutes when the servos are only on hold. For the time lapse, I had to manually disconnected power from the façade. Automating the power regulation would be a great addition to this façade since it would save the amount of energy being used and prolong the servo lifespan.

2. When the servos are on, they have a tendency to create a humming or buzzing noise due to the nature of how servos work. This sound may be distracting to some occupants in the room. Using better quality servos may help reduce the humming noise or exploring the use of stepper motors may resolve this issue.

3. For this thesis, I used Arduino MEGA microcontroller and Firefly to communicate between my computer and the microcontroller. I’ve noticed that Firefly has tendencies to send incorrect signals to the servos. With the use of other programming software and different type of microcontroller could potentially help with sending proper servo positions signals.

4. Varying the sizes of the single fan units can help with the façade layout so that there are no “dead” spaces.

5. Instead of relying on a large single sheet of plywood for the façade surface, modularizing the individual fan units that can be assembled together could help bring down the cost of the façade and have greater freedom in layout design.

6. Exploring the use of light sensors for each fan units would help automate the façade instead of relying on a daylight simulation. Light sensors would be able to detect shadows cast by nearby buildings or obstacles and change the fan positions more accurately for its surroundings.

7. Developing a user friendly interface, such as a phone app or a touch screen device, to control the positions of the fans can help accommodate for occupant uses and needs. For example, if the occupant needs more light, they could manually set different positons for the fans or change the Lux cutoff threshold.
5.4 Closing Thoughts:

With an ever increasing interest in energy efficient buildings, adaptive façades are an important topic to explore. Building façades can be a critical factor to energy performance by providing thermal shield and help regulate the amount of indoor daylight. However, static building façades cannot accommodate for the outside environmental changes such as the changing direction of the sun and the amount of the sunlight. This can be addressed by the use of adaptive façades because they have the capability to change in real time according to the outdoor conditions.

The current existing adaptive façades are either considered as a luxury equipment or still in development in high-tech laboratory settings. Through this thesis, I wanted to design and fabricate an affordable adaptive façade that can easily be replicated by someone with an access to a maker space. I used plywood, fabric, museum board, and servos to create a working proof-of-concept of the Folding Fan Façade prototype. Because of the simplicity behind the actuation mechanism, the façade is easily scalable for different needs. Also rough calculations showed that the façade requires much less energy to operate than having artificial light on constantly.

This research has shown that affordable adaptive façades can be developed and easily fabricated. There is much more research to be done to optimize and refine the design, but in the future, adaptive façades can become a key factor to buildings of all types.
References


Appendix A: Luminous Intensity, Luminance, Illuminance

Luminous Flux:
Luminous flux is a measurement of the perceived brightness or power of a light source. The unit for luminous flux is lumens; light source is perceived as brighter for higher the lumen value. Often times, wattage is incorrectly used in place of lumens. Wattage or watts are a measurement of electrical power consumption of a lamp or a light bulb. For example, a 60W incandescent light bulb, 14W modern compact fluorescent lamp (CFL), and 10W light emitting diode (LED) bulb may emit the same luminous flux around 750 lumen, which is why manufacturers indicate on their product package that it “delivers the same output as a 60W incandescent light bulb.” Instead of luminous flux, luminous efficacy is a more direct way of comparing different light sources. Luminous efficacy is the amount of lumens produced for each watt of electrical power or overall radiation in the case of daylight, measuring how well a light source produces visible light. Daylight luminous efficacy can vary from 107 lumen/watt for direct sunlight and 144 lumen/watt for diffused daylight (Reinhart 2014).

Luminous Intensity:
Luminous intensity describes the power emitted by a light source in a particular direction, or the spatial distribution of light. The luminous intensity can be expressed in equation as seen below.

\[
\text{Luminous Intensity} \ [\text{candela}] = \frac{\text{Luminous Flux} \ [\text{lumen}]}{\text{Solid Angle Steradian}}
\]

1 Candela is the uniform luminous intensity that a common wax candle emits, which is the candle’s luminous flux summed over all angles of a sphere (4π steradian), equaling 4π lumen. Luminous flux and luminous intensity are quantities that can be used to describe the amount of light emitted by a light source.

Luminance:
Luminance is “the photometric quantity used to describe the light reflected off or transmitted through a surface in various directions, measuring the luminous intensity per surface area.” (Reinhart 2014)

\[
\text{Luminance} \ [\text{luminance}] = \frac{\text{Luminous intensity} \ [\text{candela}]}{\text{Area} \ [m^2]}
\]

The luminance caused by a point light source, such as the common wax candle, in the eye of a nearby person depends on the relative distance of the light source to the person as well as obstacles that change the light distribution within the person’s field of view. Even when the point light source is emitting a constant luminous intensity over time, luminance decreases as the nearby person moves away from the point light source since the density of photons from the light source entering the surface area of the eye decrease. However, for a collimated light
source, such as the sun, the luminance will not decrease with distance from the light source since collimated light source emits parallel light beams instead of radial light beams that a point source would emit. Therefore, the sun’s ray as seen from earth can be assumed to be constant and parallel.