LEAF (LOW ENERGY ADAPTIVE FAÇADE)

Self-adapting micro shading façade design using responsive polymer sheets

Jin Young Song
Department of Architecture
University at Buffalo
jysong@gmail.com

Haiqing Lin
Department of Chemical and Biological Engineering
University at Buffalo
haiqingl@buffalo.edu

Jongmin Shim
Department of Civil, Structural and Environmental Engineering
University at Buffalo
jshim@buffalo.edu

ABSTRACT

In a mission of producing energy-efficient buildings, building enclosures play a critical role by controlling heat gain, natural lighting, and maintaining visual comfort. All windows and glass walls have shadings and blinds to control heat gain and glare problem. However, human hands are unreliable, and recent dynamic shading systems based on mechanical hinges are expensive and consume additional energy. The Low Energy Adaptive Facade (LEAF) integrates a photochemical responsive polymer sheet into building facades through an origami inspired folding pattern. It aims to emulate the diffuse, dappled light quality created by deciduous trees in the summertime by sensitively responding to daylighting conditions. LEAF achieves the integration between the shape changing polymer sheets and parametric design for sustainability and artistry through building envelope design. The basic principle is to fabricate surface using laminated films consisting of a bilayer system: a light responsive layer and a non-responsive layer. The surface can be designed to contract during the light irradiation. This mechanism enables development of hinges that can reversibly fold with the control of mountain and valley assignments. LEAF suggests the specific folding pattern for its geometric efficiency and folding mechanism. This design frees the burden of complex construction and maintenance of mechanical dynamic façades, while it allows diffused shading with millimeter-scale panel folds, just like sunshine through leaves. This scale factor can also specifically respond to the problem of glare. The module size can be very small and LEAF's bi-directional shrinking capability also maximizes the diffusing quality. Lastly, this method can be applied to mass production of dynamic façade systems with relatively low material cost and a high degree of design flexibility. Established on well-known route of polymer synthesis, LEAF addresses the building envelope application using photochemical reaction of polymer sheets, integrating photochemical phenomenon and parametric design.

ABSTRACT

친환경 건축에 있어서 건물의 외피는 실내 온도를 유지하고 자연광을 조절하며 밖을 볼수 있게 해주는 등 중요한 역할을 하고 있다. 그래서 대부분의 유리로된 창문과 벽은 커튼, 블라인드, 차양등을 내, 외부에 설치해서 열을 차단하고 눈부심 현상을 방지하는데 손으로 조절하는 장치들은 효율적이지 않고 기계적인 모터를 이용한 장치들은 비싸고 추가적인 에너지를 필요로한다. 이에 대해 리프(LEAF, Low Energy Adaptive Façade)는 광화학적인 반응을 하는 폴리머 시트를 오리가미의 접기방식을 응용해서 건물의 입면에 적용하는 친환경적인 쉐이딩 장치이다. 형태가 변하는 폴리머 시트의 특성과 패러매트릭 다자인을 통합함으로 친환경적이면서도 미적인 건물 입면을 구현할 수 있다. 빛에 반응하는 레이어와 반응하지 않는 두 레이어로 구성된 폴리머 시트는 빛에 노출되면 한쪽 면이 수축됨으로 인해서 접히는 현상이 발생하는데 리프(LEAF)는 이를 이용해서 건물 입면에 최적화된 기하학적으로 효율적인 접기방식을 도출한다. 이는 기존의 복잡한 기계식 입면 쉐이딩 보다 적은 비용으로 만들수 있고 에너지 효율적이며 관리가 쉬운 장점이 있다. 또한 밀리미터 스케일의 작은 크기로 만들수 있기

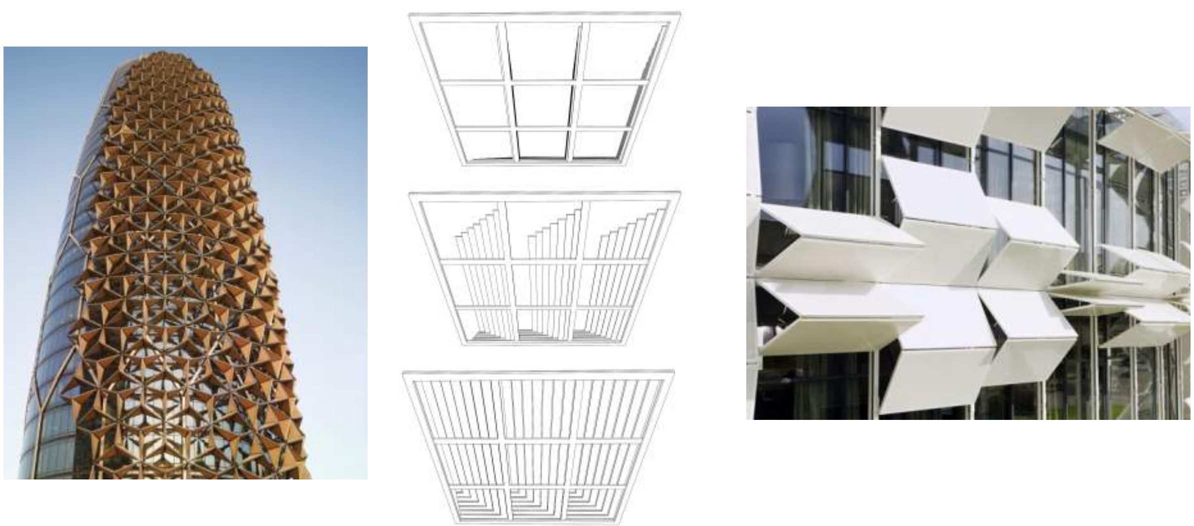
때문에 빛을 산란시킴을 통해 눈부심 현상에 효율적이며, 상대적으로 대량생산이 용이하다. 리프는 기존의 증명된 폴리머 관련 연구 성과를 통해서 광화학 작용과 패러매트릭 디자인 방법을 통합하는 건물 입면에 응용할수 있는 방법을 제안한다.

KEYWORDS

Adaptive-kinetic-dynamic, Polymers, Adaptability, Computational design, Shading, Self-folding, Aesthetics, Origami

SUSTAINABILITY AND BUILDING ENVELOPE

In the United States, buildings account for 41 % of energy use and 38 % CO_2 emission. According to U.S. Department of Energy, green buildings (designed to achieve sustainability rating) consume 25 % less energy, have 19 % lower maintenance costs and produce 34 % lower greenhouse gas emissions. Along with this great mission regarding the energy performance, in recent decades, the power of digital technology became pervasive in the building industry. Manufacturing techniques using parametric tools and robotics have opened up new ways of delivering projects. In these contexts, the design and construction of the building façade provide a direct and convenient platform for the experiments to respond to the need of energy efficient building. Recently, there are successful dynamic envelope systems developed to address this concern. Glass buildings have a mechanical folding system to shade the building (Figure 1a and 1c). Mechanical shifting and overlapping creates a ceiling shade in Abu-Dhabi (Figure 1b). In these examples, the building façade design becomes the major element embodying socio-cultural aspect of the city, client or program on top of the mission of sustainability. Despite the limitation of the mechanical actuated system such as high cost, additional energy consumption and maintenance, mechanical innovation presented in these pioneer works will continue to emphasize the role of façade design.



(a) (b) (c)

Figure 1. Built dynamic façade systems actuated by mechanical hinges/motors. (a) Abu-Dhabi Investment Council Headquarters (Photo courtesy of AHR Architects), (b) Dynamic shading at Aldar Central Market by Foster + Partners, Hoberman Associates and Adaptive Building Initiative (Diagram by author), (c) Kiefer Technic Showroom (Photo courtesy of Giselbrecht+Partner).

Advances in material science and engineering have also contributed to the mission of smarter building envelope. For instance, electrochromic glass (electronically tintable glass) uses voltage to change light transmission property (Figure 2a). Other Smart glass such as Suspended Particle Devices provides the same function (Figure 2b). Another great example is a form-changing polymer developed by Elliott Schlam of New Visual Media Group. A thin polymer sheet is wrapped and installed in the glazing unit and it rolls out to provide shading (Schlam et. al., 2014) (Figure 2c). Compared to the mechanical dynamic shading, these glass systems can efficiently provide substantial energy saving with low cost, though the façade design becomes independent gear added to the irrelevant building design.

(a) (b) (c)

Figure 2: Commercially available dynamic façade systems actuated by electro-field control. (a) Electrochromic glass by Sage Glass (Photo courtesy of Jeffrey Totaro, 2015), (b) Switchable Smartglass (Suspended Particle Devices), Photo courtesy of Smart Glass International), (c) Dynamic window by Elliott Schlam, New Visual Media Group, LLC. Photo courtesy of New Visual Media Group.

All of these cases with mechanical actuation (Figure 1) and electric actuation (Figure 2) focus on shifting the state between an opened (bright) and a closed (dark) condition providing the function of shading. However, LEAF (Low Energy Adaptive Facade) focuses on the material property of polymeric sheets and the nature of actuation (heat, light or both), which mimics the nature's subtle change in illumination and color from the sun. By designing the photochemically actuated motion with parametric folding pattern, the self-shading system based on origami and self-folding polymer sheets pursues not only a low energy actuation but also the sensation of diffused light quality smoothly responding to daylighting just like we see deciduous vegetation shade as shown in Figure 3.

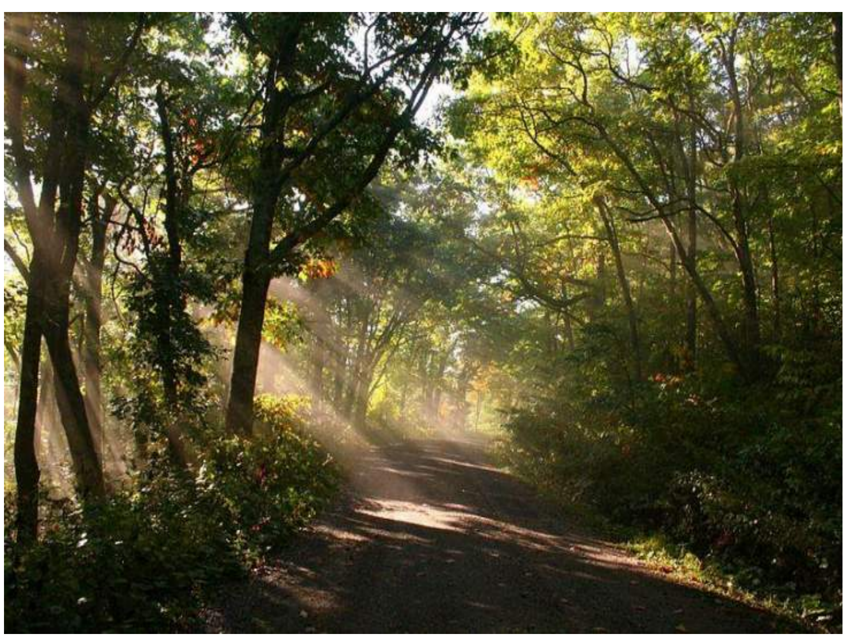


Figure 3: Shading from vegetation (Photo courtesy of Creative Commons Attribution-Share Alike 3.0 United States license.)

APPLICATION OF POLYMER SHEETS TO BUILDING FAÇADE

There is significant amount of research exploring folding or bending mechanism converting a 2-dimenional polymer sheet into a 3-dimensional shape. Thermal expansion in a bi-layer polymer sheet actuated by heat provides self-folding mechanism (Stoychev et. al., 2015). In a hydrogel, thermal actuation can program reversible origami (Na et. al., 2015). Using halftone gel lithography, the surface can generate patterned swelling, producing complex curvature (Kim et. al., 2012). Similar to the electroactive polymer which can change the form controlled by electricity shown in Fig 2c, light can actuate the shape change. Azobenzene Liquid-Crystalline can make the sheet bend responding to light exposure (Ikedaet.al., 2003). The shape programming of polymeric materials gives a great potential to building envelop applications for the following reasons. (1) Polymer sheets can be mass-produced with a relatively low cost. (2) The manufacturing process can be also simple and inexpensive due to various patterning techniques such as inkjet printing and screen printing. (3) The products can be applied to existing glass walls by simple attachment behind the façade layers. On the other hand, there are several challenges to commercialize this idea into the building envelopes. (1) Reversibility: some heat actuated polymers are not reversible. (2) Scalability (micrometer to millimeter scale): small scale must provide the functionality to the building scale. (3) Sensitivity (actuation at room temperature). Actuation in an elevated temperature makes it less applicable to the building temperature condition. Therefore, the design speculation of LEAF relies on azobenzene based polymeric materials which triggered by light (Fig 4). At the R/D level, the data show reversibility and successful movement at millimeter scale at the range of room temperature. Same speculation can be applied to hydrogel with heat actuation, containing water in the interlayer of the glass. It is also reasonable to expect further development in this technique will allow centimeter scale of operation with low cost. LEAF speculates the function of patterns, the parametric folding mechanism with the unique materiality toward leaves like shading solution.

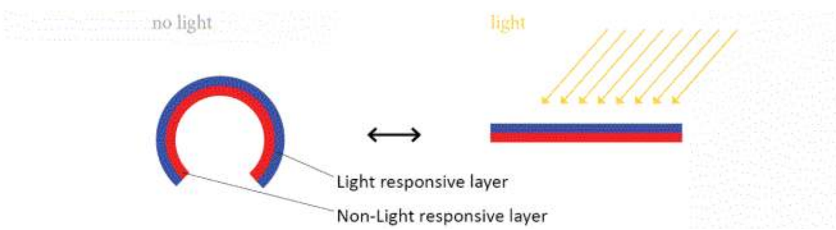


Figure 4: A schematic illustration of bending mechanism of crosslinked liquid-crystalline polymer and polyethylene bilayer films actuated by natural light (Cheng et. al., 2010).

DESIGN SPECULATION

Cheng has created hinge conditions (Fig 4) with arm, wrist and handle to bend with only light actuation. This light driven plastic micro-robot successfully demonstrated picking, lifting, moving, and placing the object in vertical and horizontal directions (Cheng et. al., 2010). To obtain the self-shading device based on origami, this daylight responsive polymer sheet of crosslinked liquid-crystalline polymers (CLCPs) provides a great potential to use natural light. Figure 5 represents the operational principle of the polymer sheet folding. Stress is developed to bilayer films from crosslinked liquid-crystalline polymer and polyethylene during the light irradiation to the polymer sheet bonded to thin stiff polymer layers. It allows the creation of hinges that can reversibly fold with control of mountain and valley assignments. This approach can provides complex folding patterns in small scales by creating mountain and valley edges in both sides with programmed folding angles based on the manufacturing property of CLCPs. This method can be applied to the mass production using a relatively inexpensive material with design flexibility.

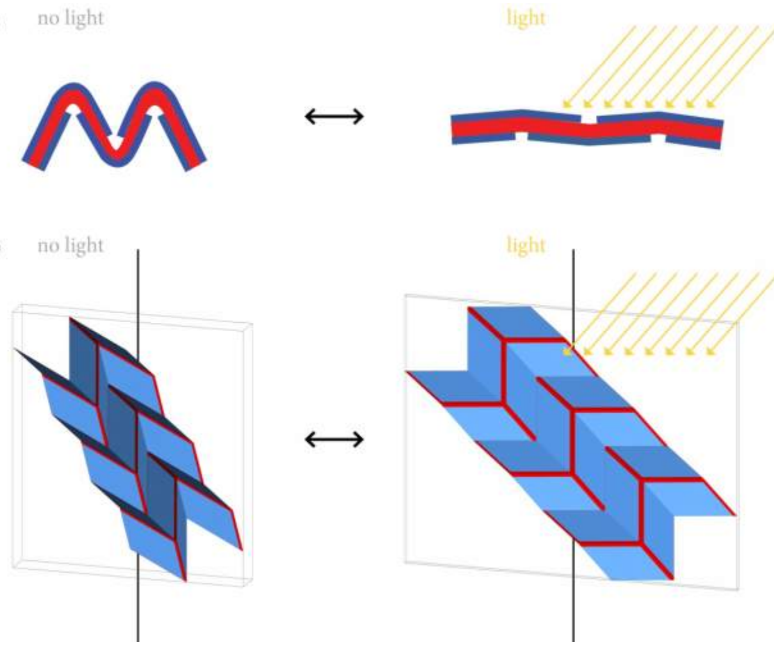


Figure 5 (a) Schematic illustration of polymer sheet folding. Blue represents stiff polymer layer which is non-responsive to light, red represents light responsive polymer film layer. When there is no light, it is folded to minimize the surface. When there is light, the photo chemical process makes it unfold to enlarge the surface. ***(b)*** *3D diagram of the LEAF's schematic film structure based on Miura-ori.*

This strategy must be for the glazing units with an efficient folding mechanism. The minimum depth with the maximum shading area is desired. Therefore, the well-studied Miura-ori (see Fig. 6), which ideally behaves as a compressible sheet with a negative in-plane Poisson's ratio. It allows us to make L/D (Length of the module / Depth of the module) value maximum. Here, D is associated with the cost and difficulty of building envelope construction while L is relating to the shading capacity. Geometrically, every folding angle of Miura-ori can be created with plane angle S, while unit plane has two vertices and each vertex consists of three mountain and one valley creases (or vice-versa) as shown in Fig 6. Since Miura-ori structure has negative in-plane Poisson's ratio, both L1 and L2 decreases while D increases during the folding process. Fig 7 presents the physical simulation of Miura folding using Shape Memory Polymer actuated by heat. Attaching the strip on either front or back side, simple hinge formation programed with folded and unfolded by temperature change defines either mountain or valley.

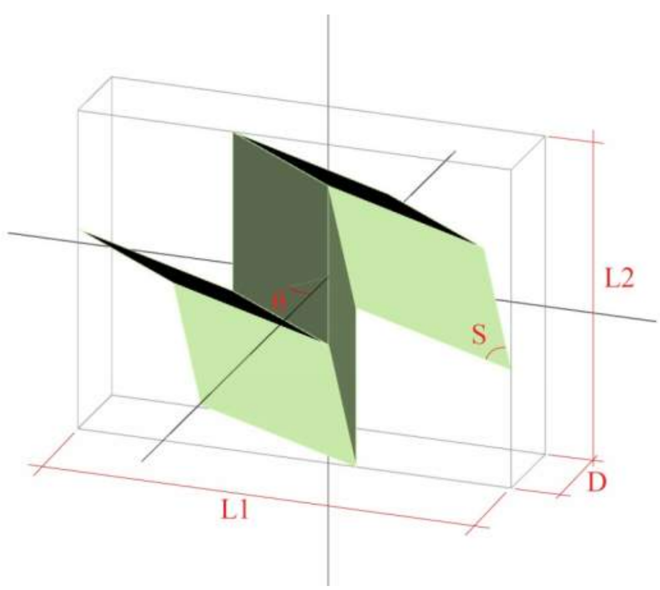


Figure 6: Schematic simulation of Origami folding. D= depth of the module, L1=horizontal length of the module. L2= vertical length of the module.

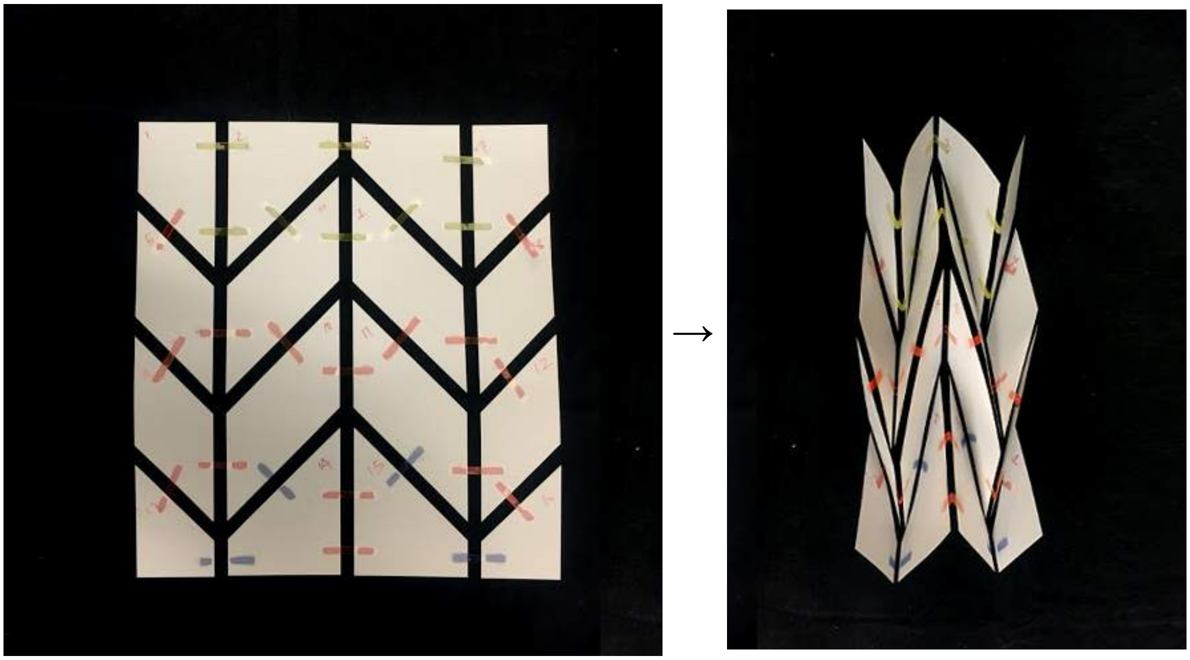
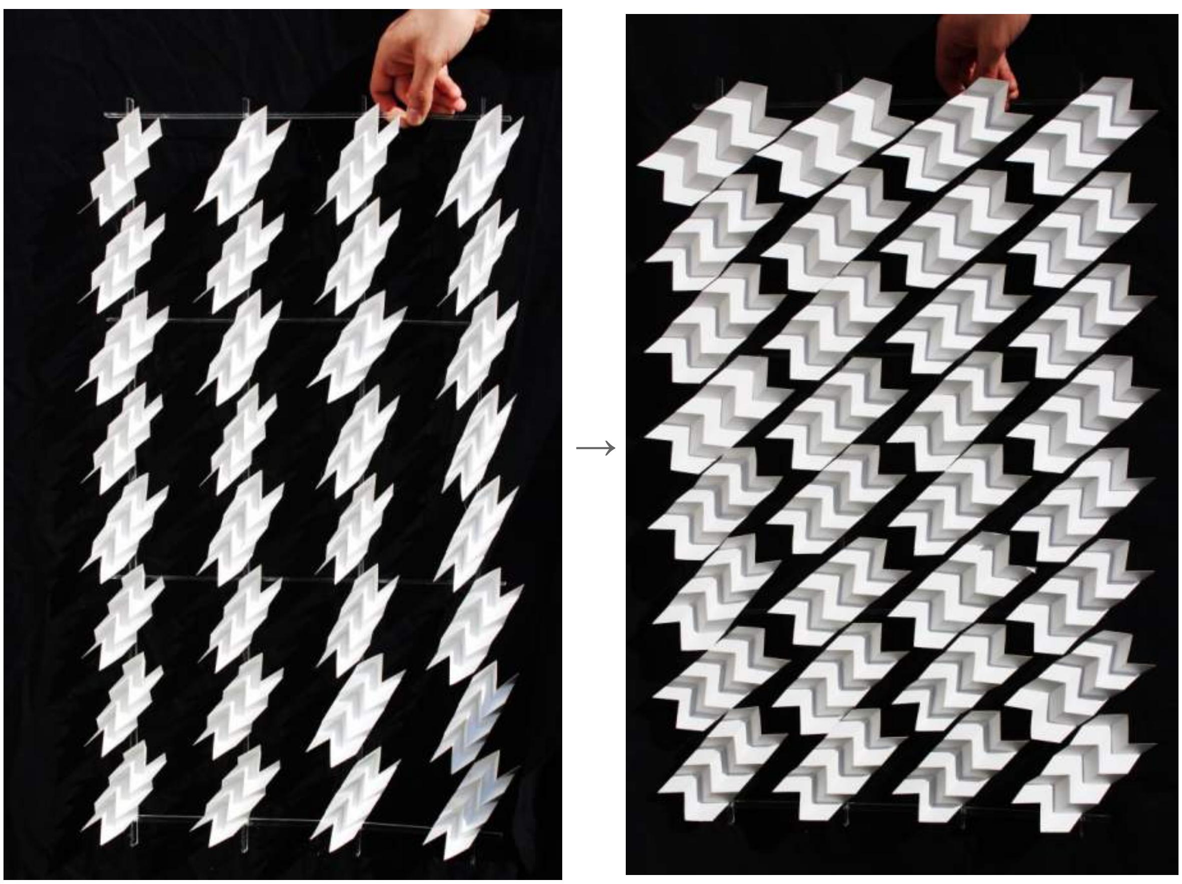


Figure 7: Hinge configuration using Shape Memory Polymer, 1/8" width 1/32" thickness strips commercially available with inexpensive cost. Despite this actuation cannot happen in the room temperature variation, it shows the potential method to overcome the size limitation of current polymeric material.



(a) *(b)*

Figure 8: Folding simulation with paper model

LEAF system is developed to repeat this base module, consisting of 18 parallelograms (Figs. 8 and 9a), each module sized by 1.28a”×7.6a”×a” (L1 × L2 × D) at its folded state (base state) and becomes 10a”×8a”×0.08a” when light hits. If the module is designed with more parallelograms, it can make L2 value bigger when unfolded. LEAF is designed to make a continuous vertical fin shape when folded so that the change of L2 value remains small. The one edge in the center of the module is anchored to the external structure (using thin wires). The effect of the plane angle S (shown in Fig 6) is studied to create an alignment to maximize the shading capacity when nearby modules are unfolded together. By nature, Miura-ori avoids collision to the next modules in x and y axis since it shrinks in both directions. Figure 8(a) shows the computational simulation of 4 modules showing a progressive transition from a folded state (base state when there is no light) to unfolded states when light hit the surface. The more unfolded LEAF is, the larger the surface faces the light source creates. This mechanism accelerates the speed of unfolding. Figure 9(b) shows opening pattern simulation in a panel condition.

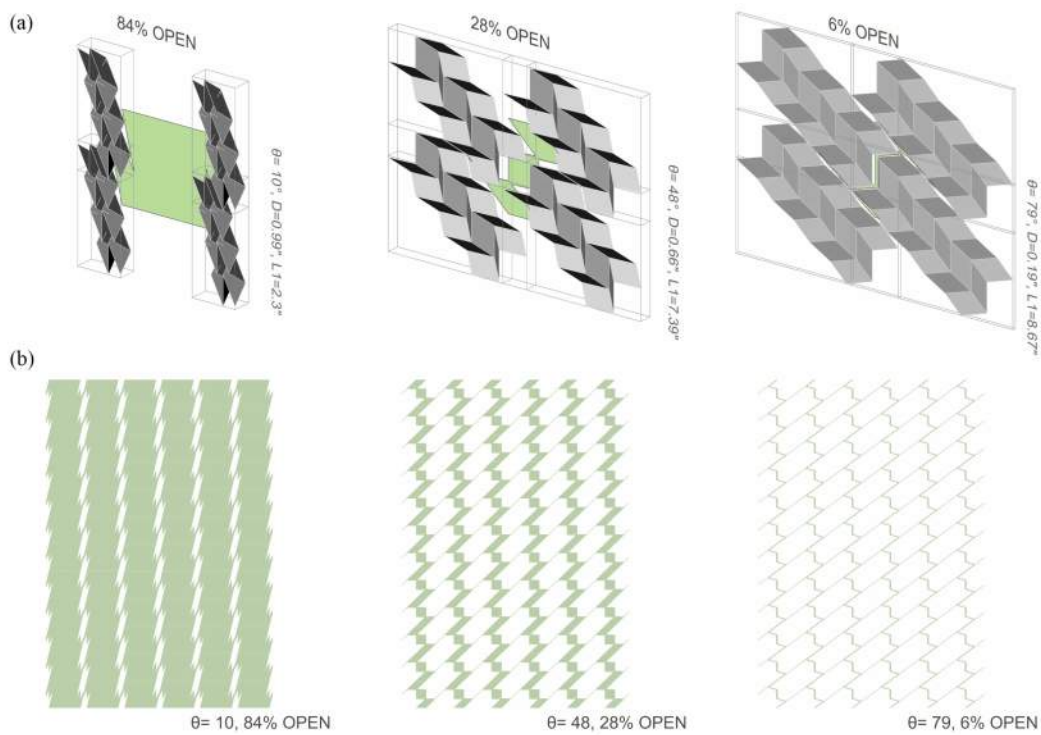


Figure 9: (a) Schematic simulation of 4 modules in LEAF system. When they are folded (basic state when there is no light), it forms vertical lines. When there is light, it unfolds to block light, (b) Projected area diagram of opening percentage change in LEAF system from folded state (10 °) to unfolded state (79 °). Green color represents the projected open area.

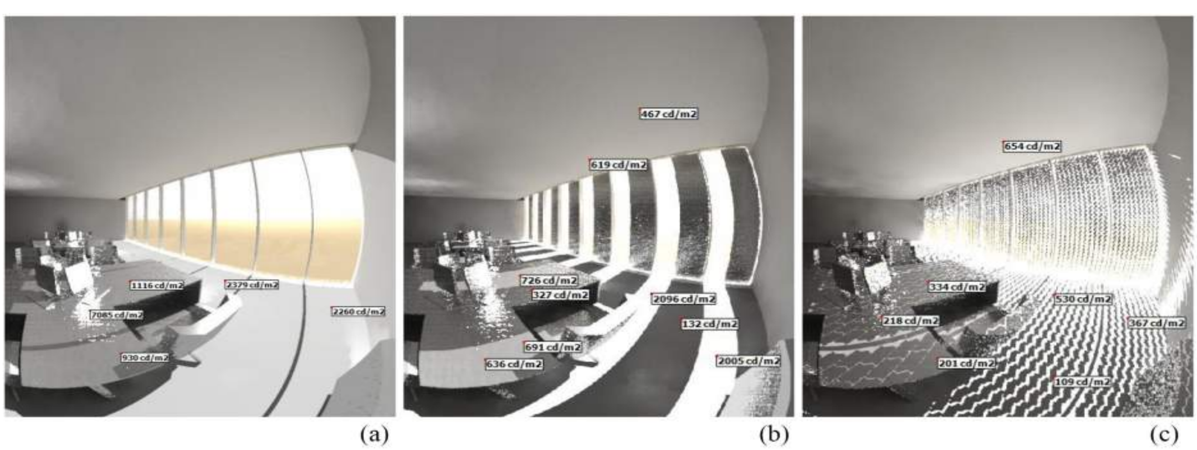
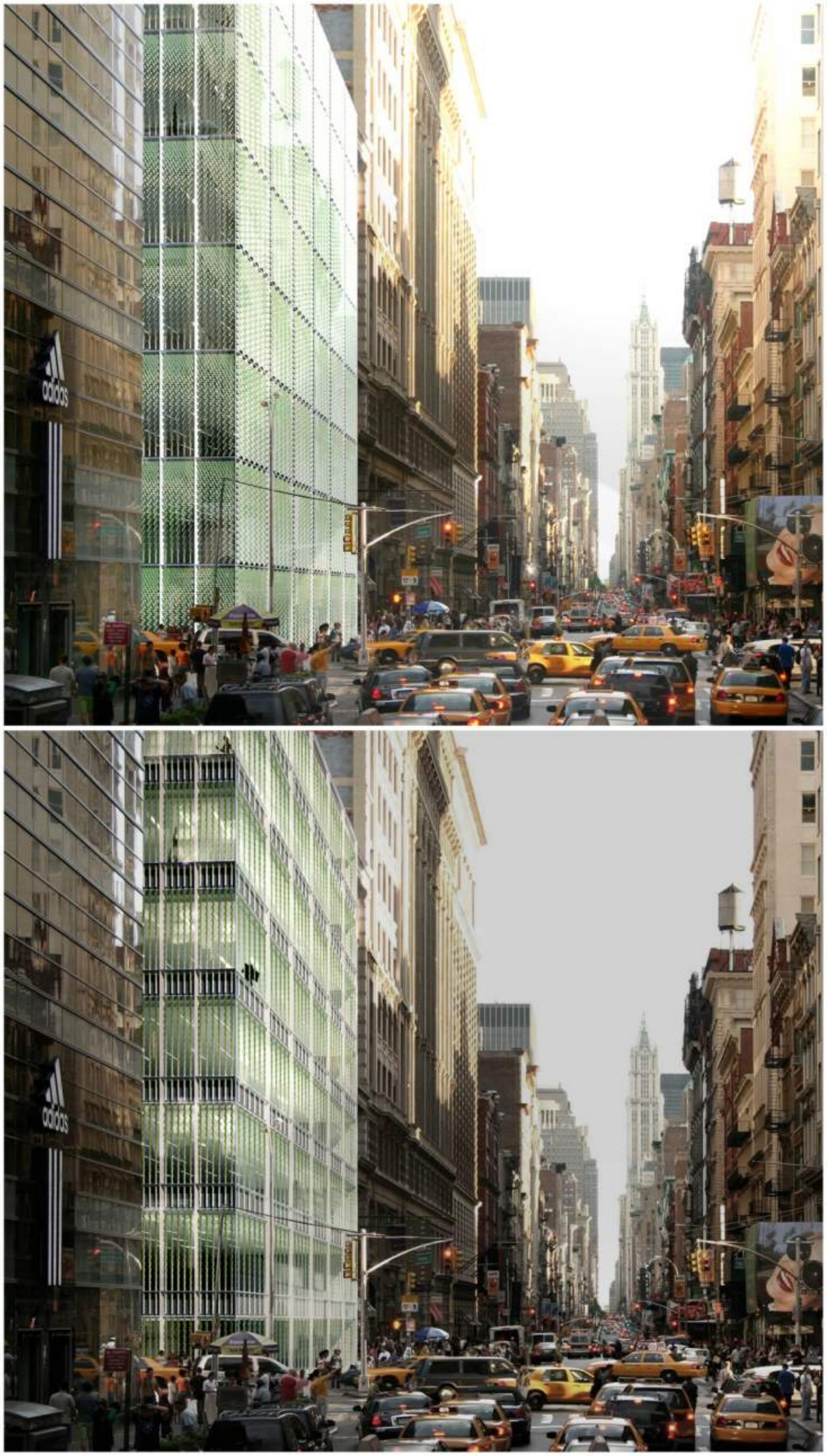


Figure 10: Lighting simulation using DIVA. (a) Typical glazing unit. (b) Generic shading device (or it can be considered as opening design) which has 57% opening. (c) LEAF with same 57 % opening.

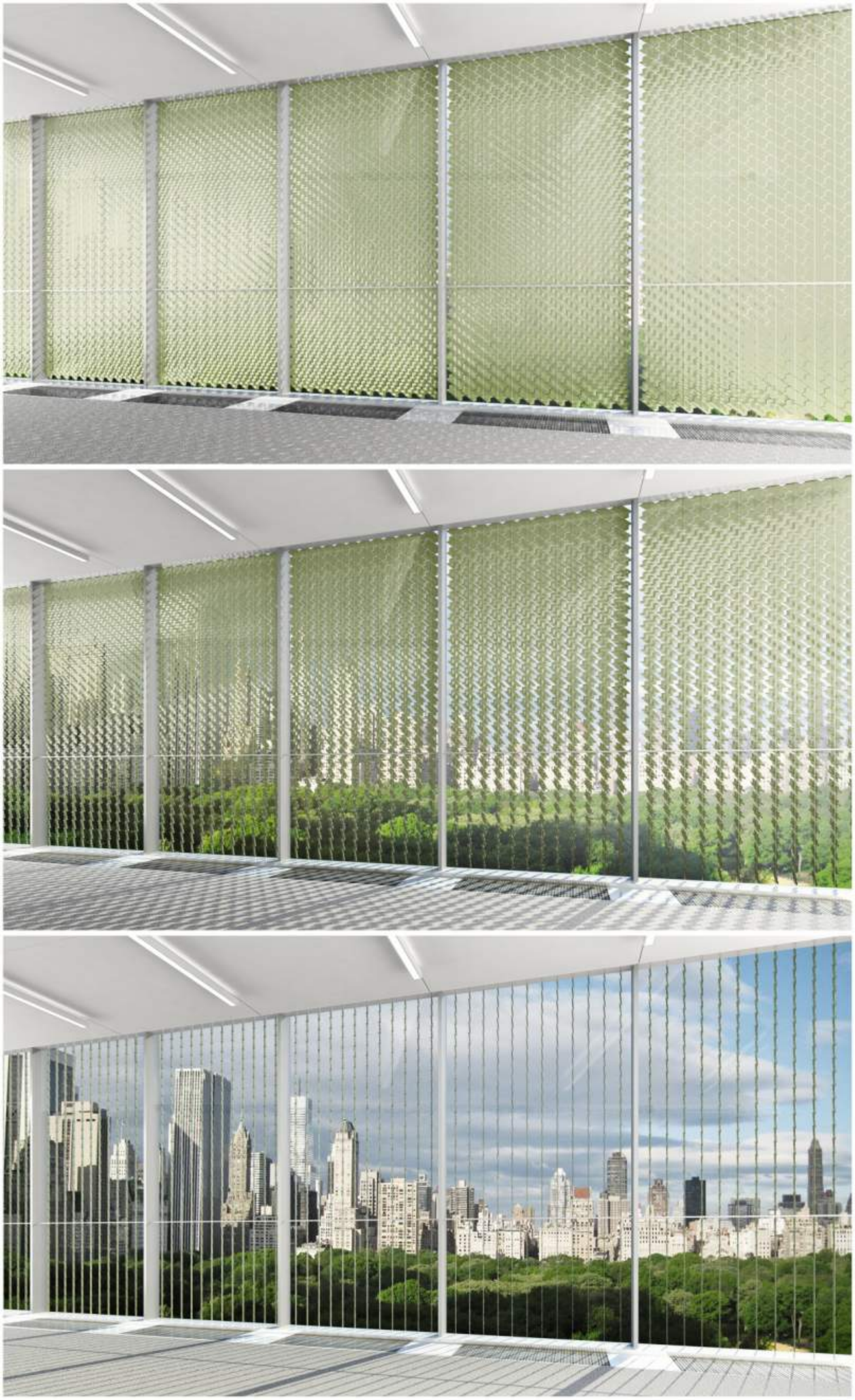
From the standpoint of a daylighting design, LEAF can specifically respond to the glare problem. Unlike mechanical actuating shading device, LEAF's module size can be very small to produce more diffused light. In addition to the size factor, the shrinking capability in both directions also maximizes the diffusing quality. Figure 10 shows simple lighting simulation using DIVA (http://diva4rhino.com/). The test site is an office facing southwest in Los Angeles, CA. The test time is summer day 4pm. Figure 9(a) shows just a typical glass facade without any shading device. The luminance level on the workstation shows 1116 lux (cd/m2). Figure 9(b) shows generic vertical shading devices - or just window openings - which allow 57 % opening ratio. In this case, the work surface has big contrast between 327 lux to 726 lux, which is still uncomfortable condition. LEAF system that has the same 57 % opening ratio will make the workstation with constant 201 lux to 334 lux. Based on this superior function and sensational quality, Figures 11 and 12 show interior and exterior renderings depending on different light conditions.



(a)

(b)

Figure 11: Renderings of LEAF building in different lighting scenario. (a) The facade on the right side of building in this rendering shows 6 % opening. Left side of facade shows 57 % opening. (b) All facades have 84 % opening since there is no direct light hitting the building.



(a) (b) (c)

Figure 12: Interior Renderings of LEAF to show opening simulation. (a) 6 % opening. (b) 57 % opening. (c) 84 % opening.

CONCLUSION AND FUTURE WORK

Shape-programming of polymer sheets is a very attractive strategy for the building envelope design for its self-folding mechanism, low energy operation/maintenance, artistry of mechanism and noble shading effect. LEAF proposes a design speculation for the application of the emerging research emphasizing the integration of parametric design and photochemical actuation beyond a simple open and close shading system. To achieve the folding mechanism, LEAF can use alternative stimulus (e.g., heat, solvents, water with temperature change, magnetic field and pneumatics). Further progress on these polymeric materials and the performance of shape change will need to be integrated with a parametric design procedure. Despite the promising advantages, proven benefits and alternative stimulus described (Liu et. al., 2016), the current reviews of the shape programmable materials may address the size limitation. The simulation of LEAF in a more elevated temperature change (Fig. 7, pattern change simulation by author) suggests alternative hinge configuration to achieve the same performance using much smaller shape changing polymer sheet used only in the hinge definition. Therefore, in continuation of existing body of research using light actuation, the next step of the LEAF is to fabricate a light responsive polymer sheet performing the LEAF folding mechanism with size variations. In that prototype, different hinge mechanism will be explored and the optimum radius of curvature to make folding structure in the daylight condition and folding angle calibration with different mountain and valley programming need to tested. The anchor connection using the center edge of the LEAF module will be also explored with various methods in the context of glass wall to address the flexible deployment of this product to any existing building envelope condition.

ACKNOWLEDGMENTS

We thank NYSCA (New York State Council of Art) with Architectural League of New York for the independent project grant and University at Buffalo for the SMART Exploratory Grant.

REFERENCES

Cheng, Futao, Ruoyuan Yin, Yuanyuan Zhang, Chu-Chun Yen, and Yanlei Yu. "Fully plastic microrobots which manipulate objects using only visible light." *Soft Matter,* 6, no. 15 (2010): 3447-3449.

Ikeda, Tomiki, Makoto Nakano, Yanlei Yu, Osamu Tsutsumi, and Akihiko Kanazawa. "Anisotropic Bending and Unbending Behavior of Azobenzene Liquid-Crystalline Gels by Light Exposure." *Advanced Materials*, 15, no. 3 (2003): 201-205.

Kim, Jungwook, James A. Hanna, Myunghwan Byun, Christian D. Santangelo, and Ryan C. Hayward. "Designing responsive buckled surfaces by halftone gel lithography." Science, 335, no. 6073 (2012): 1201-1205.

Liu, Ying, Jan Genzer, and Michael D. Dickey. "“2D or not 2D”: Shape-programming polymer sheets." *Progress in Polymer Science*, 52 (2016): 79-106.

Na, Jun-Hee, Arthur A. Evans, Jinhye Bae, Maria C. Chiappelli, Christian D. Santangelo, Robert J. Lang, Thomas C. Hull, and Ryan C. Hayward. "Programming Reversibly Self-Folding Origami with Micropatterned Photo-Crosslinkable Polymer Trilayers." Advanced Materials, 27, no. 1 (2015): 79-85.

Schlam, Elliott, Mark S. Slater, Jeffrey P. Koskulics, and Joshua S. Finch. "Electronically controlled insulated glazing unit providing energy savings and privacy." U.S. Patent 8,736,938, issued May 27, 2014.

Stoychev, Georgi, Nikolay Puretskiy, and Leonid Ionov. "Self-folding all-polymer thermoresponsive microcapsules." Soft Matter, 7, no. 7 (2011): 3277-3279.

(All images are by the author except Figure 1, 2 and 3)