Kinetic Solar Panels: A Transformative and Expandable Geometric System for Photovoltaic Structures

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ABSTRACT
This paper focuses on the applications of geometrically transformable and expandable structures with deployed "energy production" mode and retracted "wind shedding" mode to replace the fixed photovoltaic (PV) panels and racking systems currently used in buildings rooftop installations. The significance of this expandable geometric system relies on its embedded motion grammar, i.e. rotation and translation transformations, in the system. The research draws inspiration from reconfiguration of compound tree leaves in nature, and addresses issues of redesign and modeling challenges that led to digital fabrication of the prototype.

KEYWORDS: Kinetic system, photovoltaic panels, geometric transformation, motion grammar, parametric modeling

Rethinking Photovoltaic Panels

Photovoltaic systems have proved to be a successful and affordable method of energy production in building and urban scale when implemented in architecture. PV panels can integrated into roof and façade of new or existing buildings to generate entire or part of the required residential electrical energy (Guiavarch and Peuportier, 2006). However, the installation of PV panels is typically an elaborate and time consuming task in which the panels are ballasted or attached to over-sized rigid structures to withstand the possible damage due to wind pressure in severe weather conditions (Goodman et al. 2012). Moreover, conventional solar panels are typically oriented in a fixed direction, calculated to optimize the solar energy collection. Recent research has examined new three-dimensional arrangements for PV panels to increase the energy gain (Bernardi et al., 2012).

While there are many ongoing studies on improving the energy production level of the PV cells, the form of the PV panels is limited to certain sizes and shapes due to production and installation efficiencies. From an architectural-aesthetic point of view, this predefined rectangular shape of the PV panel is limiting for designers. As a result, the pragmatic and aesthetic reassessment of the form of the current PV panel systems, to achieve more flexibility and adaptability for incorporation into architecture seems well-reasoned. This research therefore proposes a kinetic expandable system for PV panels to decrease the weather-related damage risk, and simultaneously increase surface area coverage and solar energy gain, while departing from typical fixed form and arrangement of the PV panels.

Reconfiguration, A Solution Derived from Nature

This project departs from current practice of rigid, fixed-direction PV mounting and takes cues from nature, which deploys different strategies for similar problems such as folding or collapsing in plant leaves to increase sun gain and protection from the wind. Studying these methods evolved by natural systems offers design solutions, which have been tested and improved over a long time period in nature. Specifically, for the current research, study of plant leaves becomes the focus, as plants are dependent on photosynthesis for energy production, a system that requires solar energy (Goodman et al. 2012). As a result, plants have developed methods to maximize the surface area of leaves while simultaneously able to morph geometrically to resist the wind pressure. A main factor in measuring the wind resistance is the drag of a tree that is determined by exposed surface area of the leaves, especially in broad-leaved trees. There two main methods that plants have adapted as a solution, folding in leaves with corrugated patterns (De Focatiis and Guest, 2002), and reconfiguration of leaflets in compound leaves (Vogel, 1989), which both are fully reversible methods. Leaves folding mechanism have been previously studied and adapted for solar panels and lightweight antennae of satellites (Kobayashi, Kresling and Vincent, 1998), while for this research the reconfiguration of compound leaves in trees such as black locust and black walnut was adopted. In this method, which was studied by Vogel, trees with elongated leaflets or leaves in an alternate sequence along a branch are reconfigured and appressed toward the branch in wind to resist the pressure. Consequently, a reconfigurable and collapsible panel system to resist the wind pressure and increase the surface area for solar gain has been adapted for the current research.

An Expandable Geometric Structure

Kinetic structures consisting of rigid bars and/or plates connected by revolute joints - also known as deployable, retractable or expandable structures - are intriguing motion system that can be packed very small, and expanded, uni-directionally or omni-directionally to a predetermined size and shape providing for greater surface area and enclosed volume. These systems provide a wide range of applications from solar panels and lightweight antennae for satellites to large-span roof structures and consumer products such as toys or lamps (Patel and Ananthasuresh, 2007) (Luo, Mao and You, 2007). These kinetic structures, often with a single degree of freedom, have different types based on their structural configurations, such as angulated scissor-like frame elements invented by Hoberman (Hoberman 1991), which was extended into structures in which their bar elements were covered or replaced with rigid planes (Kassabian and Pellegrino, 1999). There is another type of kinetic structures, referred to by Joseph Clinton as transformation structures that are the main focus of this research (Clinton, 1971). In the past, this type of expandable geometric structures have been studied and proposed for possible applications in the aerospace technologies in 60's and 70's by researchers and designers such as Fuller and Clinton. The rigid geometric expandable structures are divided into two main types: two-dimensional tessellation transformation structures and three-dimensional polyhedral transformation structures (Figure 1).

The two-dimensional tessellation and three-dimensional polyhedral transformation structures are composed of two parts: *main modules* - in shape of triangle, square and hexagon - and the *connecting modules* - in shape of three-, four- or six-armed stars (Figure 1). In these structures, each end point of the connecting modules links to one of the corners of the main modules. It should be taken into account that the specified module shapes would result in final regular Euclidean 2D and 3D forms. In addition, both the two- and three-dimensional systems have two main geometric transformations in a simultaneous operation: translation and rotation, one planar and the other spatial. The combination of these transformations demonstrates a visually complex kinetic movement, while maintaining mechanical simplicity necessary for fabrication and operation of the system. A specific type of two-dimensional tessellation structure with square shaped main modules and cross-shaped connecting module has been selected for this study

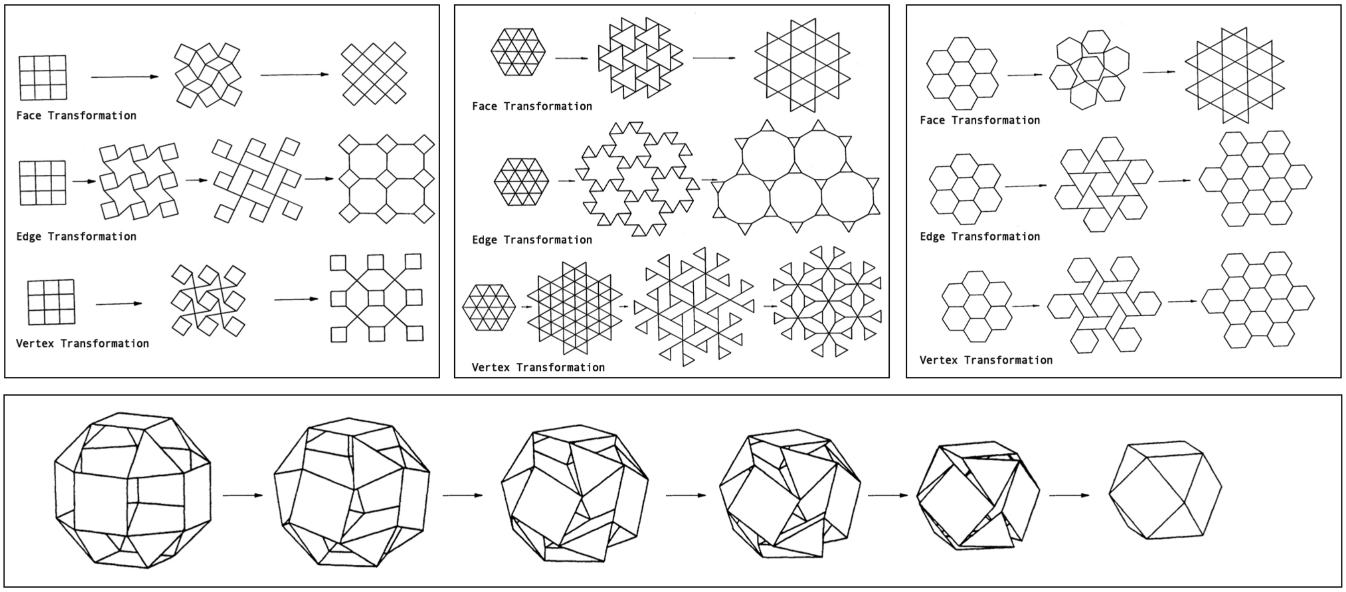

Fig. 1. Top: Two-dimensional Tessellation Transformations (Clinton, 1971), Bottom: Three-dimensional Polyhedral Transformation (Verheyen, 1989)

due to two factors, the planar form of this tessellation would facilitate its integration on the roof or façade of buildings, and existing rectangular PV cells would fit on the structure.

Development of Form: From Geometry to Fabrication

At the first stage of the study, the selected two-dimensional tessellation transformative structure with square and cross-shaped elements have been analyzed in order to decipher the exact movement mechanism, based on an embedded motion grammar in the system, composed of transmitted rotation and transformation from the central module to the adjacent and consequently to the entire system (Figure 2). The discerned motion grammar has been adopted as the basis for a parametric model to facilitate the reconstruction of the abstract linear geometric concept into a materialized kinetic model.

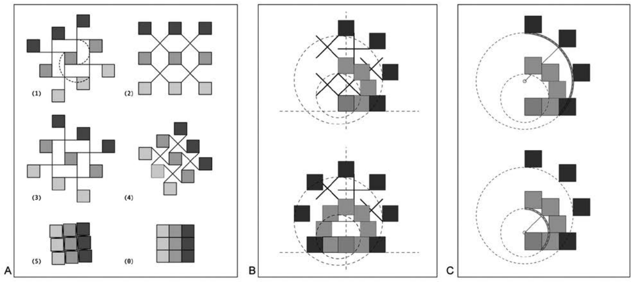

Fig. 2. Motion study of the tessellation transformation with square-shape main modules

Consequently, the first model for the fabrication based on the material thickness and type of hinged joints has been designed based on the original geometric model. In this model, the connecting modules maintained the original cross shape with added thickness to the axis line. These connecting modules proved to be problematic due to the undesired overlap of the elements. Thus, the connecting modules were redesigned and replaced with offset cross-shape modules that could rotate and nest next to each other in the closed arrangement of the system (Figure 3).

This change in the shape of the connecting module, necessary for materialization and fabrication, results in some limitations in the total rotation angle of the system compared to linear geometric model. With this change, the system can only rotate 90 degrees to open and close - from closed (0° R) to open (90° R)- compared the geometric model that would allow for 180 degrees rotation for bidirectional operation -from closed (0° R) to open (90°R) to closed (180°R).

The fabricated transformable square tessellation has the expansion rate of 3.7, ratio of open gross area to closed gross area. However, the area of the covered surface remains the same in the open and closed arrangements. The second stage of the process was concentrated on increasing the surface area coverage in the deployed arrangement of the system to maximize the exposure to the sun and solar energy gain. To increase the surface area, more PV panels have to be added to the current system while these panels should not interfere with the main kinetics of the system and the movement of existing panels. As the first step, the addition of the panels to the connecting modules has been explored. This method proved to be feasible and increased the surface area coverage of the open arrangement two times more then the basic pattern. In addition, the shape of the connecting modules was changed in order to embed the new panels within the connecting modules to not interfere with main role of the connecting modules for linking and moving all the system parts (Figure 4).

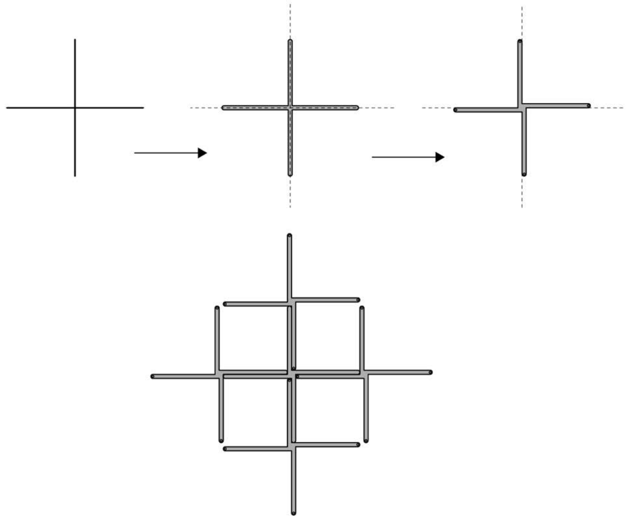

Fig. 3. Cross-shape connecting module

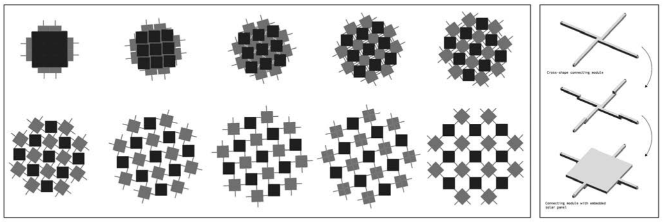

Fig. 4. Kinetic solar panels with two overlapped layers

Finally, the main modules of the system had to be redesigned. The flat main square modules were divided into four square segments, elevated, rotated 90 degrees and enlarged to increase the total size of the modules. Taking advantage of a weaving pattern, and taking into account the sequence of the elevated modules, the panels in the final proposed system have 3.3 times more surface coverage (compare to the 3.7 expansion rate of the whole system) in the open arrangement of the modules. An instance of the system, with a total coverage of 3.24 square meter in closed mode (60cm x

60cm main modules) and 10.70 square meter in open mode and designed to produce 0.6 kilowatts of peak power, is currently being prototyped (Figure 5).

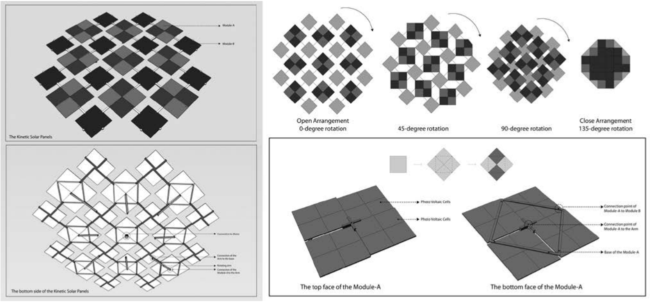

Fig. 5. Final model of the kinetic solar panels

Conclusion

Drawing inspiration from natural system such as trees with compound leaves and looking into their novel wind resistance methods like reconfiguration of the leaflets results in proposing new structures for redesign of solar panel systems. The kinetic and transformative solar panel tessellations offer new applications in spatial optimization by addressing how transformable objects can dynamically occupy predefined physical space. In addition, as described by Fox and Kemp: "One of the main benefits of an active sustainable system is that it can intelligently combine the resources of a number of systems so that when working together, the individual elements or systems achieve more than the sum of their parts." (Fox and Kemp, 2009)

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