Ruga Architectural Skin (RAS): Toward Building Smart Self-folding Topology

Jiangmei Wu, Indiana University, USA
Sohel Anwar, Indiana University–Purdue University Indianapolis, USA

Abstract: This paper presents the concept and design requirements of an innovative architectural skin that can potentially be deployed instantaneously for temporary architecture and other related applications. "Ruga" is a Latin word for making winkles, creases, and folds, and the word has recently been used by material scientists to describe these various qualities. RAS is inspired by the use of folding, namely, the art of origami, to create complex topological forms from flat thin sheet materials. Focusing specifically on the Yoshimura pattern, the RAS project explores its potential for being an architectural fabric for temporary use. This architectural skin comes from two-dimensional sheet materials that can be pre-fabricated and assembled off-site and then shipped flat to the site, thus tremendously reducing the required amount of energy and resources in comparison to conventional structures. Once arriving on the site, it can be reconfigured to work for various spatial functions. This paper presents the initial results of this ongoing RAS project by identifying the following: first the design considerations, tools, techniques, methods, and processes for the construction and installation of full scale mock-ups using corrugated cardboard, secondly the design requirements for the actuation system while identifying a number of potential candidates from active and passive systems, and thirdly the self-folding mechanism and related remote micro-processor control system appropriate for this application. The findings of this study show that the design and construction of such topologies are within the purview of currently available technology.

Keywords: Sustainability, Origami, Architectural Skin, Folded Structure, Temporary Architecture

1. Introduction

In architectural design, skin is a familiar metaphor for building envelopes that provide flexible layers of protection and are often dependent upon rigid structural supports. With advances in material technology and sustainable development, architectural skins are changing, creating new topological forms, providing new visual and tactile experiences, and becoming the conceptual bridge between our body and our environment. Can a three-dimensional architectural skin be self-assembled or self-folded from two-dimensional sheet material? Can this architectural skin be made of non-rigid material and yet provide semi-rigid structural support? What are the design considerations, tools, techniques, methods and processes of building such an architectural skin? And how can a new approach to developing an innovative architectural skin contribute to our ongoing search for energy-efficient building design, self-assembling deployable shelter, as well as sustainable construction techniques? This paper introduces Ruga Architectural Skin (RAS), an ongoing research project exploring the potentiality of a new type of architectural skin.

"Ruga" is a Latin word for making winkles, creases, and folds, and the word has been recently used by material scientists to describe the various physical qualities of these various folded states. RAS is inspired by the use of folding to create complex topological forms from flat thin sheet material with simple and low cost tools. Folded forms have inherently rigid properties and at the same time are flexible. In comparison to other fabrication techniques, folding or bending allows for complex and innovative structures formed with simple and low cost tools at the point of assembly. From flat sheet material, folded designs can be easily deployed into a three-dimensional volume and then can be collapsed back to a two-dimensional flat shape that is much smaller for ease shipping and storage.

Many folded designs are inspired by origami, the Japanese art of paper folding. The original purpose of origami is to obtain various shapes, ranging from animals figures to objects, both abstract and figurative, by folding a flat sheet of uncut paper. Constructing a three-dimensional surface from two-dimensional sheet material in origami has inspired designers and engineers to

The International Journal of the Constructed Environment
Volume #, Issue #, Publication Year, www.constructedenvironment.com, ISSN 2154-8587

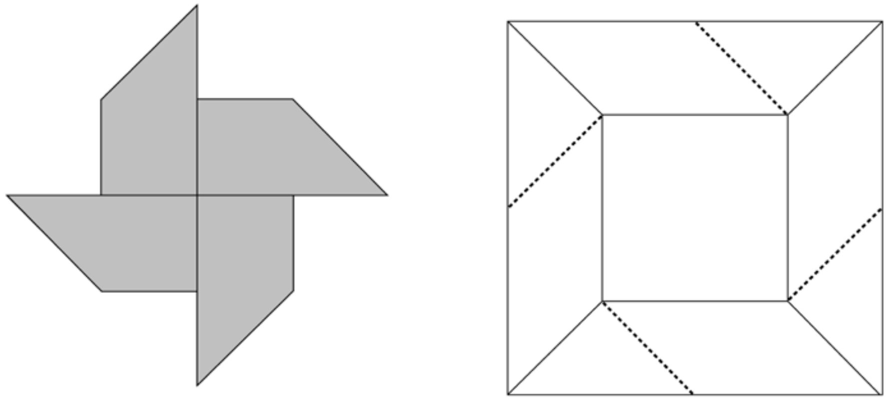
come up with novel ways to fabricate, assemble, store and morph structures that are safe, efficient and energy saving (Edwin, Hartl, Malak, and Lagoudas 2014), from collapsible medical stents for hearts (Kuribayashi et al. 2006) to airbags for cars. In architectural design, one of the earliest examples of exploration of paper folding and topological design of architectural system was conducted by Ronald D. Resch (1973). In the last two decades, folding, both as a theoretical idea and as a means for form generation in architecture, has inspired a new generation of architects and designers to create morphogenesis architectural volumes with continuous variations and interpolations that overlaps gaps and avoid fracture (Lynn 2004). Morphological architectural structures are starting to make use of one of the main characteristics of folding design—the kinetic ability to deploy and collapse in three-dimensional space (Liapi 2002; Motro 2009). More recently, researchers have been looking into using active materials that can convert various form of energy into mechanical work for folding to create self-folding (Edwin et al. 2014). However, low cost architectural skins that are deployable, configurable and that are in large scales, continue to be very challenging for architects and designers.

This architectural skin comes from two-dimensional sheet materials that can be pre-fabricated off-site and then shipped flat to the site, thus tremendously reducing the required amount of energy and resources in comparison to conventional structures. Once arriving on the site, it can be self-assembled or self-folded, suspended and reconfigured differently into various semi-structural surfaces. Although this architectural skin has roots in a paper folding art form, it proposes not only to significantly advance the technology of the art form, but also to transform this technology to the self-assembling structures that can potentially shift the paradigm in building temporary architecture.

This paper starts with a discussion of the application of origami in self-assemble and deployable architectural topologies. While objective of this paper is towards building smart self-folding architectural topology, this paper currently focuses on identifying the design considerations, tools, techniques, methods and processes of making and installing of several 1:1 scale mock-ups in corrugated cardboard, testing of varies materials, and surveying of the self-folding mechanism design and remote micro-processor control system design. Pending funding opportunity will allow us to build a 1:1 scale smart architectural skin prototype.

2. Origami Tessellations in Design

Typically, geometric crease patterns are focused when paper folding is applied in design. The crease pattern refers to a set of mountain folded lines and valley folded lines appearing on a sheet of paper when a folded structure is open flat. Figure 1 shows an origami pinwheel figure (a) and the associated crease pattern (b). Solid lines and dash lines represent mountain folds and valley folds respectively.

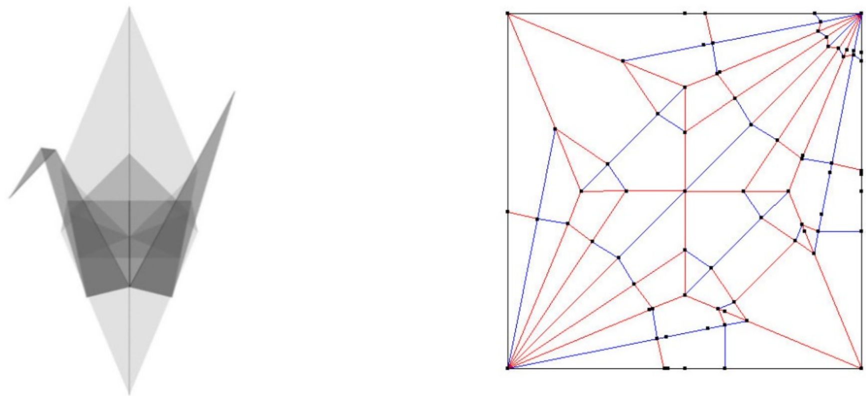


(a) (b)

Figure 1: (a) An origami pinwheel; (b) Crease pattern of (a). Computer simulation using ORIPA: Origami Pattern Editor by Jun Mitani.
Source: http://mitani.cs.tsukuba.ac.jp/oripa

Perhaps the interesting part of origami design is to fold a desired 2D or 3D shape from a single piece of paper. It has been mathematically proven that any 2D polygon or 3D polyhedral can be folded from a flat sheet of paper, as long as the paper is big enough (Demaine and O'Rourke 2008). Computer programs for origami or paper folding design have been explored by a few mathematicians and computer scientists, including Jun Mitani's ORIPA and Robert Lang's TreeMaker (Lang 1998; 2003). However, it has been quick difficult to come up with crease patterns that can generate desirable form. While there are many different types of crease patterns in origami design, only the origami tessellations employing crease patterns that are able to create rigid foldable structures are focused. Rigid origami is an essential feature when creating folded design that can be deployed into a three dimensional topology from a two dimensional shape.

One of the ways to understand rigid origami is that the folded three-dimensional forms are not locked and they can be folded into their final state by bending the material just at the crease lines. In other words, rigid origami is an origami that is continuously transformable along its folds without deformation by bending or folding of any facet and therefore can be realized in a deployment structure using stiff panels and hinges (Tachi 2011). In a typical traditional origami model such as the crane shown in Figure 2, the folding and unfolding of the model needs to follow a step-by-step sequence. In order to reach a folded state in a crane origami, one must finish a previous folded state. Therefore the folded structure can't not be deployed simultaneously in a self-organized manner.



(a) (b)

Figure 2: (a) An origami crane; (b) Crease pattern of (a). Computer simulation using ORIPA: Origami Pattern Editor by Jun Mitani.
Source: http://mitani.cs.tsukuba.ac.jp/oripa

In contrast, in a deployable and rigid-foldable structure, the folding pattern needs to be self-organized. A folding pattern inspired by these shorts of self-organized creased patterns, such as the Miura pattern (Miura 2009), is the bases for a self-folding map and deployable solar cell array on Space Flyer Unit, a space platform launched in Japan in 1994–1995. Figure 3 shows various deployable states of a rigid-foldable design based on Miura pattern, discovered by Japanese scientist Miura Ori when researching ways to uniformly buckling of a thin plate structure. The primary deployable feature of Miura pattern includes its ability to deploy simultaneously in orthogonal directions and to retract and deploy on the same path (Miura 2009).

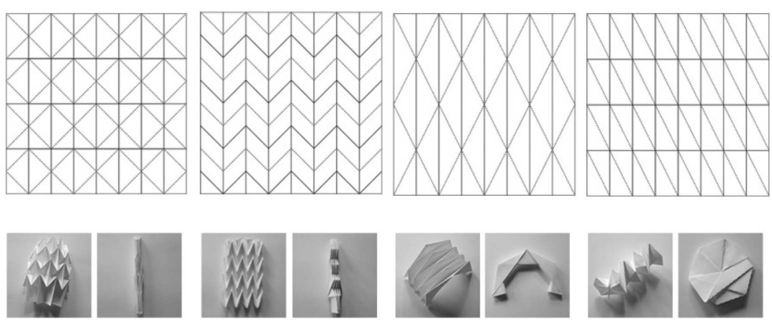
Figure 3: Various deployable states of a Miura pattern. Computer simulations created using FreeForm Origami by Tomohiro Tachi.
Source: http://www.tsg.ne.jp/TT/software

In traditional origami, paper is often regarded as having an ideal zero-thickness surface in a mathematical context, and paper folding is often done by hand. However, in origami inspired structures, particularly in architectural structures, folding thick panels is necessary in order for the structure to be load-bearing and to have the appropriate insulations. Tomohiro Tachi has proposed methods to fold thick-panel origami in order to achieve the exact kinematics of ideal origami with zero thickness (Tachi, 2011). Figure 4 demonstrates the new approaches by Tomohiro Tachi for folding thick-panel origami. In the first approach, the axis of folding is shifted and the resulting folding motion is only approximated by the kinematics of ideal origami. In the second approach, the thick panels are tapered by relocating the rotational axes on the surface of thick panel to lie on the edges of ideal origami, thus producing the exact kinematics as the ideal origami. In the third approach, the tapered thick panels are replaced by panels with constant thickness. Tachi demonstrated that by offsetting panels with constant thickness, the exact kinematics as the ideal origami can be also achieved. In comparison to the tapered panels, constant thickness panels can be easily manufactured via a simple 2-axis cutting machine, thus significantly simplifying the fabrication procedures.

(a) (b) (c)

Figure 4. Folding of thick-panel origami. The dash lines represent an ideal origami with zero-thickness. (a) Axial shifting in thick-panel origami. (b) Tapered panels. (c) Offset panels.

Furthermore, hands-free self-folding origami in structures, in some circumstances, also becomes the necessary condition (for example, in constructing large scale folded solar arrays for space application, folding by hand is impossible). Therefore, origami-inspired self-assembling or self-folding smart structures have recently been garnering great attention from researchers and designers, often composed of a multi-disciplinary team of artists, designers, engineers, scientists and mathematicians. In order to create large array of large deployable design, only origami tessellations are focused. An origami tessellation is a folded design where both the crease pattern and the folded structure use continuous and repeated elements based on the symmetries found in seventeen crystallographic design (Davis, Demaine, Demaine, and Ramseyer 2013). One of the foremost pioneers of origami tessellation is Shuzo Fujimoto, who often uses motifs made from hexagons, squares and triangles (Rutzky and Palmer 2011). Beside catching the interests of origami artists, the origami tessellations, or the periodic folded forms, also caught the interests of computer scientists and artists such as Ron Resch (1968), David Huffman (1976), and Paulo Taborda Barreto (1997). Perhaps the most well-known flat-foldable and deployable origami tessellations are Waterbomb pattern, the Miura pattern, the Yoshimura pattern and Nojima's helical triangle pattern. Figure 5 shows these four aforementioned patterns and their folded forms in their respective deployable and flat-folded states.



(a) (b) (c) (d)

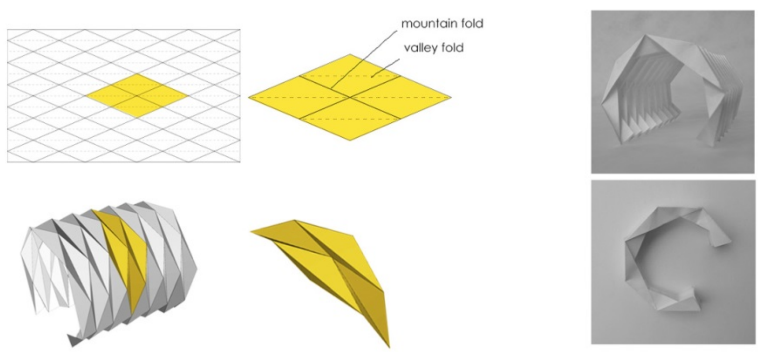
Figure 5. Crease patterns and the associate folded forms in flat-foldable states and deployable states. (a) Waterbomb pattern. (b) Miura pattern. (c) Yoshimura pattern. (d) Nojima's Helical Triangle pattern.

3. Research Making of Ruga Architectural Skin

One of the goals of RAS project is to understand and identity the design considerations, tools, techniques, methods and processes of building a smart three-dimensional semi-structural interior skin. The project consists of the following phases: form finding, 1:1 scale mock-up in cardboard, material selection, self-folding mechanism design, remote micro-processor control system design and final 1:1 scale mock-up. Currently, we have successfully finished and installed several 1:1 scale mock-up in corrugated cardboard. Various materials that are appropriate for the RAS project are tested. Self-folding mechanism design and remote micro-processor control system have been studied. Pending funding opportunity will enable us to work on the final 1:1 scale mock-up.

3.1 Form Finding Using Yoshimura Folding Pattern

Focusing specifically on one of the most fundamental folding patterns, the Yoshimura pattern (Yoshimura 1955), RAS project explores its potential for being an architectural fabric for temporary use, or for an ephemeral architectural or interior structure. The Yoshimura pattern was discovered by scientist Y. Yoshimura while he was researching the buckling patterns of thin-walled cylinders. One of the most important features of the Yoshimura pattern is its ability to allow the form to reduce the dimensions in all directions when compressed or folded, facilitating easy transportation and storage. A regular deployment of the pattern produces an approximated arc form that has great structural stability (Figure 6).



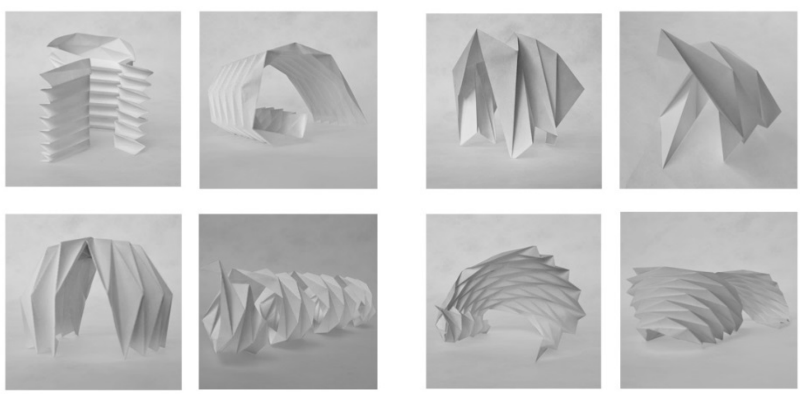
(a) (b)

Figure 6. Yoshimura pattern and its deployment. (a) Yoshimura pattern allows the form to reduce the dimensions in all directions when compressed or folded. (b) Paper folded model showing the Yoshimura arch and its flattened form.

Instead of a regular deployment of the Yoshimura pattern, the RAS project focuses on an irregular deployment. The goal is to generate a variety of topologies to increase their versatility for working with a variety of spatial functions. Two methods are used in the process of topological form finding: small scale physical models and computer simulations. The digital CAD models generated from computer simulations will then allow us to further our design verification process. The first step of form finding in small scale model involves an approach that allows us to start by working with material tactilely. This approach is very different than a typical approach in which CAD programs play central roles, rather this approach allows the material, in this case, the paper folds, to be at the center of the morphogenetic process.

According to Manuel De Landa, French philosopher Gilles Deleuze stresses that form can be generated on its own because of the morphogenetic capability of matter that acts as an active material agent (De Landa 2000). In contrast to essentialist views of genesis of forms (which imply that form is not resulting from matter, rather, what make the form what it is because of the essence of the form), Deleuze argued for the notion of new materialism which states that matter, or an active material agent, is capable of morphogenesis and creating the form on its own (Deleuze 1994). For example, soap molecules in a thin layer of soap film, working together collectively, are constantly in a process of achieving the equilibrium state, namely, a condition of minimum potential energy that results in a minimal surface. Many artists and designers have been fascinated by the beauty of minimal surfaces as seen in the soap films. One of the earlier explorers of soap film surfaces is Frei Otto. In coming in up with the tensile roof forms for West Germany Pavilion in Montreal in 1967 and Olympic Stadium in Munich in 1972, Otto constructed a large plywood model that was made of evenly spaced pillars and strings that were loosely hung between the pillars. He then submerged the model in a tub full of soap water to get interestingly shaped soap films, which became the bases for his tensile structure design. While the CAD programs and simulation software that are able to generate the minimal surfaces today weren't available in the '60s and '70s, Frei Otto was a pioneer in form finding using material as an active agent. As an architect and a structural engineer, instead of dominating and controlling the material agents, he entered into a partnership with the material and allowed the material to work on its own according to natural laws.

In the form finding step with paper folds, two-dimensional Yoshimura crease patterns that are able to generate a variety of topologies are focused. While design tools such as Adobe Illustrator and AutoCAD will allow us to draw two-dimensional lines, to work more efficiently parametric design tools such as Grasshopper and Lunch Box are used to generated a variety of Yoshimura patterns. These crease patterns are then sent to a digital cutter for perforation and cutting so that small scale paper models can be folded quickly. In this way, two-dimensional paper sheets, embedded with the crease patterns, demonstrate the capability of morphogenesis on its own, in other words, the resulting complex three-dimensional forms came directly from the paper folds rather than from the CAD programs. These paper physical models can shed light upon the structural stability of topologies and their global kinetic properties. Crease patterns are further adjusted in order to produce forms that can be reconfigured globally (Figure 7).



(a) (b)

Figure 7. Folded paper model showing a variety Yoshimura deployment.
(a) Regular Deployment of Yoshimura Pattern. (b) Irregular Deployment of Yoshimura Pattern.

Paper folding is a real physics. To model the paper folding in the computer, one needs to work in a simulated physical environment. Describing paper folding scientifically to a level of generalization and representing the morphology happened when a flat sheet of paper is folded, would essentially require complex mathematical modeling. Therefore, origami-inspired paper designs have been the subjects of many scientific research projects. For example, mathematical theorems concerning geometric properties in folded paper have been studied (Demaine and O'Rourke 2008). Computer algorithms have been developed to help fold desirable objects and to understand the best ways to fold tray cartons (Mullineux 2010). Finite element analysis has been used to study the behavior of paper during the folding process (Beex and Peerlings 2009). Since folding is real physics, Kangaroo, a live physics engine for simulation, optimization, and form finding is used to study the kinetic features as well as the final folded mesh topologies (Figure 8). The mathematical linkages between these folded mesh topologies and the crease patterns will be studied by consulting with the experts in the fields of applied geometry and topology in the future phase of this project. Furthermore, mathematical models and computational algorithms will be generated in order to produce desirable forms that can be reconfigured globally.

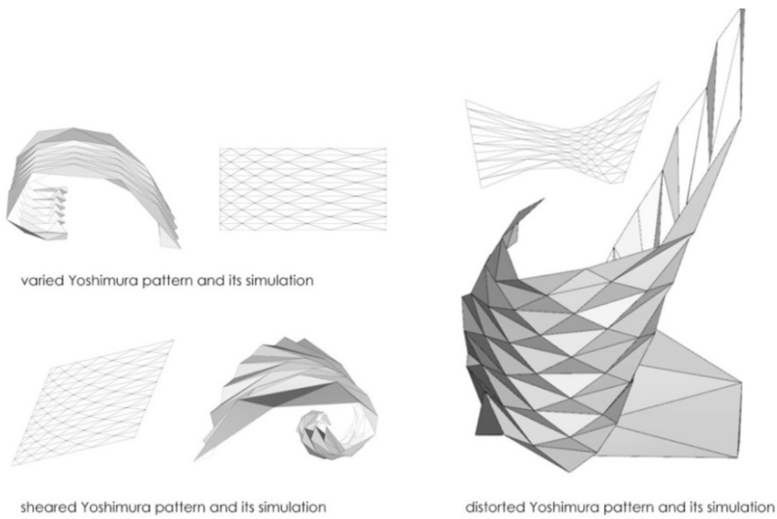


Figure 8. Digital simulations of Yoshimura pattern designs.

3.2.1: 1 Scale Mock Up in Cardboard

Corrugated cardboard has been chosen for the 1:1 scale model due to its economic, light weight, and environmental qualities. In addition, the rigid corrugated cardboard panels can be easily folded and layered to add thickness to mimic the real architectural skin. The creased and folded cardboard hinges store some kinetic energy so that fold kinematics and mechanical responses of the 1:1 scale structure can be studied. These initial studies will shed light on the material selections for the rigid panels, active hinges and the design of micro-processor controlled systems.

Large cardboard panels were laser cut. Some panels were glued together to add strength and thickness. Because of the added thickness, careful design decisions regarding folding thick-panel origami were considered by offsetting panels and cutting away the corners. These panels were later scored using a simple scoring tool, folded by hand and connected together into large cardboard sheets using plastic rivets. These rivets are removable and reusable, thus allowing the cardboard sheets to be modified easily. The overall dimensions of a cardboard sheet when lying flat are about 20 feet by 10 feet. Folding such a large piece of flat sheet is impossible by hand, and hands-free origami is necessary. In order to achieve the desirable topologies, these large cardboard sheets are therefore suspended and configured differently. In some cases, they are joined together to create dramatic spatial configurations. Figure 9 shows the making of the 1:1 scale Ruga Architecture Skin and its various topologies when suspended differently.

Figure 9. The making of a 1:1 scale RAS in corrugated cardboard.

3.3 Actuator Design and Material Selection

There are two types of materials selections: active material selection for the self-folding hinges and passive material selection for the rigid panels. Self-folding refers to the structure's ability to fold and unfold by itself without adding external forces. In order for the structure to be self-foldable, the folding hinges must be designed using active materials, which inherently convert other forms of energy, such as heat, magnetic fields, light, or electricity, into mechanical power for folding and unfolding (Edwin et al. 2014). Quantitative analysis of the actuation strain and actuation stress of an active material, as well as the fold-specific characteristics of the structure, such as the folding angle and the radius of folding curvature, need to be conducted in order to determine the appropriateness for the project.

One example of active materials is the electroactive polymer (EAP). Since the early 1990s, new polymers have emerged that respond to electrical stimulation with a significant shape or size change. They are sometimes called "Artificial Muscles" since they behave in similar fashion to biological muscles (Bar-Cohen 2004; Lee et al. 2006) investigated the application of a type of EAP called IPMC (Ionic Polymer Metal Composite) to robotic fingers. Although they had limited success, mostly due to robustness issues, this concept can be extended to folding structures (Figure 11). Kruusamae et al. (2010) further enhanced such an IPMC actuation device that is also able to sense its resistance. This is also a good candidate for the actuation of the proposed self-folding structure.

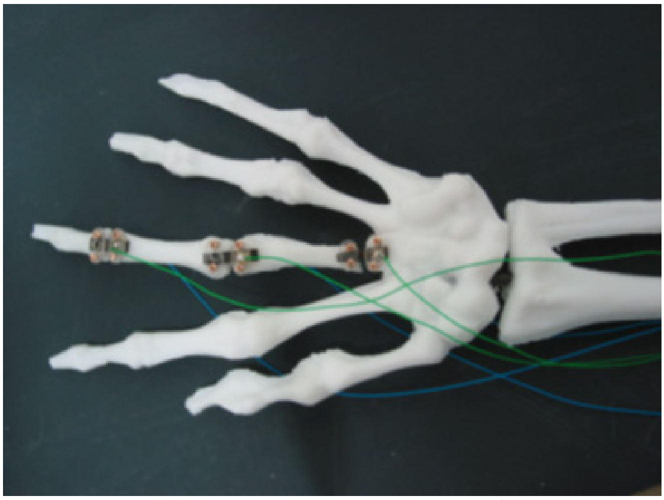


Figure 11. Electroactive polymer (EAP) used as artificial muscle.
Source: Lee et al. 2006

One of the potential materials for the rigid panels is polyester felt (a passive material), made of recycled plastic bottles by using needle punch non-woven techniques. This felt has superior acoustic quality and currently has been used in interior carpets and wall panels. While it is non-rigid, folding adds rigidity to the material. Figure 12 shows an initial test conducted with a stiffened polyester felt panel that is about 5/8 inch thick. The material can be easily cut and scored using a laser cutter and CNC router. If the material is not completely cut through, it can then be folded easily by hands.

Figure 12. Cutting, scoring and folding of stiffened polyester felt panel.

Other potential materials include HDPE, composite resin, fiberglass, polycarbonate, etc. One of such materials is paper fiber panel Kraftplex. Like paper, Kraftplex is made entirely of pure cellulose that comes from cellulose fibers of renewable softwoods in a process using only water, pressure and heat without any chemical additives, bleach, or adhesive agents. Therefore it is a hundred percent recyclable. Though it has high-density like sheet metal and plastics, it is at the same time very pliable and it can be deep-drawn into desirable creases for folding. Further studies will need to be conducted in order to test the feasibility of these different sheet materials.

3.4. Self-folding Mechanism Design

Typically, there are three methods for generating hinge-type folds using active materials, namely, “extensional,” “torsional,” and “flexural,” and they are differentiated by the ways the folds are actuated locally (Edwin et al. 2014). ‘Extensional’ method uses rods or springs that are made of active materials and that are connected to the faces of the folded panels to actuate the folding and unfolding of the panels. "Torsional" method uses active elements at the hinge to provide the twist. The twist angle of the active material thus controls how much the hinge is folded. "Flexural" method uses active material that has been manufactured to have folding memory and then flattened. This active material is then connected to the faces of the passive material. When this active material is active, it will try to return to its original folded state thus inducing the folding of the connected passive panels. These three methods for self-folding mechanism design will be studied and tested in order to determine the appropriate scheme for the 1:1 scale smart structure.

3.5. Micro-processor-based Control System

As mentioned earlier, the folded structure is dynamic and reconfigurable. Changing the angles of folding globally will result in overall three-dimensional configuration of structure. In small origami paper model, such configurability can be simply done by pulling or compressing the paper model by hand. However, in a macro-scale design where hand manipulation is impossible, automation design using remote micro-processor control systems is required. Based on the current 1:1 scale cardboard prototypes, we discovered that reconfiguration of the structure can be achieved by suspending the folded structures at strategically placed points. Such suspensions allow the gravity of the structure to be transferred into energy for self-reconfiguration. The overall system will be controlled via a micro-processor based control system, including the suspension mechanism of the structure. The structure can be reconfigured through precision control of the actuation system for folding as well as for suspension. A block diagram representation of such a control system is shown below (Figure 13).

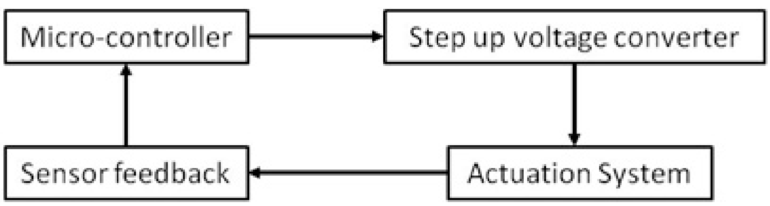


Figure 13. An example of micro-processor based control system.

It is to be noted that the design of such control system requires rigorous dynamic modeling of the folding panels, the hinge design, the actuators, the position sensor feedbacks, and the sequence of folding. Overall system stability is critical to the desired performance of the folding structure.

4. Design Verification Process

The structural rigidity, actuation mechanism performance, and self-folding control of the proposed design must be verified before building the prototype. The structural rigidity of the proposed design has been verified to certain extent through scale model prototype builds. However, for the full scale prototype would require extensive design verification process through appropriate numerical simulations and experiments.

Based on the past scale models, it can be projected that the proposed felt material as the rigid panels offers a feasible solution. The tensile, compressive, and flexural strengths and modulus elasticities are available from published literature (Kim, Shioya, Kobayashi, Kaneko, and Kido 2004a; 2004b). However, the crease patterns of the rigid panels would also contribute to strengthening of the overall structure. The strength properties of the felt material are given in the table below.

Table I: Felt Mechanical Properties (Kim et al. 2004a; 2004b)

Mechanical Property	Units in Pascal or N/m^2
Yield Strength (Tensile)	$4 X 10^8$
Yield Strength (Compressive)	$4 X 10^8$
Modulus of Elasticity (Tensile)	$40 X 10^9$
Modulus of Elasticity (Compressive)	$50 X 10^9$

The active material actuation capabilities depend on the material's stress-strain properties as well as driving voltages. Capri et al. (2007) provided a comparison of different active materials for actuation purposes. Based on this comparison, electro-restrictive polymers is deemed a feasible candidate for actuation which exhibits moderate active stresses a low active strain levels with good durability and reliability characteristics. Modulus of Elasticity for an electro-restrictive type active material is in the range of 1 – 10 GPa (Carpi, Salaris, and De Rossi 2007). In addition, these active materials can be folded for greater force generation (Carpi et al. 2007).

A finite element analysis of the overall structure will need be performed to identify any potential structural strength / rigidity issues with the materials used. Extraneous variables such as wind, heat, etc. on the structural rigidity will be investigated as a follow up study as well. The following tests are planned for design verification and expected outcomes from the tests.

i) Finite Element Analysis (FEA): One the design finalized using a CAD model, the overall structure is to be analyzed for any potential structural weaknesses with respect to a set of input variables that include the specified rigidity of the structure, wind resistance, thermal stresses, impact resistance, and any additional inputs as deemed appropriate. This analysis will be performed for both static and dynamic loading conditions to ensure that the structure is capable of withstanding such loading conditions. The CAD design needs to be updated based on the FEA analysis finding.

ii) Actuation System Modeling and Simulation: The active material based actuation system is to be modeled using analytical tools for simulating its performance characteristics. The expected outcome from this simulation would be to verify that the force/torque generation requirements are met by the selected actuator materials.

iii) Hardware-In-Loop (HIL) Simulation: The HIL simulation will be performed based on the microprocessor control system and the actuators implemented in physical hardware (scale model) where the generated force is to be measured in real time. This experiment is aimed at further verifying that the actuation system would generate the required forces and torques as per overall system requirements.

5. Conclusion

This paper presents the initial results of an ongoing RAS project by identifying the following: the design considerations, tools, techniques, methods, and processes for the construction and installation of full scale mock-ups using corrugated cardboard; the design requirements for the actuation system while identifying a number of potential candidates from active and passive systems; and the self-folding mechanism and related remote micro-processor control system appropriate for this application. While the aim of this research is to build a full scale prototype of the proposed smart, self-folding architectural skin, it is important to perform testing of such a construction in different situations in terms of site constraints and functional requirements, such as a temporary roof for public events (e.g., markets, exhibitions, and performances), a disaster relief shelter, and other public assemblies. A follow-up study is planned where different non-rigid materials would be investigated for their applications in rigid or semi-rigid structures to understand how the performances of these materials, such as cardboards, polyester felt panels and paper fiber panels, can be strengthened by applying functional coatings. Developing and using these materials by cutting, scoring, and folding require innovative and open-minded approaches from architects, designers/engineers, researchers, manufacturers, marketing professionals, and product developers. This study would be aimed at contributing to the further development of origami by experimenting with ways to unleash the potentiality of folding in self-folding and morphological architectural design. Finally, it needs to be noted that the current study focuses on the deployment of a semi-structural skin, it is understood that the full functionality of such architectural skin would depend on a full structural support system.

REFERENCES

Bar-Cohen, Y. 2004. *Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges*. Bellingham WA: SPIE Publications.

Barreto, P. T. 1997. *Lines Meeting on a Surface: The "Mars" Paperfolding*. Paper presented at the Second International Meeting of Origami Science and Scientific Origami.

Beex, L. A. A., and R. H. Peerlings. 2009. "An Experimental and Computational Study of Laminated Paperboard Creasing and Folding." *International Journal of Solids and Structures* 46: 4192–207.

Carpi, F., C. Salaris, and D. De Rossi. 2007. "Folded Dielectric Elastomer Actuators." *Smart Matertial and Structre*.16: S300–S305.

Davis, E., E. D. Demaine, M. L. Demaine, and J. Ramseyer. 2013. "Reconstructing David Huffman's Origami Tessellations." *Journal of Mechanical Design* 135 (11): 111010-1–111010-7.

De Landa, M. 2000. "Deleuze, Diagrams, and the Genesis of Form." *Amerikastudien/American Studies* 45 (1, Chaos/Control: Complexity): 33–41.

Deleuze, G. 1994. *Difference and Repetition*. New York, NY: Columbia University Press.

Demaine, E. D., and J. O'Rourke. 2008. *Geometric Folding Algorithms : Linkages, Origami, Polyhedra*. Cambridge and New York: Cambridge University Press.

Edwin, A., D. J. Hartl, R. J. J. Malak, and D. C. Lagoudas. 2014. "Origami-inspired Active Structures: A Synthesis and Review." *Smart Material and Structure*, 23 (9), 094001

Huffman, D. A. 1976. "Curvature and Creases: A Primer on Paper." *IEEE Transactions on Computers* C-25 (10): 1010–9.

Kim, J., M. Shioya, H. Kobayashi, J. Kaneko, and M. Kido. 2004a. "Mechanical Properties of Woven Laminates and Felt Composites Using Carbon Fibers. Part 1: In-plane Properties." *Composite Science and Technology* 64: 2221–9.

———. 2004b. "Mechanical Properties of Woven Laminates and Felt Composites Using Carbon Fibers. Part 2: Interlaminar Properties." *Composite Science and Technology* 64: 2231–8.

Kruusamae, K., P. Brunetto, S. Graziani, A. Punning, G. Di Pasqualeb, and A. Aabloo. 2010. "Self-sensing Ionic Polymer–Metal Composite Actuating Device with Patterned Surface." *Polymer International* 59. 3: 300–304.

Kuribayashi, K., K. Tsuchiya, Z. You, D. Tomus, M. Umemoto, T. Ito, and M. Sasaki. 2006. "Self-deployable Origami Stent Grafts as a Biomedical Application of Ni-rich TiNi Shape Memory Alloy Foil." *Material Science and Engineering.* A419: 131–7.

Lang, R. J. 1998. TreeMaker. Accessed January 30, 2015. http://www.langorigami.com/science/computational/treemaker/treemaker.php.

———. 2003. *Origami Design Secrets: Mathematical Methods for an Ancient Art*. Natick, MA: A. K. Peters.

Lee, S. J., M. J. Han, S. J. Kim, J. Jho, H. Y. Lee, and Y. H. Kim. 2006. "A New Fabrication Method for IPMC Actuators and Application to Artificial Fingers." *Smart Material Structure* 15: 1217–24.

Liapi, K. A. 2002. *Transformable Architecture Inspired by the Origami Art: Computer Visualization as a Tool for Form Exploration*. Paper presented at the 2002 Annual Conference of the Association for Computer Aided Design in Architecture, Pomona, California, October 24–27.

Lynn, G. 2004. *Folding in Architecture* Revised ed. Chichester, West Sussex and Hoboken, NJ: Wiley-Academy.

Miura, K. 2009. *The Science of Miura-Ori: A Review*. Paper presented at the Fourth International Meeting of Origami: Science, Mathematics, and Education.

Motro, R. 2009. *An Anthology of Structural Morphology*. Singapore and Hackensack, NJ: World Scientific.

Mullineux, G. M., J. 2010. "Constraint-based Simulation of Carton Folding Operations. *Computer-Aided Design* 42: 257–65.

Resch, R. D. 1968. U. Patent.

———. 1973. *The Topological Design of Sculptural and Architectural Systems*. Paper presented at the National Computer Conference and Exposition New York, NY, June 4–8.

Rutzky, J., and C. K. Palmer. 2011. *Shadowfolds: Surprisingly Easy-to-make Geometric Designs in Fabric*. New York: Kodansha International.

Tachi, T. 2011. *Rigid-foldable Thick Origami*. Paper presented at the Fifth International Meeting of Origami: Science, Mathematics, and Education.

Yoshimura, Y. 1955 "On the Mechanism of a Circular Cylindrical Shell under Axial Compression." *Technical Report, NACA TM 1390*.

ABOUT THE AUTHORS

Jiangmei Wu: Assistant Professor, Department of Apparel Merchandising and Interior Design, Indiana University, Bloomington, Indiana, USA

Dr. Sohel Anwar: Associate Professor, Mechanical Engineering Department, Purdue School of Engineering and Technology, Indiana University–Purdue University Indianapolis, Indianapolis, Indiana, USA