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ADAPTIVE ORIGAMI FOR EFFICIENTLY FOLDED STRUCTURES

FY14 Origami Annual Task Report

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Aerospace Vehicles Division

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Interim Report

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14. ABSTRACT

Three objectives to address the fundamental challenges of adaptive origami design guided the effort: 1) Identify metrics to quantitatively compare fold performance between polymeric materials, 2) Build an integrated optimization and mechanical analysis toolset to design and evaluate origami structures on both the macro and micro scale, and 3) Design, fabricate and demonstrate repeatable self-folding origami structures with remote activation capability. These three goals are highly complementary, requiring constant interchange of ideas and results, but at the same time allow work to progress in parallel until such time where they can be brought together into a complete demonstration of the concept.

The cross directorate AFRL Laboratory Research Independent Research (LRIR) team (RQ and RX) ultimately envisions the addition of unforeseen capabilities bridging both TDs.

The research developed the toolsets necessary to transfer the 2D to 3D reconfiguration capacity of origami into a design strategy for solving engineering challenges with mechanically relevant performance criteria.

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Table of Contents

Section **Page**

List of Figures

List of Tables

1. Research Objectives

This research will develop the toolsets necessary to transfer the 2D to 3D reconfiguration capacity of origami into a design strategy for solving engineering challenges with mechanically relevant performance criteria. The key objectives are:

- Identify criteria to quantitatively compare fold performance between polymeric materials
- Build an integrated optimization and mechanical analysis toolset to design and evaluate origami structures on both the macro and micro scale
- Design, fabricate and demonstrate self-folding origami structures with remote activation capability using stimuli responsive materials and novel material patterning techniques

Applications include optimal packaging of solar cell panels, sensor platforms, and remotely actuated structures.

2. Summary of Progress and Forecast for Next FY

2.1 Material failure behavior underlying fold performance

First, the important clarification on the definition of "fold" was established, with bending referring to an elastic fold and crease denoting a plastically deformed fold. Mechanically relevant metrics for folding were identified, including residual fold angle, fold angle relaxation, dissipated mechanical energy, and size of the surface plastic zone. A custom crease test apparatus and protocol enabled a comparison of fold behavior between polymeric films with different microstructures and failure mechanisms. A presentation of this work was awarded ***1st place in the 2014 Midwest SAMPE student research symposium.***

2.2 Comprehensive mechanical analysis toolsets with full integration into the design optimizer

Design optimization inherently involves a tradeoff between modeling complexity and computational expense. Three mechanical analysis tools with increasing levels of complexity were developed to enable specific design regimes. **1) Truss elements** were developed for efficient analysis of intermediate fold angle and nearly rigid problems; **2) frame elements** for larger fold and compliant fold line problems; and **3) brick finite elements** (FE) with anisotropic director profiling for modeling liquid crystal elastomers (LCE). A gradient-based optimization tool was integrated with these tools to design an actuator, identify the fold direction for maximal in-plane compression, and determine the LCE director profile to create a hinge. ***(3 publications in press)***

2.3 Origami patterns with tunable dynamic material response

The fundamental building block of the waterbomb origami pattern undergoes a snap-through bifurcation when mechanically loaded through this geometric instability. Through a nonlinear implementation of the truss model, the critical load was determined to be tunable through modulating the fold stiffness. Experimental results with laser machined polypropylene qualitatively agreed with model predictions, but revealed a distinct difference in peak load between samples with and without the vertex. The dynamic response of the snap-through structure shows potential for trigger, sensor, and toggle switch applications.

2.4 Inverse design of self-folding LCE and Nafion material systems

Two stimuli responsive material systems were utilized to fabricate the fundamental origami motif: a hinge. The shape memory response of Nafion was discovered to be reversibly locked through local patterning of sodium hydroxide ***(in press in Advanced Materials)***. Single-use folding motions could be generated through programming a hinge pattern. Locking was released via acid treatment and then ready for reprograming. Point-by-point LCE director patterning tools (PI: White, T.J.) were leveraged to fabricate origami hinges from director profile designs predicted using the mechanical and optimizer toolboxes. This novel approach drives design to the microscale, enabling origami concepts to dictate the anisotropy of the material. Localized joule heating through printed Ag ink circuits has been experimentally demonstrated, which opens the door for real-time, sequenced folding.

During FY14, 4 peer-reviewed papers were accepted for publication, 1 are currently under review and 4 are in preparation. 12 research presentations (4 invited) were given by task personnel. AFRL team members led or co-organized 2 workshops/seminars focused on origami material design. 4 on-site technical exchange events with ODESSI-EFRI awardees were held. The next FY will focus on 1) developing a multi-physics tool integrating EM and origami folding for antenna design, 2) identifying new design examples and 3) developing reliable intrinsic vs. external actuation techniques

Table 1. Use of Funds (FY 14, $K)

Gov't Salary & Supplies	On-site (VS, Students)	Capital	External Contracts
0	376	0	0

Funding Profile ($K):

Reporting FY	FY+1	FY+2
172	376	376

2.5 Goal and Broader Impacts:

The function of an engineering design is inherently tied to the geometry of the device. For example, the profile of an airfoil or the curvature of an antenna ultimately dictates whether the device successfully functions within its intended design criteria. However, what if a single design could access multiple geometric conformations? What if this design could access those shapes without human intervention, but instead morph when triggered by an environmental cue? One possible strategy for this type of shape change is *origami*. Novel origami patterns reduce an arbitrary mapping between two geometric states into a series of rotations about predefined fold lines. The actuation of shape change is likewise localized to the folding motions, making self-folding design more tractable. An origami approach has the added benefit of 2D to 3D mapping. 2D structures are more efficient to manufacture and transport, and are ideal for deployment applications requiring large surface areas, such as emergency shelters and solar cell arrays. The design concepts of origami are oriented towards aesthetic and recreational applications, such as artwork and toys. Transferring origami concepts to engineering tools involves a not only the apparent technical challenges, but also the philosophical and communication challenges associated with bridging different communities.

The appeal of origami and programmed folding is its simplicity, versatility, and ability to harnesses the multitude of 2D patterning techniques (e.g., deskjet, screen printing, lithography) to convert surface patterns on substrates into stable 3D objects within seconds upon exposure to an energy stimulus. The design and fabrication of structures based on folding/unfolding of 2D sheets is a novel paradigm that will deliver unprecedented function with relevance in many AFRL S&T priority areas. Broader impacts for AF include lightweight structural designs (weight savings to increased system capabilities), energy harvesting systems (energy efficiency and power), active and passive damping (sustainment), unfoldable air foils for precision airdrop (autonomy), threat triggered hardening of structures and sensors (operation in contested environment), and deployment/tuning of antennas and other sensors (ISR). Additionally, the reconfigurable nature of an active origami system multiplies the potential value of the technology, ranging from a logistic standpoint (able to replace a number of different parts) to an operational one (able to carry packaged systems for later deployment, and able to create a number of different systems from a single system)

3. Technical Objectives and LRIR Approach

To address the fundamental challenges of adaptive origami design, we will focus on three objectives: (1) Identify metrics to quantitatively compare fold performance between polymeric materials, (2) Build an integrated optimization and mechanical analysis toolset to design and evaluate origami structures on both the macro and micro scale, and (3) Design, fabricate and demonstrate repeatable self-folding origami structures with remote activation capability. These three goals are highly complementary, requiring constant interchange of ideas and results, but at the same time allow work to progress in parallel until such time where they can be brought together into a complete demonstration of the concept. The cross directorate AFRL LRIR team (RQ-RX) ultimately envisions the addition of unforeseen capabilities bridging the both TDs. The team organization chart (Figure 1) outlines how the optimization and mechanical design tool sets interface with the experiment efforts of polymer fold characterization and patterning of stimuli responsive materials.

To develop a frame work to achieve the above mentioned objectives, the LRIR has three main tasks:

1. Build an origami design tool with optimization of mechanical analysis. Develop a framework that integrates mechanics analysis into crease pattern design optimization. This physics-based computational origami design tool will be based on finite element models and evaluate mechanical metrics such as stiffness and input energy to quantify the performance of the structure, which the existing geometry based design tools cannot address. More importantly, geometric approaches assume the target shape is known, which is typically not the case for design criteria based on mechanical function. The mechanical analysis toolsets will be also integrated into a gradient-based optimization algorithm to design an actuator, identify the fold direction for maximal in-plane compression, and determine the LCE director profile to create a hinge.
2. Design and fabricate self-folding origami adaptive structures and materials. Establish the requisite materials and processing knowledge for development of repeatable motion enabling technologies. First, we need to develop a custom fold test and characterized failure morphology to define origami terminology of “fold”, “bend”, and “crease” for scientists and engineers to develop rigid definitions and establish distinguishing characteristics of these terms to create a universal language for the engineering community. Second, we will develop a bending mechanics model with material specific data predicts residual fold angle to compare computationally predict and empirically determine fold angle performance. Third, we will develop stimuli responsive material systems using smart material such as LCE or Nafion. With the understanding of the fundamental materials systems and strategies that will be used to create such multifunctional designs, we can build a framework to define maximize efficient fold sequences through synergy of material and structure, as well as developing new materials and device structures that are capable of folding along a pre-defined fold structure in an automatic fashion – that is, in response to a stimulus (i.e. light, electrical, magnetic, thermal, etc.).
3. Identifying Air Force Applications: For applications ranging from lightweight structures, adaptive materials, and unmanned vehicles, the ability to create complex multifunctional materials and structures from a simple 2-D sheet of material is very attractive. There are a multitude of other applications in which such folded architectures could be useful. These

include lightweight structures, energy harvesting / absorbable systems, expandable stents, air bags, expandable shelters, and heat exchangers. Moreover, this also can be extended to AF applications such as rapid access to space, reconfigurable ISR, packaging for logistics and supply, and precision drop via deployment of control surfaces. Longer term applications are also envisioned to have mathematical and computational impact on macromolecular design for specificity (capturing analytes, design of autonomic and responsive materials, etc.) akin to protein folding or DNA origami to maximize function from tertiary structure. For all of these applications, we will focus on demonstrating strategies to create such multifunctional designs based on origami engineering.

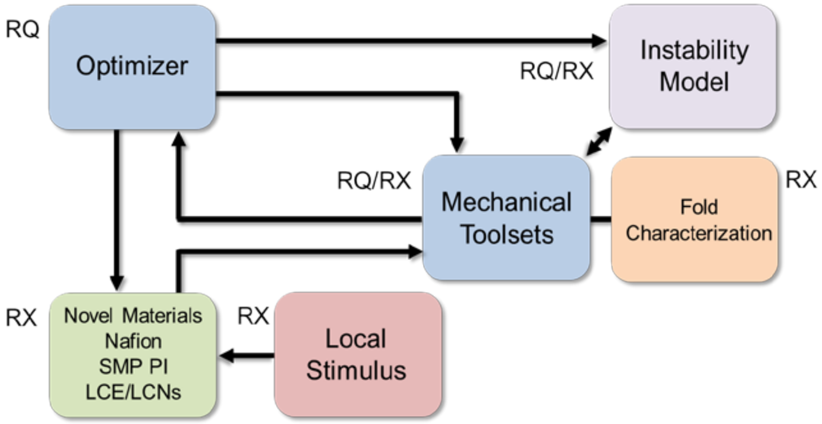

Figure 1 AFRL LRIR Organization Chart

Outlines how the optimization and mechanical design toolsets interface with the experiment efforts of polymer fold characterization and patterning of stimuli responsive materials. Directorate leads for each focus area are denoted. (RQ – Aerospace Systems, RX – Materials & Manufacturing)

4. Research Summary

4.1 Material failure behavior underlying fold performance

4.1.1 The team identified terminology to distinguish types of folding

Origami terminology of “fold”, “bend”, and “crease” are currently poorly defined terms and are often used interchangeably by artists. A need therefore exists for scientists and engineers to develop specific definitions and establish distinguishing characteristics of these terms to create a universal language for the engineering community. Here, it is proposed that the term “fold” be used as a broad term comprised of the subcategories “bend” and “crease.” A bend refers to elastic, non-localized, recoverable deformation and is represented on a force-deformation curve in **Figure 2A** as the darker region at low deformations. Formation of a crease begins when a specimen is bent past the onset of plastic deformation resulting in localized and some degree of non-recoverable deformation shown as the lighter region in Figure 2A.

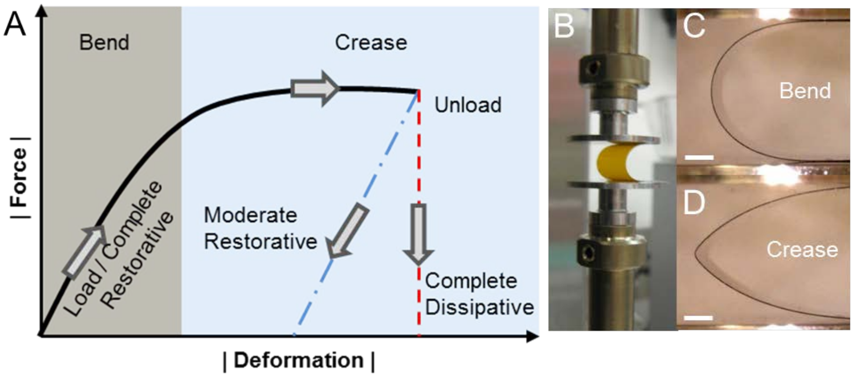

Figure 2 Fold behavior defined according to loading regime
A) *Schematic of the definition of “fold” as defined by elastic (bend) vs permanent (crease) deformation. Crease behavior depends on the failure mechanism and dissipative nature of the material.* ***B)*** *Image of parallel plate fold test with Kapton. The film is rigidly attached at the bottom contact point and allowed to freely slide at top.* ***C)*** *Side view of compressed film within the elastic range.* ***D)*** *Side view of compressed film after loading into the plastic range. Scale bar = 0.5 mm*

4.1.2 Developed custom fold test and characterized failure morphology

Crease behavior ultimately depends on the failure mechanism and dissipative nature of the material. However, this is an underdeveloped area of research for polymeric materials. Most fold research focuses on paper and paperboard for the packaging industry where it is critical to generate reproducible creases with predictable bending properties for automated assembly. A number of testing methods exist to measure bending stiffness, but are generally limited to small fold angles and low strain regime, and do not evaluate crease formation. Therefore, a new folding technique was developed to overcome these limitations. Polymer films were bent to fit between parallel compression plates (**Figure 2B**) of a displacement controlled mechanical testing apparatus equipped with a high precision force transducer. Specimens were loaded at a rate of 10 mm/min until the gap distance reached twice the specimen thickness, loading through the bend (**Figure 2C**) and crease (**Figure 2D**) regimes. Energy dissipation due to creasing was characterized by comparing the areas under the loading and unloading force-displacement curves. The crease surface morphology was evaluated using polarized microscopy, scanning electron microscopy (SEM), and profilometry **(Figure 3 A-C)**. Identification of the crease birefringence with the polarized microscope enabled approximate measurement of the crease width. **Figure 3B** shows an example of interior crease surface (compression) deformation for Kapton manifested as localized buckling. The periodicity of the surface wrinkling correlates with profilometry width measurement, with height measurements indicating deformation intensity. SEM micrographs provide an additional estimate of the crease surface morphology, collectively showing that increased localized plastic deformation drives increases in residual fold angle retention.

4.1.3 Bending mechanics model with material specific data predicts residual fold angle

The fold test facilitates direct measurement of residual fold angle, fold stiffness, and morphological details of the material failure at the crease. However, for specific applications where fold angle is of singular interest, a model of a crease deformation may be able to computationally predict versus empirically determine fold angle performance. Using readily available uniaxial tension data, the polymer film near the crease was modeled as a beam under pure bending. Assuming a linear strain field through the thickness of the beam, the strain field was calculated based on the applied curvature. Elastic and plastic strains were identified in the beam cross-section using the yield point from experimental uniaxial tension stress-strain curves. Unavailable compression stress-strain curves were taken to be symmetric to the tension data. After computationally accruing plastic deformation by applying curvature to the beam, residual curvature is calculated by solving zero moment balance across the beam cross-section. Residual fold angle is then calculated from the residual curvature and an estimate of the plastic zone of the beam, currently taken as the experimental cease width. The residual fold angle contour plot shown in **Figure 3E** shows the dependence of residual fold angle on applied curvature and specimen thickness, using uniaxial tension data for Kapton. Experimental fold angles for Kapton (dots) overlay the model data in **Figure 3E** and demonstrate good agreement, even without a fitting parameter. However, the model is not completely independent of the folding test data, as measured crease width was need to estimate the plastic zone. A database of crease width as function of applied curvature and thickness is being created to identify trends, which may eliminate the need to testing across all material and specimen geometries. Next steps include evaluating materials with different material failure mechanisms and integrate these constitutive details into the origami design toolsets.

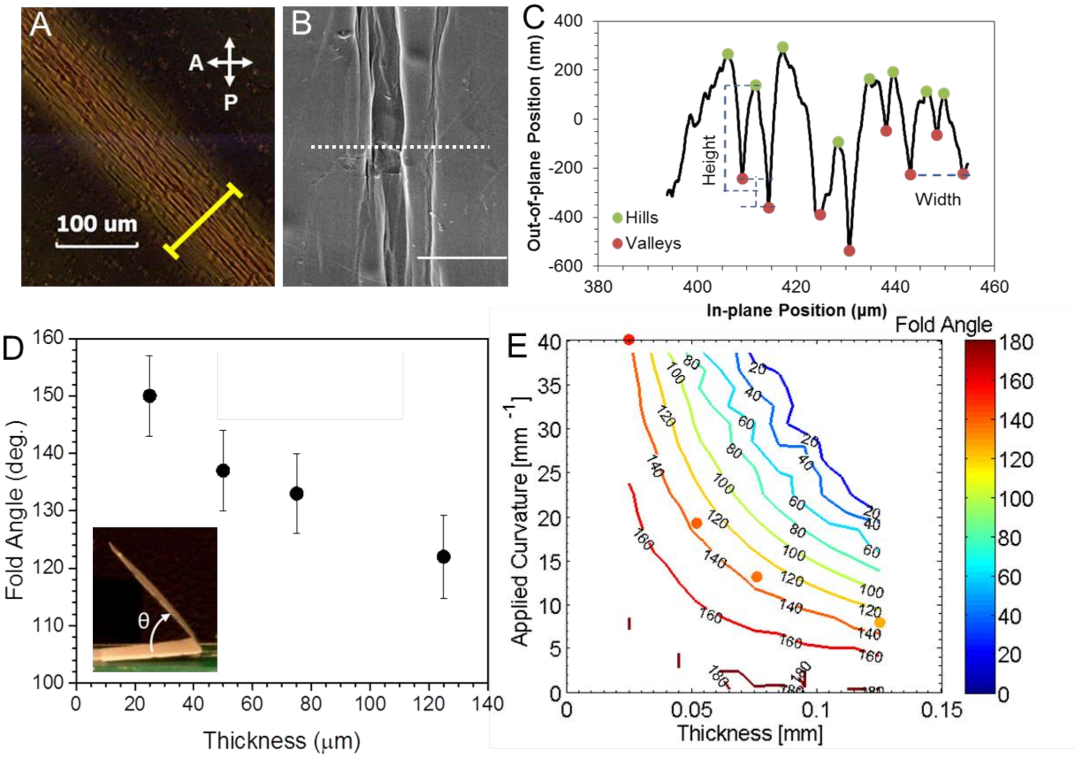

Figure 3 Residual fold angle is predictable from uniaxial tension data and morphology at crease surface

A) *Polarized microscopy image of Kapton film surface at the interior of the crease. Yellow bar denotes the crease width.* ***B)*** *Representative SEM image of interior crease surface of a Kapton film, indicating distribution of wrinkle wavelengths. Scale bar = 10um.* ***C)*** *Profilometer data of Kapton interior crease surface confirming wavelength distribution and amplitude diversity. Representative location of profilometer trace is denoted by dashed line across crease in subfigure B.* ***D)*** *Residual fold angle of Kapton films with different thickness after loading to R/t=1. The increased plastic deformation near the surface in thicker films reduces the spring-back response, resulting in lower residual fold angles. mean ± std, Inset: side view of crease polymer denoting fold angle convention* ***E)*** *Linear bending mechanics model using uniaxial tension data and crease width data quantitatively predicts the residual fold angle as function of applied curvature (mm^{-1}) and film thickness (mm). Colormap indicates fold angle. Data presented corresponds to Kapton specimens.*

4.1.4 Comprehensive mechanical analysis toolsets with full integration into the design optimizer:

Origami provides a strategy for mapping between two or more geometric states through a series of fold operations. However, even with a strategy, designing origami structures presents several challenges:

- What is the optimal pattern of fold lines to achieve a target folded shape?
- What is the optimal fold direction?
- What is the optimal distribution of fold stiffness to minimize the required input energy or bias the direction of folding under complex loading?
- How can facet and fold line compliance be used to create dissipative structures?

Geometry based design tools, such as Treemaker and Rigid Origami Simulator, address some of these challenges, i.e., finding the 2D pattern of fold lines required to achieve a target 3D shape.

However, these tools do not evaluate mechanical metrics such as stiffness and input energy, but instead assume rigid origami with inextensible fold lines and perfect hinges. More importantly, geometric approaches assume the target shape is known, which is typically not the case for design criteria based on mechanical function. To address these challenges, mechanical analysis toolsets were developed and integrated into a gradient-based optimization algorithm to create a design tool for origami structures with mechanically relevant functions.

Design optimization inherently involves a tradeoff between modeling complexity and computational expense. Three mechanical analysis tools with increasing levels of complexity were developed to enable design in specific regimes. **Truss elements** were developed for computationally efficient analysis of intermediate ranges of fold angles ($< 30^{\circ}$) and nearly rigid problems. Truss elements can only transmit load along the member connecting neighboring nodes. A network of truss members can therefore by described strictly by the 3 translational degrees of the freedom (DOF) at each node *(6 DOFs per element)*. To incorporate folding, the stiffness associated with the fold angle between two adjacent facets is prescribed based on a trigonometric relationship. The truss toolbox is computationally inexpensive due its low number of DOFs, which is excellent for optimization problems. However, the tool is undefined near fold closure and facet compliance can only be approximated as another foldline, which together focuses this element's utility to compliant perturbation problems or rigid origami with intermediate fold angles.

Frame elements (*full beams*) are similar to truss elements, but allow for transverse loading and torsion. Additional DOFs, slopes and angle of twist, are assigned to each end of the frame element, along with the corresponding moments and torque *(12 DOFs per element)*. An analog of the torsion angle is used to explicitly define fold angle. With the additional DOFs, the in-plane and out-of-plane bending compliance may be locally optimized, enabling design of structures with facet and fold stiffness on similar orders of magnitude. By appropriately scaling the material moduli related to these modes of deformation, the response of the system can be separated out according to different strain energy levels. For instance, an origami structure with compliant, but inextensible facets can be defined using modest moments of inertia for the member while retaining a high axial stiffness (see **Figure 4A**). Similarly, folding-only deformations may be isolated by assigning the fold stiffness to be much smaller than the stiffness of stretching and bending, as shown in **Figure 4B.** The fold stiffness of the two dashed lines is varied relative to the fixed stiffness of the solid lines, highlighting how specific types of mode shapes, which are a representation of possible fold schemes that can be energetically arranged through the redistribution of fold stiffness.

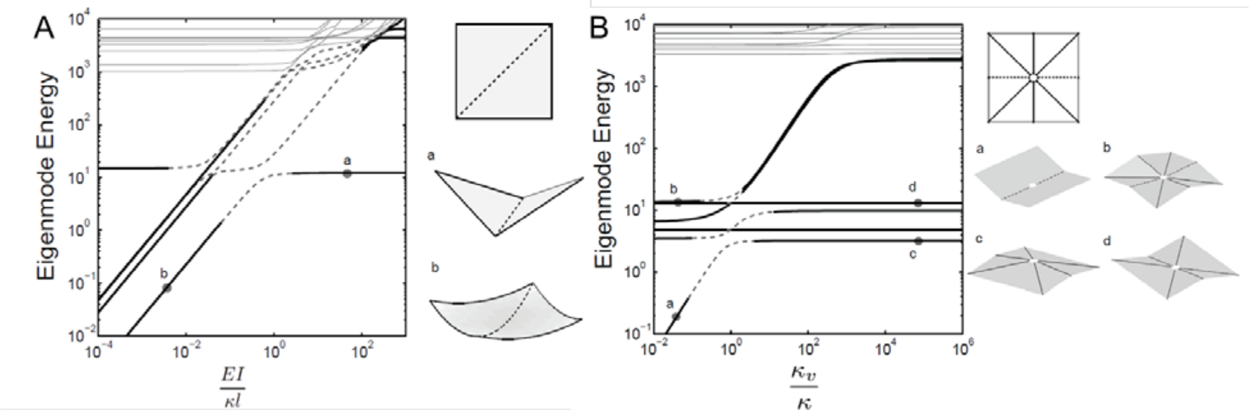

Figure 4 Energetic ranking of deformation regimes

A) *Eigenmode energy vs the ratio of bending stiffness to fold stiffness, EI/κl of a single fold a) Folding mode in rigid facet regime; b) Facet bending mode in compliant regime; characteristic length, l = 1.* ***B)*** *Eigenmode energy vs fold stiffness ratio, k_v/k, where k_v is the varying fold stiffness of the two dashed lines and k is the constant stiffness of the solid lines. Subplots a-d detail specific mode shapes as called out on the energy and stiffness ratio plot.*

The truss and frame element toolset are specifically tailored to analyze macroscale origami designs. Material properties do not vary through the thickness of the structure, or if they do, may only be approximated though higher level parameters, such as an angle dependent fold stiffness or other geometric nonlinearity. However, in order to apply origami concepts to the design of material microstructures, mechanical modeling of through-thickness gradients and spatially heterogeneous material anisotropy is required. Layered, 8-node, linear **brick elements**, with anisotropic material properties, were developed to model the heterogeneities of tailored microstructures. Brick elements have only twice as many DOFs as frame elements *(24 DOFs per element)*, but more bricks are needed to spatially resolve microscale features, resulting in more computational expense. More details of this toolbox and optimization study using brick elements is included in the LCE inverse design section (**Figure 12**).

Optimization Case Study #1: Design of 2D-to-3D Mechanism

A novel computational origami design tool that integrates mechanics analysis into crease pattern design optimization was developed and used for mechanism design. Adaptation of truss-based FEA allows for the translation of an action origami design problem conventionally described in artistic or purely mathematical terns into an engineering problem. For instance, performance of an origami-based mechanism design is expressed in terms of the displacement of select nodes upon application of a prescribed force input with a given input energy. Moreover, the crease design can be described as distribution of fold stiffness or intentional material defects, which facilitates the application of topology optimization traditionally used to solve structural design problems via addition or removal of the constituent material.

The example in **Figure 5** shows the optimal crease pattern and its folded configuration, reproducing a known action origami called "Chomper". The result illustrates a mechanism that achieves 3D performance, but is designed within a 2D design space, leveraging one of the most relevant characteristics of origami. Various crease types were studied; results converge to the same solution when matching the problem specifications, indicating the robustness of the optimization algorithm.

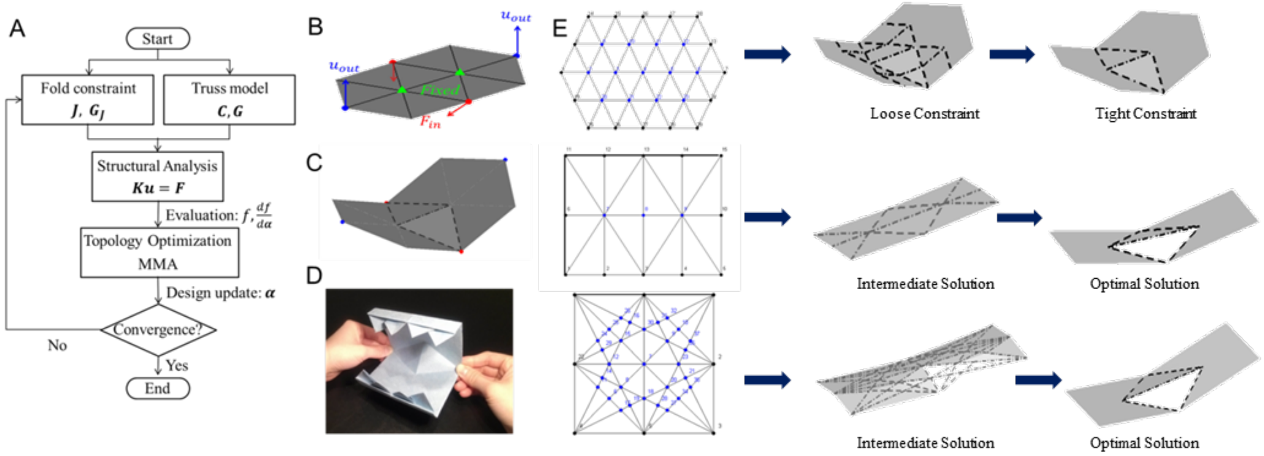

Figure 5 Mechanism design through topology optimization of origami crease pattern
A) *Optimization flowchart;* ***B)*** *problem specifications;* ***C)*** *folded configuration of the optimal design;* ***D)*** *known action origami design "Chomper ";* ***E)*** *crease design optimization with different reference crease patterns.*

Optimization Case Study #2: Optimal fold direction of in-plane compression

An in-house frame-based FEA model was developed in order to specify the characteristics of the origami components: facets and foldlines explicitly, instead of the implicit characterization of folds used in the truss-based FEA. The model was used in the design of an origami folding pattern for in-plane compression. Modal analysis was used to identify fold directions off of a flat configuration, by separating out higher-energy deformations such as stretching, bending and twisting across facets. The problem of finding how to fold a flat sheet using in-plane compression is cast as designing a perturbation off of the flat configuration by optimizing a linear combination of fold mode shapes.

The designed origami folds with a tight constraint on the perturbation energy input and a relaxed energy constraint are shown in **Figure 6B** and **6C**, respectively. The more complex solution in **Figure 6C** required a 2-fold increase in perturbation energy, but resulted in marginal performance improvement (< 2%) over the lower energy solution in **Figure 6B**. Perturbation energy is a particularly relevant metric for adaptive origami as the perturbation off of the flat configuration is the "decider" of the shape, which requires an orchestrated network of actuators or self-folding patterning. The origami design with a tighter energy constraint reduces to the well-known Miura-ori pattern, which is empirically known for its efficiency in flat-folding to a compact structure. This feature motivates the use of the Miura-ori pattern as a replacement array for the warfighter's solar cell (**Figure 6D-F**). The Miura offers a 5-fold increase in deployed area with a comparable carrying size to the current "wallet" type array. This is just one example of how origami design concepts can convert into engineering solutions supporting the AF mission.

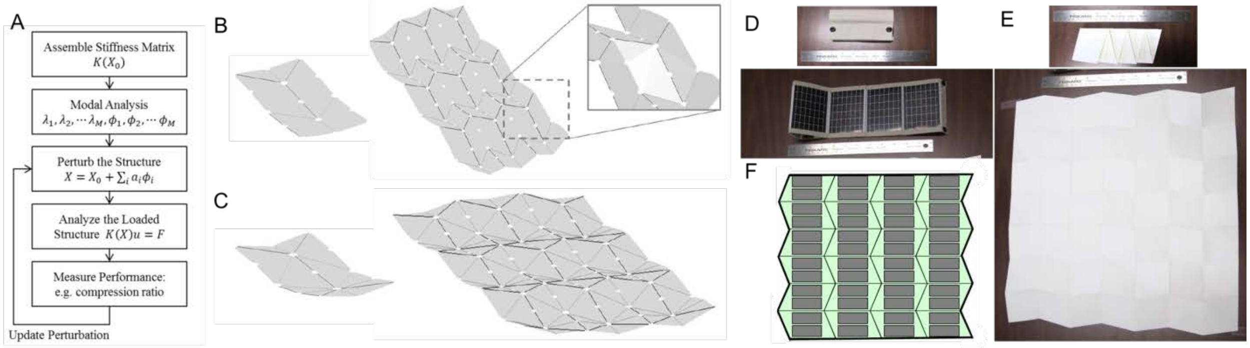

Figure 6 Optimization for in-plane compression converges to Miura pattern

A) *Flowchart of the design optimization process;* ***B)*** *solution in the unit cell (left) and a periodic structure (right) with low perturbation energy requirement (Miura);* ***C)*** *Higher perturbation energy solution, but only marginal improvement over Miura (< 2%)* ***D)*** *Miura-Ori proposed as a replacement pattern for warfighter solar cell array. Folded and deployed areas of current wallet solar cell array.* ***E)*** *Demo of folded and deployed areas of next generation solar array using Miura-Ori pattern (5x increase in deployed area for same carrying size).* ***F)*** *Schematic of deployed Miura-Ori structure with solar cell distribution.*

Origami pattern with a tunable dynamic material response:

Action origami is an important subset of origami that includes designs that can actuate between two or more states. The prospect of robust, tunable actuators that are also inexpensive to manufacture motivates the identification and analysis of action origami structures. One such structure is the fundamental building block of the waterbomb origami pattern, which undergoes a snap-through bifurcation when mechanically loaded through a geometric instability. The snap-through structure has two stable states (**Figure 7A,B**) between which it dynamically transitions (<0.5s) when compressed beyond a critical load. Through a nonlinear implementation of the truss model, the critical load was determined to be tunable through modulating the fold stiffness (**Figure 7C**). Experimental results with laser machined polypropylene qualitatively agreed with model predictions, but revealed a distinct difference in peak load between samples with and without the vertex (**Figure 7D**). Samples with the vertex intact required a small (~10%) increase in load to snap to the other stable state. This is due to the inversion of the folds near the vertex, while away from the vertex all the mountain and valley folds retain their orientation. The dynamic response of the snap-through structure shows potential for trigger, sensor, and toggle switch applications.

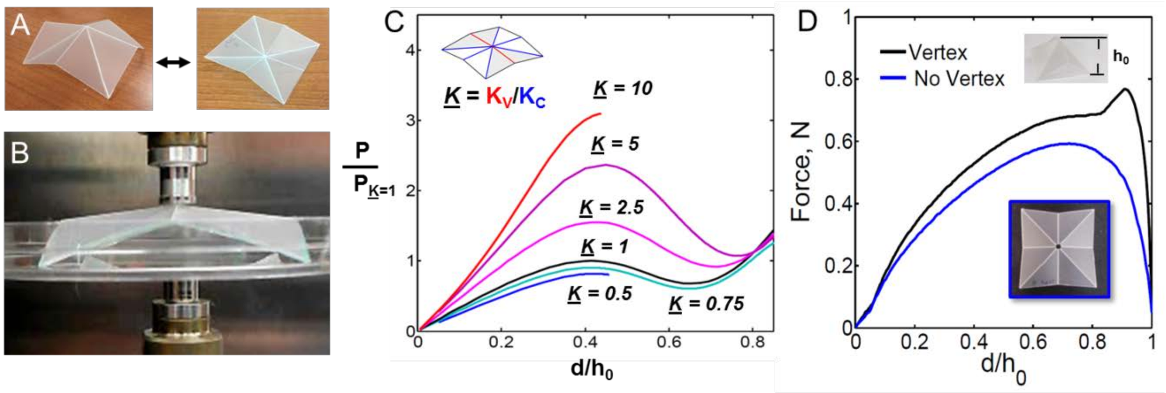

Figure 7 Dynamic snap-through origami structure is tunable via fold stiffness

A) *Two stable configurations of the waterbomb snap-through structure constructed from laser machined polypropylene.* ***B)*** *Experimental setup of mechanical loading with compressive load applied at center vertex and sliding at corner nodes.* ***C)*** *Nonlinear implementation of the truss element generated force-displacement curves for the snap-through structure with varying stiffness of the interior fold lines.* $K = K_v/K_c$ *where* K_v *is the varying fold stiffness of the two red lines and* K_c *is the constant fold stiffness of the blue lines.* ***D)*** *Experiments with polypropylene show that vertex inversion increases critical load. Model generates data qualitatively similar to no vertex specimens. Insets: picture of structure before loading and top view of structure with vertex removed.*

Inverse design of self-folding LCE and Nafion material systems:

Self-folding origami requires materials that generate strain or release stored strain in response to a stimulus. Shape memory polymers allow mechanically induced strains to be temporarily stored, and then released with heating above the storage temperature. Complex, folded shapes can be generated through this shape memory response. The temporary shape of Nafion was discovered to be reversibly locked through local patterning with a basic solution (NaOH). Base treatment deprotonates the side chain of the Nafion polymer increasing the stiffness and temperature cooperative relaxation (100 °C - T_{H^+} vs 260 °C - T_{Na^+}) of the polymer (**Figure 8 A-C**). By patterning the base locally, the film will take on complex 3D conformations when released due to the incompatibility of the strain fields between the locked and unlocked regions. The 2D to 3D transformation of a uniaxial stretched bar with a locked strip in the center was predicted by FE modeling (**Figure 8D**). The simulations showed that only a through-thickness penetration of the locking reagent, with increased locked area on bottom vs the top (+10% A_{bot} vs A_{top}) was capable of generating the upward bend of the film when thermally released (**Figure 8 E-I**). Precise patterning of the locking agent was performed through printing, as seen with the honeycomb structure in **Figure 8 J-K**. Inverse patterning is also possible, where by the entire film is locked in the stretched state and then select regions are unlocked with a localized treatment of an acidic solution, such as HCl. Inverse patterning is advantageous for origami applications because only the hinge will deform at the release temperature, while the facets remain locked (**Figure 8L**). The robust temperature separation of this chemical locking strategy, combined with the precision of the printing approach, make Nafion a novel candidate for single-use, deployable, origami structures.

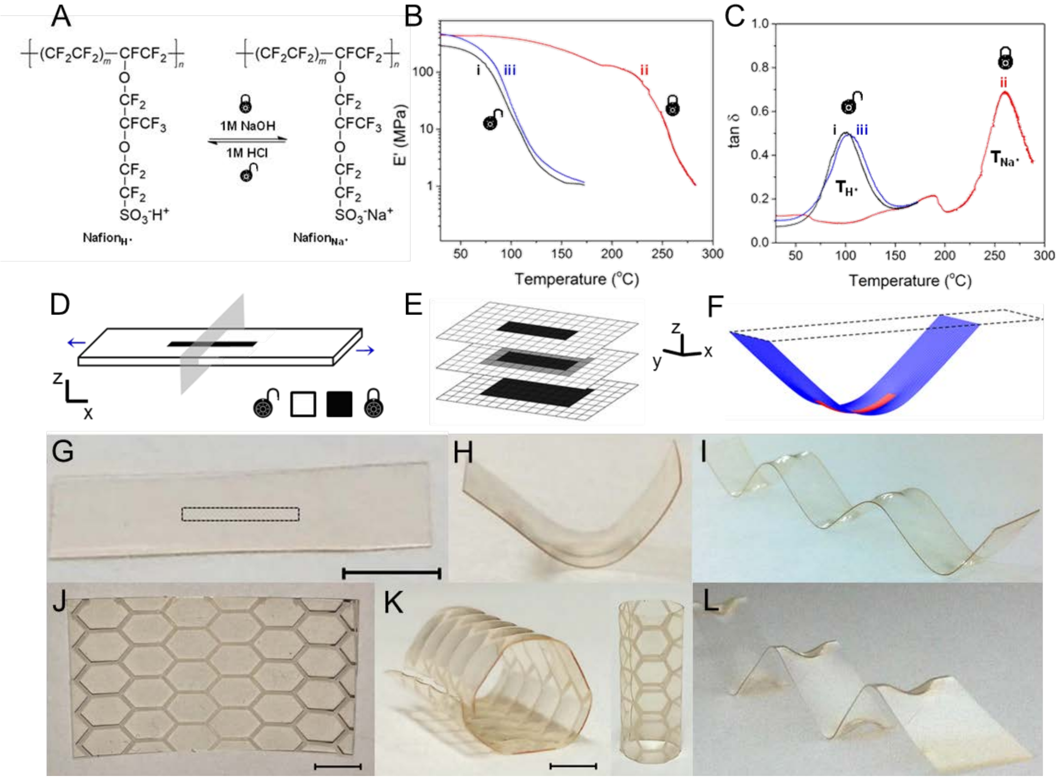

Figure 8 Temporary locking of Nafion shape memory effect generates complex 3D structures
A) *Schematic of Nafion deprotonated with NaOH treatment and reprotonated with HCl. Chemical locking of Nafion increased the recovery temperature of the temporary shape as shown in* ***B)*** *the storage modulus and* ***C)*** *tan δ plots, where i) is the unlocked, ii) locked with 1M NaOH and iii) recovered unlocked film via 1M HCl treatment.* ***D)*** *Schematic of uniaxial shape memory with* ***E)*** *through-thickness diffusion gradient.* ***F)*** *Shell FE model of shape memory response with locked and unlocked regions, confirming experimental results shown in* ***G-H.*** ***I)*** *Series of alternating top and bottom application of 1M HCl generates fold-like zig-zag shape.* ***J,K)*** *Honeycomb pattern of the locking agent created via felt-tip printing technique, which highlights the versatility of this locking approach for 3D shape design.* ***L)*** *Zig-zag fold pattern using the inverse locking method, where the entire temporary shape is locked and only select regions exhibit a shape memory effect. Scale bars = 0.5cm*

Many adaptive origami applications require cyclic actuation, such as opening and closing of a solar array or the precision tuning of an airfoil's topology for optimal lift. Such applications necessitate stimuli response materials with the ability to precisely and reversibly actuate through a range of folding motions. LCEs in development at AFRL generate strains up to 60% and show good reversibility in preliminary testing (> 100 cycles). Using an in-house, optical patterning tool, the local director of the LCEs can be arbitrarily oriented in the plane of the film, as well as through-thickness for films under 100 µm thick. This novel approach enables origami design concepts to inform the material anisotropy at the microscale. To facilitate the preparation of spatially heterogeneous LCEs, we assembled an optical patterning system in which the polarization of an irradiating 445 nm laser over an area as small as 0.01 mm^2 is controlled. The optical setup manipulates the local surface alignment of the LC cells and subsequently controls the mechanical response of the LCE. As an illustration of the tool's resolution, a grayscale image of the first powered flight of the Wright brothers was converted to an array of director orientations between 0° (dark) and 45° (bright) (**Figure 9A-C**). Note the retention of detail, even after conversion from an image to a mapping of an LCE material property. Three-dimensional displacement can be generated by introducing non-uniform director profiles through the thickness, as demonstrated in **Figure 9D**. “Mountain” and “valley” folds are prepared by writing twisted nematic, where the orientation of the nematic director rotates by 90° through the sample thickness. The Miura-ori pattern describes a series of both mountain and valley folds that can be simultaneously folded or unfolded with a mechanical stimulus. **Figure 9E** shows a Miura with 84 hinges that was patterned, and closely replicated the response of a macroscale Miura fold. Each hinge folds and unfolds on heating and cooling respectively, which leads to a reversible five-fold reduction in area between room temperature and 140 °C.

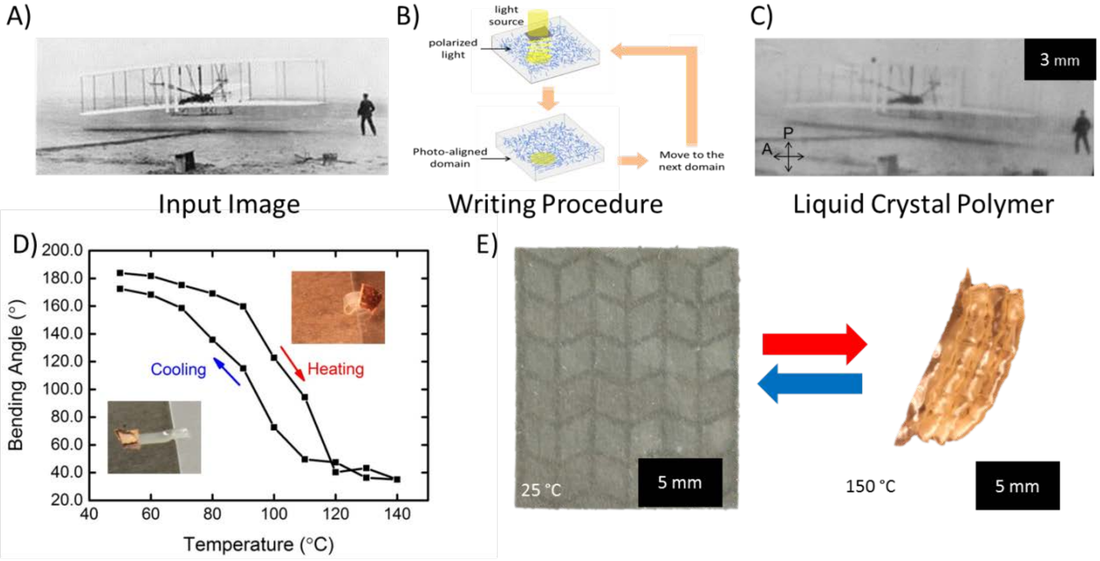

Figure 9 Liquid crystals can be aligned point-by-point by altering surface conditions
A-C) *an image is digitized, and the gray scale value is converted to an alignment condition. Between crossed polars the programmed optical rotation of the liquid crystal introduces light and dark regions.* ***D)*** *Bending response of a twisted nematic hinge in response to temperature change.* ***E)*** *At room temperature the LCE film is flat and upon heating above 150 °C collapses in a way reminiscent of Miura-ori***.**

Further control of actuation can be introduced by localizing the thermal stimulus. Localized joule heating via inkjet printing of Ag resistors has been experimentally demonstrated (**Figure 10**), which opens the door for real-time, sequenced folding. Device fabrication on a substrate that changes shape with temperature places a variety of demands on the method of fabrication, including low processing temperatures and strain resistance. After screening a variety of printable conductors, a reactive Ag Ink was selected. In **Figure 10**, a single joule heated hinge is shown in flat and bent state after 20 cycles. The IR image shows how Joule heating allows for localize heating with very precise temperature control and fast heating and cooling process.

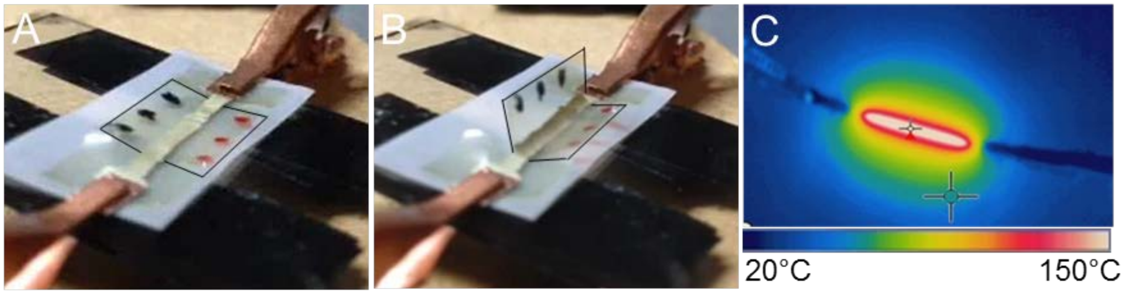

Figure 10 LCE hinge with printed Ag line

A) *hinge in flat state before heating.* ***B)*** *hinge with 90° fold after Joule heating (1V, 250 mA). Edge of hinge outlined to assist viewing.* ***C)*** *IR image of the heated hinge demonstrating the intensity (150°C) and localization of this approach.*

Experimentally, a number of non-idealities have been observed in precisely controlling the deformation LCEs. This can be attributed to the isochoric mechanical response of each active voxel and discontinuities within the director field. To overcome these challenges, the mechanical analysis and optimization toolboxes have been adapted to identify robust hinge designs. An inverse design problem is cast as a problem of finding an optimal director orientation pattern of the active polymer to match the desired deformation. The deformation analysis, as well as the sensitivity analysis, is done through FE approximation of the elastic and thermal strains using low fidelity linear brick elements. The optimization, modelling and characterization process flow is depicted in **Figure 11**. Upon convergence of the optimization problem, the produced pattern is characterized using a nonlinear shell analysis and then programmed into a LCE elastomer film. Future efforts will focus on understanding network effects of interconnected hinges, by leveraging the feedback between the design and experimental elements of the LCE system.

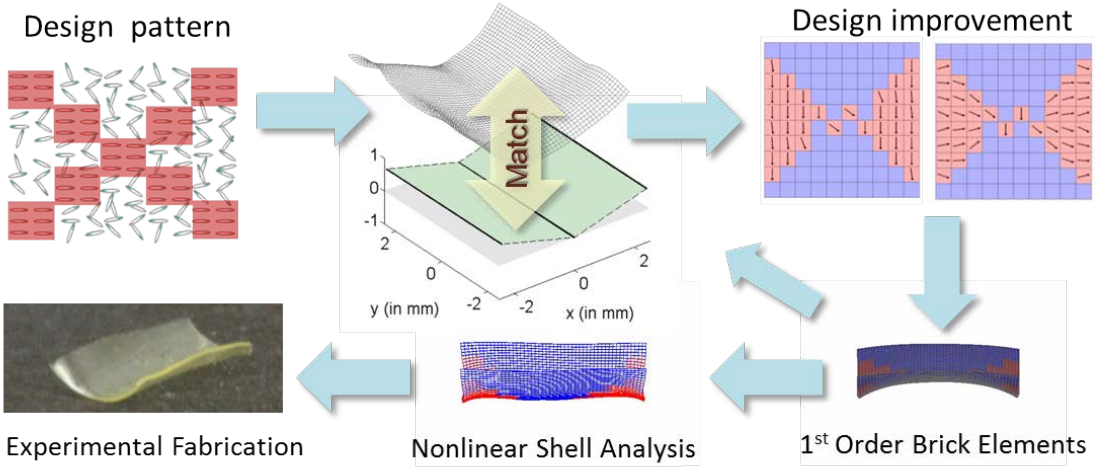

Figure 11 Optimized LCE director patterns are needed to generate origami-like structures

The design process consists of optimization of the director profile to match a target shape. The resulting designs are then verified using nonlinear shell analysis and subsequent experimental fabrication.

APPENDIX A: In-house Activities

Personnel:

Air Force

NAME	Directorate	DEGREE	DISCIPLINE	INVOLVEMENT (PY)
James Joo	RQ	PhD	Mechanical Eng.	0.2
Greg Reich	RQ	PhD	Aerospace Eng	0.1
Michael Durstock	RX	PhD	Materials Science	0.1
Loon-Seng Tan	RX	PhD	Chemistry	0.1
Richard Vaia	RX	PhD	Materials Science	0.1
Tim White	RX	PhD	Materials Science	0.1

On-Site Contractors

NAME	DEGREE	DISCIPLINE	INVOLVEMENT (PY)
Andrew Abbott	MS	Materials Eng.	1.0
Giorgio Bazzan	PhD	Chemistry	1.0
Phil Buskohl	PhD	Theoretical Mechanics	1.0
Kazuko Fuchi	PhD	Mechanical Eng.	1.0
Ryan Kohlmeyer	PhD	Chemistry	0.1
Jared Needle	BA	Mathematics	1.0
Taylor Ware	PhD	Materials Science	0.2
JJ Wie	PhD	Chemical Eng.	0.2

APPENDIX B: Outreach and Community Leadership by LRIR Personnel

1. White, T. Co-Organizer, Shape Programmable Materials Symposium at the 2014 MRS Spring Meeting, 20-24 Apr 2014, San Francisco, CA
2. Joo. J. Co-Organizer, Symposium on Origami-Based Engineering Design, ASME International Design Engineering Technical Conference (IDETC), 17-20 Aug 2014 Buffalo, NY
3. Fuchi, K. Guest Speaker, Educational Outreach, Workshop on Aerospace Systems and Origami at the Dayton Regional Stem School, June 6, 2014
4. Fuchi, K. Course Instructor, EGR 7040 Design Optimization at Wright State University, Fall 2014
5. AFRL site visits and student exchange from ODESSEI teams:
    - Stavros Georgakopoulos, “Origami Reconfigurable Antennas,” April 2014, FIU
    - Manos Tentzeris “Inkjet-Printed Nanotechnology-enabled RFID, Internet of Things” and "Zero-Power" Wireless Sensor Nodes”, June 2014, GIT;
    - Darren Hartl, “Analysis and Design of Functionally Optimized SMA-Based Reconfigurable Structures” May 2014, TAMU;
    - Spencer Magleby, “Origami-Inspired Design of Mechanical Systems”, June, 2014, BYU
    - Student Exchange: John Gibson, EE Graduate Student (FIU, Georgakopoulos Lab) May-Aug 2014

APPENDIX C: Publications, Presentations

C1. Refereed Publications:

1. Kohlmeyer, R.R., Buskohl, P.R., Deneault, J.R., Durstock, M.F., Vaia, R.A., Chen, J. Shape reprogrammable polymers: encoding, erasing, and re-encoding. **Advanced Materials** 2014, (in press)
2. Wie, Jeong Jae; Wang, David H.; Lee, Kyung Min; Tan, Loon-Seng; White, Timothy J. "Molecular Engineering of Azobenzene-Functionalized Polyimides to Enhance Both Photomechanical Work and Motion" **Chemistry of Materials** (2014), Ahead of Print-online (joint with LRIR 09RX06COR: PI Tan, PM: C. Lee)
3. Jeong Jae Wie, David H. Wang, incent P. Tondiglia, Nelson V. Tabiryan, Rafael O. Vergara-Toloza, Loon-Seng Tan, and Timothy J. White, "Photopiezoelectric Composites of Azobenzene-Functionalized Polyimides and Polyvinylidene Fluoride", **Macromolecular Rapid Communications**, 2014 (in press). (joint with LRIR 09RX06COR: PI Tan, PM: C. Lee)
4. Fuchi, K., Buskohl, P.R., Joo, J.J., Reich, G.W, Vaia, R.A. Topology optimization for design of origami-based active mechanisms. **Proceedings of the ASME International Design Engineering Technical Conference**, Buffalo, NY, August 17-20, 2014 (in press)
5. Fuchi, K., Buskohl, P.R., Ware, T., Vaia, R.A., White, T.J., Reich, G.W, Joo, J.J. Inverse design of LCN films for origami applications using topology optimization. **Proceedings of the Smart Material, Adaptive Structures, and Intelligent Systems Meeting**, Newport, RI, Sept. 8-10, 2014 (in press)
6. Abbott, A.C., Buskohl, P.R., Joo, J.J., Reich, G.W., Vaia, R.A. Characterization of creases in polymers for adaptive origami structures. **Proceedings of the Smart Material, Adaptive Structures, and Intelligent Systems Meeting**, Newport, RI, Sept. 8-10, 2014 (in press)

C2. Submitted/In Preparation Refereed Publications:

1. Fuchi, K., Buskohl, P.R., Joo, J.J., Reich, G.W., Vaia, R.A. Numerical analysis of origami structures through modified frame elements. Proceedings of the 6th International meeting on Origami in Science, Mathematics and Education, August 10-13, 2014, Tokyo, Japan (submitted for review)
2. Fuchi, K., Buskohl, P.R., Joo, J.J., Reich, G.W, Vaia, R.A. Fold stiffness optimization approach to design adaptive origami structures. (in preparation)
3. Fuchi ,K. Ware, T., Buskohl, P.R., Reich, G.W, Joo, J.J., Vaia, R.A., White, T.J. The Box: Design criteria for high-fidelity printed LCE origami structures (in preparation)
4. Buskohl, P.R., Abbott, A.C., Bazzan, G., Durstock, M.J., Vaia, R.A. Tunable origami actuator for dynamic response applications (in preparation)
5. Abbott, A. C., Buskohl, P.R., Joo, J.J., Reich, G.W., Vaia, R.A. Failure mechanism guided prediction model for fold angle rentention in polymeric origami structures. (in preparation)

C3. Patents:

1. Loon-Seng Tan, David H. Wang, Hilmar Koerner, and Richard Vaia, “Cross-Linked Aromatic Polyimides and Methods of Making the Same”, U. S. Patent 8,791,227 (issued Jul 29, 2014) (joint with LRIR **09RX06COR**: PI Tan, PM: C. Lee)
2. Loon-Seng Tan, David H. Wang, Kyungmin Lee, and Timothy J. White “Azobenzene-Containing glassy Polyimides capable of photo-induced large-angle bending,” U. S. Patent 8,785,589 (issued Jul 22, 2014) (joint with LRIR **09RX06COR**: PI Tan, PM: C. Lee)
3. Loon-Seng Tan and David H. Wang, "Multifunctional Crosslinkers for Shape-Memory Polyimides, Polyamides and Poly(amide-imides) and Methods of Making the Same" U.S. Patent Appl. Serial No. 14/013,090 (filed on Aug 29, 2013). (joint with LRIR **09RX06COR**: PI Tan, PM: C. Lee)

C4. Presentations (*Invited/Keynote) (12 talks, 4 Invited):

1. Buskohl, P.R., Bazzan, G., Abbott, A.C., Durstock, M.F., Vaia, R.A. Targeting fold stiffness to design enhanced origami structures. Proceedings of the Applied Physical Society Meeting, Denver, CO, Mar. 3-7, 2014
2. Abbott, A.C., Buskohl, P.R., Joo, J.J., Reich, G.W., Vaia, R.A. "Polymeric Crease Characterization Techniques and Performance Criteria for Adaptive Origami Structures" Midwest SAMPE Student Symposium, National Composites Center, Kettering, OH, April 3, 2014. **(1st Place Award, Master's Division)**
3. Ware, T., Wie, J.J., McConney, M.E., White, T.J. Optimization of materials chemistry of photoresponsive liquid crystal polymer networks, Proceedings of the Materials Research Society Meeting, San Francisco, CA, Apr 21-25, 2014
4. Abbott, A.C., Buskohl, P.R., Needle, J., Joo, J.J., Reich, G.W., Vaia, R.A. The "Fold": Performance criteria for polymers used in adaptive origami structures. Proceedings of the Materials Research Society Meeting, San Francisco, CA, Apr 21-25, 2014
5. *Reich, G.W., Vaia, R.A., White, T.J., Joo, J.J., Durstock, M.F., Seng Tan, Adaptive Origami for Aerospace Systems. Proceedings of the Materials Research Society Meeting, San Francisco, CA, Apr 21-25, 2014
6. Buskohl, P.R., Fuchi, K., Joo, J.J., Reich, G.W, Vaia, R.A. Exploiting the rigid-compliant origami transition to design adaptive actuators. Proceedings of the Materials Research Society Meeting, San Francisco, CA, Apr 21-25, 2014
7. *Vaia et al. "Where art and technology meet: Origami for 3D adaptive devices," 2014 SPIE DDS: Micro/Nanotechnology, 3-5 May 2014, Baltimore, MD
8. Abbott, A.C. "Characterization of Creases in Polymers for Adaptive Origami Engineering" Master's Thesis Defense, University of Dayton, Dayton, OH, July 1, 2014.
9. *****Buskohl, P.R. Origami Material Design: Crossroad of Art and Engineering. University of Cincinnati Materials Science Graduate Seminar Series, Cincinnati, OH, Aug 29, 2014
10. Abbott, A.C., Buskohl, P.R., Joo, J.J., Reich, G.W., Vaia, R.A. "Characterization of Creases in Polymers for Adaptive Origami Structures" Conference on Smart Materials, Adaptive Structures and Intelligent Systems, Newport, RI, September 9, 2014
11. Fuchi,K., Ware, T., Buskohl, P.R., Vaia, R.A., White, T.J., Reich, G.W., Joo, J.J., "Inverse design of LCN films for origami applications using topology optimization" Conference on Smart Materials, Adaptive Structures and Intelligent Systems, Newport, RI, September 9, 2014
12. *Reich, G.W. Panel discussion on origami engineering, ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS) 8-10, Sept 2014. Newport, RI