ColorFolds: eSkin + Kirigami: From Cell Contractility to Sensing Materials to Adaptive Foldable Architecture

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Introduction

As part of two projects funded by the National Science Foundation in the Sabin Design Lab at Cornell University titled, eSkin and KATS (Cutting and Pasting - Kirigami in Architecture, Technology, and Science), ColorFolds is one product of ongoing trans-disciplinary research spanning across the fields of cell biology, materials science, physics, electrical and systems engineering, and architecture. The goal of the eSkin project, is to explore materiality from nano to macroscales based upon understanding of nonlinear, dynamic human cell behaviors on geometrically defined substrates (Sabin et al 2014). ColorFolds incorporates two parameters that the team is investigating: optical color and transparency change at the human scale based upon principles of structural color at a nano to micro scale (Figure 1).

Figure 1 Rendering of ColorFolds suspended in the architecture building at Cornell University. Color change within the assembly is wavelength dependent or what is also known as 'structural color' change.

In addition to these material proprieties, ColorFolds features a lightweight, tessellated array of interactive components that fold and unfold in the presence or absence of people. From architecture to chemistry, from chalkboards to micrographs, and from maps to trompe-l'oeil, we strive to communicate 3D geometry, structures, and features using 2D representations. They have allowed us not only to communicate complex information, but also to create real objects, from the act of folding a paper airplane to the construction and digital fabrication of entire buildings. ColorFolds follows the concept of "Interact Locally, Fold Globally," necessary for deployable and scalable architectures. Using mathematical modeling, architectural elements, design computation, and controlled elastic response, ColorFolds showcases new techniques, algorithms, and processes for the assembly of open, deployable structural elements and architectural surface assemblies. Each face of the tessellated and interactive components features a novel colorful film invented by 3M called Dichroic Film. Not only does this film align with our investigations into structural color, but it also allows for room-scale investigations of these nano to micro material effects and features. An array of sensors detects the presence or absence of people below, which in turn actuates a network of Flexinol® by Dynalloy, Inc. spring systems that open or close the folded components.

Background

The particular material research presented builds upon the latest prototypes and applications within the eSkin project, the optical simulation and application of geometrically defined nano/micro scale substrates that display the effects of nonlinear structural color change when deployed at the building scale. We are currently limited to a 4-inch by 4-inch maximum swath of the eSkin material due to high material costs and fabrication time. This requires that we develop and fabricate prototypes that exhibit the same material effects of eSkin, but that can be fabricated at the human scale. In the ColorFolds project, we are working with a commercially available wavelength dependent film produced and supplied by 3M called Dichroic film. Specifically, nano/micro scale pillar substrates, designed in the Shu Yang lab, form the basis of our material investigation. These substrates are fabricated via microlithography and soft lithography, first requiring a negative nano/micro pattern to be etched into a substrate in which an organic polymer known as PDMS (polydimethylsiloxane) is subsequently cast, cured, and removed, thus producing a positive relief of nano/micro pillars (see for example Thompson et al. 1994, Xia et al 1998, & Zhang et al. 2006).

Demonstrating unique angle dependent and wavelength filtering optical properties of interest, these periodic pillar arrays act as passive filters of light given the specific nano or micro scale periodicity of their structures and the angle at which they are viewed. Because of the particular periodic spacing and geometry of these arrays existing at the nano-to-micro scale, light is absorbed via the PDMS material, but also filtered as a property of the specific wavelength of light that is allowed to pass through a particular pillar array. Depending on factors such as the diameter and the periodic distance between each pillar in an array, the visible spectrum of light, which exists between 390nm to 750nm, will be filtered out, absorbed or scattered and reflected or refracted from the material. Through changes in pattern, compliance, geometry and structure, we can manipulate material features including color, transparency and opacity. Here, color change is generated by an optical effect such as refraction or interference as opposed to a change in pigment. This is known as structural color. In our case, physical structures in the form of pillars interact with light to produce a particular color. These colors are also dependent upon angle of view or ones orientation to the given materials. There are many examples of structural color change found in nature such as the wings of the Blue Morpho butterfly or the feathers of hummingbirds. We are interested in harnessing these material features and effects and translating them into scalable building skins. Imagine dynamically blocking sunlight throughout the day through simple mechanical changes of the eSkin film via stretching or compressing or in other words, creating and tuning your own window! This paper presents our next steps in integrating and arraying these material features and effects within scalable adaptive and foldable assemblies through kirigami geometry.

Methods

Kirigami Geometry: Folding with Cuts and Holes

The generative design process for ColorFolds began with an examination and study of kirigami processes as a means of creating doubly-curved surfaces through a simple implementation of gradient folding conditions. Kirigami is similar to origami, but includes the addition of cuts and holes. The origin of the word comes from the Japanese kiru, “to cut,” a geometric method and process that brings an extra, previously unattainable level of design, dynamics, and deployability to self-folding and -unfolding materials from the molecular to the architectural scale. Our tools and methods were greatly informed by collaborating and working closely with PI and theoretical physicist on the team, Randall Kamien, based at University of Pennsylvania (Castle et al 2014).

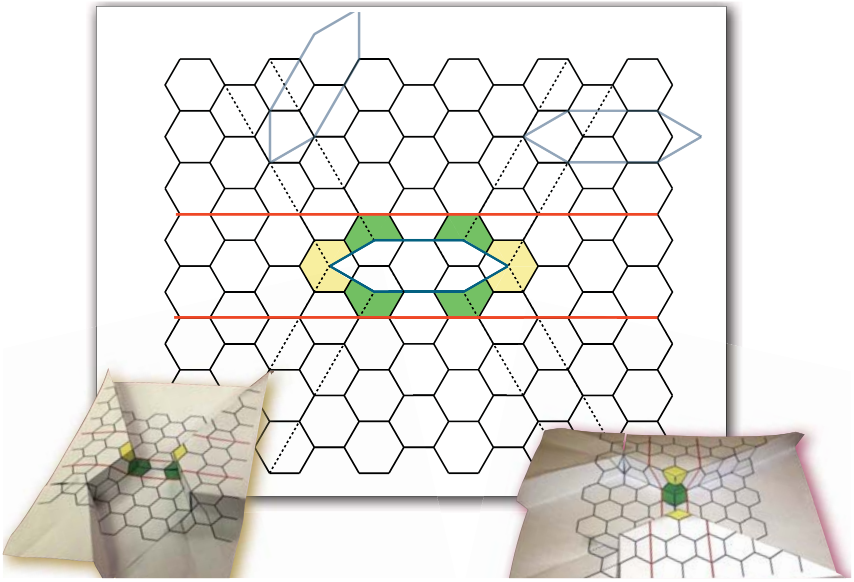

Figure 2 Precision kirigami based upon topology and geometry of defects in sheets (Castle et al 2014).

The primary geometric relationships describing Kirigami are illustrated here (Figure 2). Similar to origami, there are prescribed folds represented with dashed lines. In addition to this, we can cut out the blue hexagons shown in blue. These folds will move us from 2D flat sheet to 3D form. In addition to these studies rooted in the theoretical and pure geometric representations of kirigami geometry, are work is also informed by the dynamic conditions of material, both in shape and cut and how these parameters are designed and engineered through fractal cuts and subdivision (Cho et al 2014) (Figure 3).

Through these studies, we developed a series of algorithms for generating an adaptable spatially aware geometry that formally responds to site-based geometries with the added capacity-through its geometry and actuation system-to adapt to various user groups within the installation space. Utilizing physics-based engine Kangaroo in Grasshopper, we were able to both simulate behaviors prior to fabrication and force physical constraints onto digital geometries to ensure ideal translation from design to fabrication. Through our research, we developed several studies of singular component behaviors. This behavior was developed through a study of contingent folding behaviors in which initial folding states exist out of a single plane. These states use non-orthogonal cut patterns as a means of activating several folding panels through a singular system of actuation.

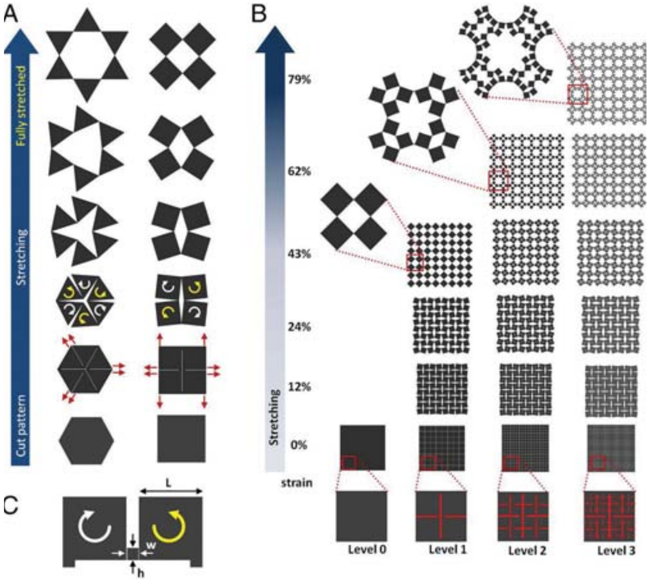

Figure 3 Basic principles of the cut design. (A) Cuts separate the material into rotating units, with connectivity dependent on the cut pattern (assuming freely rotating point hinges). A hexagon can be divided into six smaller triangles in a pattern that can be repeated to fill space or a square can be divided into foursmaller squares. Upon equal-biaxial stretching, each unit rotates clockwise (white arrows) or counterclockwise (grey arrows), yielding an expansion of the original structure. Expansion continues up to a maximum level by pure unit rotation (minimal strain within the structural units). The structures are fully stretched when moment equilibrium is achieved (Cho et al 2014).

These initial folding and cutting studies generated a series of feedback loops between analog and digital testing. After an examination of basic kirigami behaviors we created a series of customized algorithms to simulate and test large-scale aggregations. Our testing was driven by the ability to create inherent complex curvatures through precise cut and fold patterns within a planar sheet. By developing gradient conditions within the cut/fold pattern we were able to achieve final outcomes exhibiting complex double curvature. As the experimental computational tools developed, we designed a folding system that is based on a multidirectional deformation scheme. Looking at the behavior of cellular networks, our system is able to adapt to complex curvature by creating regions of higher component densities where tighter curvatures and adaptability are required. By generating a triangular mesh and extracting the dual we were able to create a more irregular pattern capable of adapting more readily to variegated folding behaviors.

Results

Materials and Fabrication

The final prototype and installation involved a third iteration of specificity within our algorithmic tool set. Responding to specific site conditions and constraints, a series of form-finding algorithms were developed as a means for nesting the system efficiently within the designated space. A series of feedback loops and nested form-finding algorithms created a final geometry that incorporated the following: Subdivision and application of a regular edge length cellular network to the inhabitable region; Generation of a linear network with surficial members to infill the cellular network; Application of force-based algorithms to geometry to simulate it's behavior in real space; Re-evaluation of input parameters to most ideally occupy the physical space; Force-based manipulation of geometry to ensure that planar geometries are adequate for digital fabrication.

The material for the final installation is a composite of .25″ extruded polycarbonate and dichroic film. Leveraging the computational nature of the project we utilized packing algorithms to optimize cut file layouts and embed assembly information within individual components. Custom nylon hinges were developed and applied to the inner folding edge of joining facets within the aggregation using blind rivets. Joining opposite corners within the aggregation are custom elements, which carry the primary tensile loads of the structure and serve as the anchoring points for the nitinol actuators. These component lengths were standardized within the form finding algorithms and therefore able to be mass-produced. The assembly consists of aluminum c-channel brackets anchoring the tensile stop members which double as the electrical return for the nitinol springs. These custom assemblies are the primary mechanical driver for the actuation of the installation (Figure 4 & 5).

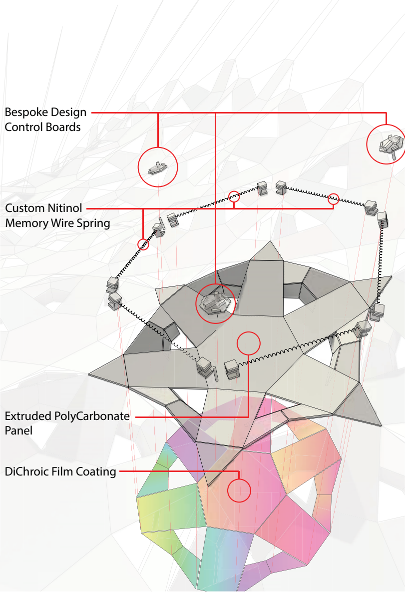

Figure 4 Component assembly featuring polycarbonate panels and lamenate dichroic film. The assembly consists of aluminum c-channel brackets, nitinol springs and custom boards with sensors and thermisters.

Figure 5 2D cut file drawing for CNC machining. Our research focuses on 2D templates for 3D foldable assemblies.

Mechatronics: Interface Design for Interactive Behavior

The main source of actuation for the kirigami installation is resistive heating of shape-memory alloy (SMA) springs. The advantages of these actuators include low weight, reasonable strength, and simple construction. However, the high power requirement for resistive heating means that specialized hardware is needed to reliably deliver power to the springs.

We combined this specialized hardware with a decentralized control scheme called an actuation automaton. Each actuation automaton consists of three springs connected to a central node board. Due to the irregular topology, some node boards controlled four springs, with two connected in series. Each node board consists of three MOSFETs that regulate the heating of the SMA springs, an Attiny 84 microcontroller, and a shift register. Several of these boards are then connected in a bus to a central 5 volt 20 amp power supply.

The microcontroller on each board heats the springs using an open-loop control scheme, turning on each MOSFET for a specific amount of time and allowing the bussed power to flow through the spring, producing the necessary heating energy to cause actuation. Each board activates its constituent springs simultaneously and broadcasts the actuation state to its neighbors. A board can broadcast its status to as many neighbors as necessary, but each board can receive a maximum of eight neighbor states. These states are communicated as a binary string through the shift register (Figure 6).

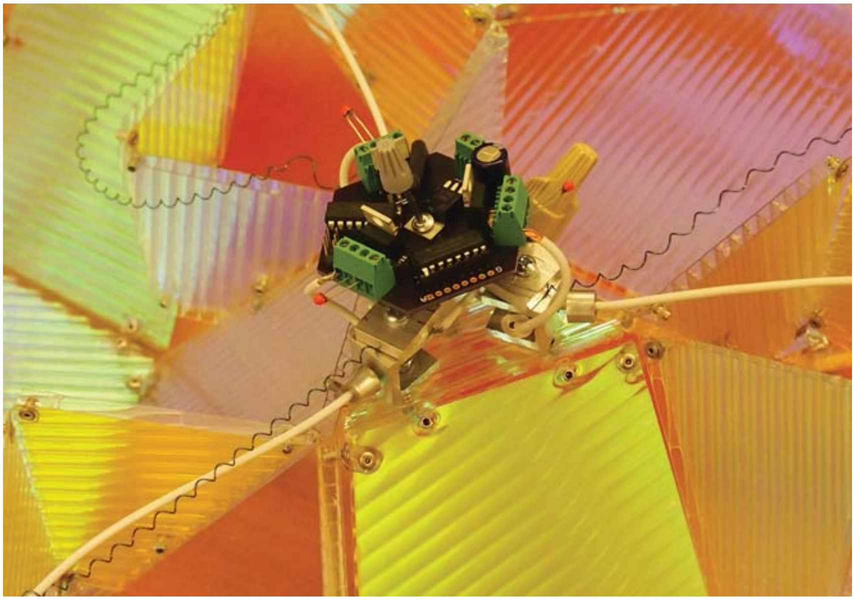

Figure 6 Photo of custom board situated within a component. Each actuation automaton consists of three springs connected to a central node board. Due to the irregular topology, some node boards control four springs, with two connected in series.

We also designed a software automaton that uses this communication and control protocol to produce complex, emergent behavior within the cellular network from a set of simple rules. The rules are:

1. Default behavior is called ‘breathing’; it involves a slow charge and discharge of the springs accomplished through pulse width modulation of the control MOSFET. The board broadcasts a state of ‘0’ to its neighbors while in the state.

2. The opposite behavior to ‘breathing’ is ‘glowing’; the springs are

heated as quickly as possible, producing a quick contraction. While in this state, the board broadcasts a ‘1’ to its neighbors.

3. While ‘breathing’, the board uses the shift register to poll the states of its nearest neighbors. The number of ‘glowing’ neighbors determines the probability that this board will, itself, enter the ‘glow’ state. When all neighbors are ‘glowing’, the probability is 1, and when all neighbors are ‘breathing’, the probability is 0.

4. After the board enters the ‘glow’ state, it will remain there for a short time, and then return to a rest state where it will ‘breathe’ but not poll its neighbor’s state.

From this set of rules, a few parameters are of importance to the behavior of the overall system:

1. The frequency with which the board polls its nearest neighbors for their status, which is, in effect, the sensitivity of a board to its surroundings.

2. The speed with which contraction occurs.

3. The length of the glow state.

4. The length of time spent resting before going back to polling neighbors.

In order to study the effect of the different parameter values on the behavior of the overall system, we constructed a simple simulation that is based on the topology and cellular network of the kirigami installation. The boards in this simulation are all initialized at a random point in the breathing cycle, and specific blocks of nodes can be made to glow at the same time, producing a perturbation of the system that could be introduced in the installation using external sensors or other forms of interaction. Given the proper balance of parameters, these glowing blocks can quickly spread outward, producing traveling waves that successfully spread throughout the array. Moreover, the glow effectively resets the breathing cycle, resynchronizing the breathing of the boards and producing complex passive behavior that mirrors the spread of the active perturbation.

Discussion

The pioneering structural designer and father of the space frame and corrugated sheet metal, Robert Le Ricolais, was obsessed with the seemingly paradoxical notion of building with holes. He stated, “The art of structure is how and where to put holes.” Our work will take this principle to the next level: buildable, bendable, and biological. Through the use of physics-based simulations and form-finding techniques, we are able to incorporate the dynamic nature of forces flowing through material and geometry as active design parameters. Kirigami offers a very robust geometric template for exploring the strategic placement of cuts and holes relative to disruptions in material and dynamic change. We did encounter significant design and fabrication hurdles through the process of scaling and with the addition of thickness in material to the kirigami components. Hinge design became a crucial factor. Our most promising result entailed the use of laser cut vinyl hinges mechanically fastened to two petals of every kirigami component. The material allowed for enough stretch or tolerance at the fold of the 6mm extruded CNC cut polycarbonate panels. Although appropriate for this prototype, we are now collaborating with Spencer Magleby, a mechanical engineer based at Brigham Young University specializing in thick stamped origami. Together, we are innovating hinge design at the architectural scale.

The incorporation of mechatronics in the ColorFolds project was purposeful, but atypical in the Sabin Design Lab. We typically favor the direct manipulation and programming of matter for actuation and dynamic response over mechanical control. However, this was a useful step as it allowed us to operate at scales not yet achievable in the materials alone. Through this scaling, significant errors were discovered predominately in the calculation of power to run the entire network of boards and array of nitinol springs. We discovered that the overall network of foldable components and boards (>60) required significantly more power to actuate than we estimated.

Conclusion

Comprised of a network of low cost sensors and wavelength dependent responsive materials, ColorFolds is conceived to be generic and homogenously structured upon installation, but readily adaptable to local heterogeneous spatiotemporal conditions and user interaction. This manner of operation not only maximizes immediate performative efficiency, but also allows

Figure 7 Final installation view of ColorFolds, seen from below.

for ongoing contextual adaptation. In this regard ColorFolds is a “learning” and adaptive skin assembly, an experimental prototype for future applications in the context of adaptive architecture (Figure 7). Our approach to kirigami-based construction will bring a new level of motifs, portability, and nuanced design to recently established techniques to form intricate structures chemically, biologically, elastically, and through 3D printing and self-assembly. Instead of post-rationalizing a complex shape through discrete surfacing – a common, unsustainable and costly practice that privileges optimization over innovation – our approach addresses how complexity is materialized in architecture by embedding fabrication logics, active materials, and deployable geometries at all scales and phases of the design and construction process.

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Jenny Sabin's work is at the forefront of a new direction for 21st century architectural practice – one that investigates the intersections of architecture and science, and applies insights and theories from biology and mathematics to the design of material structures. Sabin is the Wiesenberger Assistant Professor in the area of Design and Emerging Technologies and the newly appointed Director of Graduate Studies in the Department of Architecture at Cornell University. She is principal of Jenny Sabin Studio, an experimental architectural design studio and director of the Sabin Design Lab at Cornell AAP, a hybrid research and design unit with specialization in computational design, data visualization, and digital fabrication. She was recently awarded the prestigious Architectural League Prize for Young Architects and was named the 2016 Innovator in design by Architectural Record's national Women in Architecture Awards. Her work was exhibited in the internationally acclaimed 9th ArchiLab titled Naturalizing Architecture at FRAC Centre, Orleans, France and is currently on view as part of Beauty – Cooper Hewitt Design Triennial. Her work has been published extensively including in The Architectural Review, Azure, A+U, Metropolis, Mark Magazine, Science, the New York Times, and Wired Magazine. Her forthcoming book, *LabStudio: Design Research between Architecture & Biology*, co-authored with Peter Lloyd Jones, will be published in spring 2017.