PROGRAMMABLE MATERIALS:
Exploring hybrid techniques of origami and soft robotics on kinetic structures

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Existing kinetic systems for building are typically highly complex, mechanically actuated, and use rigid materials that are antithetical to their very purpose – to move. Designing and prototyping at smaller scale of kinetic structures and forms are often inspired by origami techniques where the material is paper. The principles underlying the art of origami paper folding can be applied to design materials with unique mechanical properties. This research addresses the incongruity between materials and movement to explore alternate materials. By exploiting the flat crease patterns that determine the dynamic folding and unfolding motion of origami, metamaterials that can perform desired controlled movements can be designed. A number of materials were tested and compared through a hybrid method using soft robotics in combination with origami forms in a series of physical prototype iterations. Some of the desirable attributes of origami that are sought after in design include: reduced number of parts, compressibility, transportability, deploy-ability, manufacturability from a flat sheet of material, a single manufacturing technique, folding, and low material volume and mass. The first step defines whether origami and soft robotics is a viable solution by evaluating a set of starting criteria on different materials. The final materials were actuated using soft robotic actuator skin and analysed for scalability, deployability and compressibility. Later, prototypes are scaled and tested. The results are analysed for controlled movement in desired direction. Iterations reveal that when these hybrid techniques were applied, materials can contract while achieving desired motion and can endure fatigue when actuated using negative air pressure. By taking advantage of their unique dynamic mechanisms, these materials are flexible to accommodate the designers needs and have great potential to be used in built environment.

Keywords. Origami; actuator; soft robotics; kinetic structures; material

1. Introduction: Research Aims and Motivations

Origami-based mechanisms are a type of compliant mechanism inspired by the kinematics of origami models. In origami, creases in paper act as hinges to achieve motion from a single flat sheet. By exploiting the flat crease patterns that determine the dynamic folding and unfolding motion of origami, metamaterials that can perform desired controlled movements can be designed. These origami mechanisms are being used in industries such as aerospace to develop deployable solar panels in satellites and other compliant mechanisms.

Through this research the potential for these mechanisms on different materials and which materials demonstrates the properties close to the properties of the paper are analyzed. These mechanisms are combined with soft robotic actuation to achieve hands free movement of materials.

2. Research Observations and Objectives

The objective of this work is to apply and analyse a hybrid method of origami and soft robotics on different materials to develop foldable expandable structures. Different materials would be tested and analysed to These foldable expandable members are made of compliant mechanisms as they use the deflection of flexible members to achieve their desired motion or displacement. By relying on deflection for motion instead of rigid links and joints these mechanisms can reduce complex, multi-part mechanisms into a single part. Origami-based mechanisms are a type of compliant mechanism inspired by the kinematics of origami models. By using the origami methods on materials to explore if the movement can be obtained with simple actuation and limited number of materials thereby examining if it can be a viable alternative to replace tiny and large number complex mechanical parts controlling the movements of traditional kinetic structures.

3. Research Questions

Potential advantages of origami soft robotic mechanisms over traditional mechanisms include fewer parts, ease of fabrication, reduced assembly, reduced cost, reduced weight, reduced friction, reduced wear, high precision, and no need for lubrication. How can this knowledge be used on different materials in built environment? Whether origami and soft robotics can be used on different materials to achieve desired movements?

Integrating origami and soft robotics as hybrid methods forms the key motivation for this research.

In what ways can origami methods combined with soft robotics addresses the incongruity between materials and movement to explore alternate materials with desired controlled movements?

4. Methodology

This research project was developed through an action research method, where the physical iterations are made by applying origami and soft robotics on different materials and tested for movement through actuation. This type of research is a reflective process with constant problem solving, continuing until the research question is answered (O'Brien, 1998).

This research tries to explore if origami and soft robotics can be used on different materials to achieve desired movements. Integrating origami and soft robotics as hybrid methods forms the research question. Different traditional origami patterns were studied and materials on which they can be applied and also suitable for soft robotic actuation are studied. Based on the research different materials and patterns were tested in three stages. First a simple origami geometry is tested, and materials are compared with paper. The successful materials are further tested for stability using cylindrical origami patterns. Observations were made, and the successful materials were tested for movement using soft robotic actuation method where the origami structure forms the kinetic element. conclusions were made by deciding whether final materials exhibited the desired properties close to that of paper and whether this hybrid method of origami and soft robotic has potential to be used as an alternative to traditional kinetic structures.

5. Background Research

A review of literature facilitated an understanding of constraints and helped shape the iterations developed as part of this research.

5.1. KINETIC SYSTEMS IN BUILT ENVIRONMENT

Robotics are not just improving fabrication in architecture but increasingly providing opportunities for improving the materiality of architecture offering responsive, performative and adaptive design possibilities for the built environment. Majority of robotics in architecture is related to incorporating the rigid systems, such as motors, often in kinetic facades.
Though there is progress in development of kinetic façade systems, several instances in engineering and architecture reported some drawbacks from

dynamically adjusting building facades as well as their responsive systems (Mallasi, 2016).

According to Loonen et al (cited in Mallasi, 2016), the current built projects using responsive kinetic elements are under researched and there is clear reference in literature to the common problems the facades are facing such as: The movement mechanism that were controlled by motors constantly failed during the operation of the building; The dynamic moving elements in a responsive system are logistically complicated, too slow, and of high maintenance cost. (Massey, cited in Mallasi 2016).

5.2. MATERIAL SELECTION

There are several design options for the general material of an origami-adapted product;
these depend on whether the material needs to be flexible, rigid, a hybrid of the two or have multiple flexible layers. Origami is primarily constructed out of paper which is a flexible material that allows flexing in the panels while folding. Special considerations must be made in order to do origami with a rigid material, hence it is ideal to research and decide the material and design options early on in product development since it affects the remainder of the design.

Considerations in selecting the general material are the rigidity and continuity requirements of the product. Rigidity refers to the stiffness of the material and has no allowance for deformation in the panels. Continuity refers to a closed surface without any perforations or interruptions. These two design considerations combine to result in four different general material design options.

The four general material design options are rigid, flexible, multiple flexible layers and hybrid. Figure 1. shows how these considerations influence the general material selection.

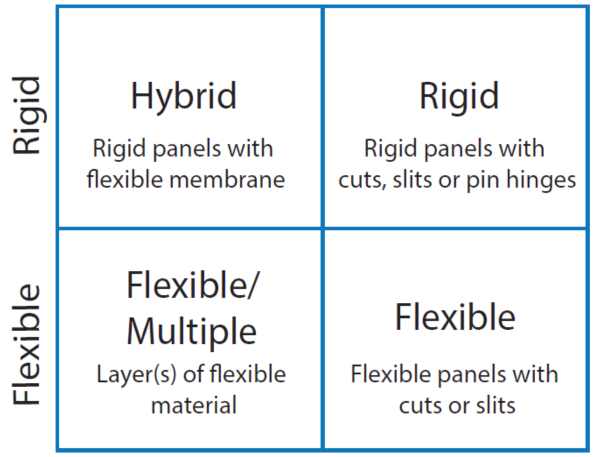


Figure 1. A diagram showing the general material design options and descriptions based on whether the structure needs to be rigid and/or flexible. (Morgan, 2015)

For structures that need to be rigid and continuous this results in a hybrid material. A hybrid material has rigid panels with a flexible membrane. If a rigid material needs to be cut to allow folding, continuity is maintained with the adhesion of a flexible membrane or a flexible material solely at the creases. For structures that need to be rigid and interrupted (non-continuous) this results a rigid material that can have cuts or slits. Structures that need to be flexible and continuous have the option of either a single continuous flexible material or multiple layers of flexible material. The need for multiple layers will not be fully determined until the selection of the final material and crease design. Some flexible materials are prone to areas of stress concentration along the folds and vertices for which holes or slits can be cut as stress relievers. In this case adhering a second layer of flexible material will maintain continuity. For structures that need to be flexible and interrupted this results in a flexible material that can have cuts or slits.

Product constraints and requirements determine the general material from the four design options. This provides foresight throughout the remainder of the design process. This concludes the problem definition phase for origami-adapted design. At this point the product requirements are known, origami is determined to be a viable design solution and the general material is selected to be a flexible, rigid, hybrid or multiple flexible materials. At this point the problem is properly defined and an origami solution can be sought.

5.3. ORIGAMI PATTERNS

Current interest in deployable structures arises not only from their potential in space but also from many other areas (Guest, 1996). Several designs of origami patterns have been researched for deployable structures.

5.3.1. Traditional pleats

Traditional pleats are basic mountain-valley-mountain-valley folds in which the folds are spaced equally in either a linear or rotational progression. The equality of spacing makes them particularly easy to fold and creates a rhythmic repetition. (Jackson, 2011)

5.3.2. Kresling pattern

Kresling pattern, whose basic mechanisms are formed by the buckling of a thin cylindrical shell under torsional loading highly regular self-organized folding pattern appears formed by inclined and elongated mountain folds, divided on their long diagonal by a valley-folds. (Jianguo, 2015)

5.3.3. Accordion pattern

Typically, accordion folds are simple zigzag folds with six panels and two parallel folds that go in opposite directions. Each panel of the accordion fold is of the same size. Also known as Z-folds, accordion folds are similar to the pleats on the musical instrument known as an accordion.

5.3.4. Miura-ori pattern

Miura-ori, which is a well-known rigid origami structure utilized in the packaging of deployable solar panels for use in space or in the folding of maps (Miura, 1980). Miura-ori provides a one degree-of-freedom (DOF) mechanism from a developed state to a flat-folded state.

5.3.5. Tachi-Miura pattern

Tachi-Miura pattern is a rigid-foldable pattern, meaning that it experiences no strain in the panels. The advantage of the Tachi-Miura is the reduced stress on the bellows panels during cycling.

5.4. MODELLING ORIGAMI

Origami can be modelled using mathematical analysis. Mathematicians were some of the first in the research community to develop an interest in origami. Demaine and O’Rourke have developed several theorems exploring the possibilities and limitations of origami, including solving origami folding problems (Morgan, 2015). The mathematical principles explaining origami in such papers are a valuable reference for engineers in modelling and understanding origami.

Mathematical modelling is used as the basis for many origami-based design considerations such as rigid foldability, thick origami, and defining kinematic motion. Articles that describe origami and its relative motion are useful for modelling and designing origami-based structures (Morgan, 2015).

5.4.1Rigid foldability

A rigidly foldable crease pattern is an origami fold pattern that can move through its full range of motion without deformation in the panels or self-intersection. If the design uses a flexible material or is static, then rigid foldability may not be a concern. For any kinematic, rigid design, the crease pattern needs to be modified for rigid foldability. The tall, rigid shopping bag is an example of a crease pattern modified for rigid foldability. It is not always possible to adjust a crease pattern to be rigidly foldable and this requirement needs be considered when selecting an origami source model. Certain creases patterns, such as the Miura-ori crease pattern, are known to be rigidly foldable crease patterns and are used often for this reason. (Butler, 2017)

5.5. SOFT ROBOTICS

Soft robots are artificial flexible actuators with capabilities similar to, or even beyond, natural muscles. They have been widely used in many applications as alternatives to more traditional rigid electromagnetic motors. Soft robots can be programmed to achieve multiaxial and controlled actuation.

5.5.1. Working of soft robotic actuators

The soft robotic actuation system consists of three fundamental components: a compressible solid skeletal structure, a flexible fluidtight skin, and a fluid medium. In this system, the skin is sealed as a membrane covering the kinetic structure. The fluid medium fills the internal empty space between the skeleton and the skin. In the initial equilibrium state, the pressures of the internal fluid and the external fluid are equal. However, as the volume of the internal fluid is changed, the shape of the structure changes. A pressure difference between the internal and external fluids creates tension in the flexible skin. This tension will act on the origami structure, driving a transformation that is regulated by its structural geometry. (Li, 2017)

These soft robotics actuators can be actuated by either positive or negative pressures, but negative-pressure operation offers greater safety, compactness, and robustness compared with other fluidic artificial muscles driven by positive pressure.

5.5.2. Alternative actuation method

In this type of soft robotic actuation, the compressible structure also acts as the flexible fluid tight skin. This type of actuators can be used in designs requiring cylindrical type of forms.

5.5.3. Silicone based soft robotic actuators

Silicone based soft robotic actuators are a type of thick tiled pneumatic actuators which are made of silicone (Ecoflex® 00-50). The actuators are cast in two parts and later adhered to each other. The main part is cast including voids for fluid chambers that will expand in the assembly once the pneumatic system is activated. The expansion of the individual components can be controlled through variations in the thickness of the silicone components or the use of different types of silicone, such as Ecoflex® 00-30, Ecoflex® 00-10, Dragon Skin® 30, that have varying degrees of elasticity. This controls the overall deformation of the actuator. The individual actuators change their shape and volume from entirely flat to slightly convex with a surface morphology that displays a multitude of protruding air pockets. (Decker, 2015)

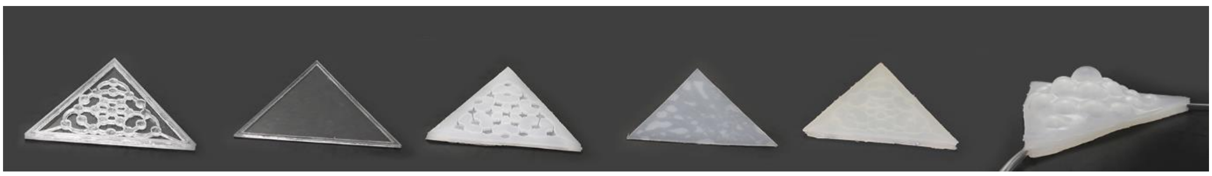


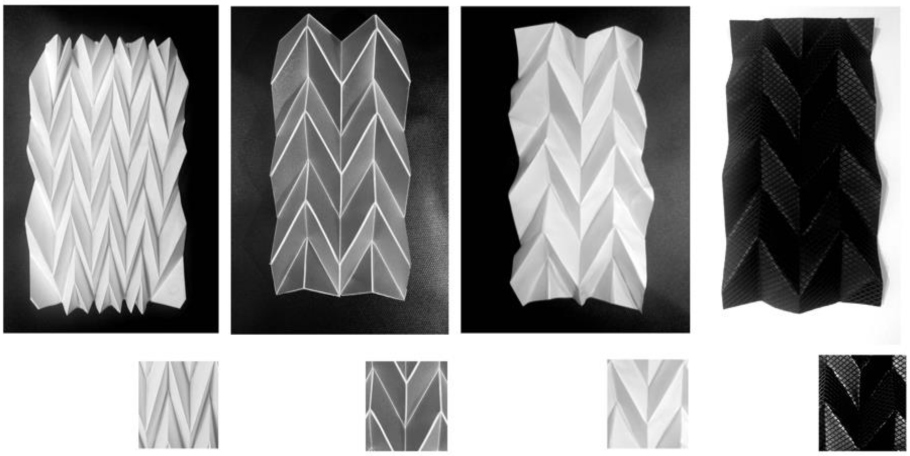
Figure 2 Soft acoustic tile fabrication at different stages (Decker, 2015).

6. Case Study

This research project is divided into three stages based on iterations. different materials were tested and evaluated at the end of each stage. The materials which failed to fit the criteria are discarded and the remaining were moved to the next stage. At the end of stage three, the materials which passes all the stages are considered to be successful in meeting the criteria and demonstrates the properties close to that of paper.

For the first stage, different materials made from polymers are considered. The considerations in selecting the material are rigid, flexible and a hybrid of multiple flexible layers. Plain white paper made of 200gsm has been used to maintain the uniformity throughout the research.

In the first phase, different origami regular and cylindrical crease patterns like traditional pleated pattern, accordion pattern and Miura Ori pattern have been studied in order to find their geometrical properties and capabilities of changing into different forms when forces were applied. The Miura Ori pattern with a regular tessellation has been selected because it proved to have the best compromise between all of the considerations such as self-supporting abilities, geometry's predictableness and easiness to control. This pattern is iterated on materials like Polyethylene, polypropylene, PVC, Vinyl, HDPE, LDPE, a hybrid of polypropylene and LDPE.



PAPER	POLYPROPYLENE	LDPE	HDPE
0.2MM THICK	0.6 – 0.8MM THICK	0.4MM THICK	1MM THICK
FLEXIBLE LESS DURABLE	HARD AND FLEXIBLE	LOW STRENGTH AND HARD	HIGH STRENGTH AND HARDNESS

Figure 3 Different materials tested and compared to paper using Muira-ori fold

After iterating, these are compared with the iteration made with paper of 200 gsm thickness for their hardness and the ability to hold the shape of the Miura-ori pattern and the results were documented in the table. From table-1, it is understood that paper is easy to fold, flexible enough to hold the crease and has good shape memory, but it is less durable since it not at all water resistant and also prone to damage when exposed to external weather conditions. The iterations made is of 0.6 and 0.8mm thick polypropylene were hard, can hold the crease and also flexible and durable. LDPE stands for low density polyethylene, it is of 0.4mm thick holds the crease, has good shape memory but is of low strength. HDPE is High Density polyethylene, is 1mm thick, it is hard material compared to LDPE. It holds the crease initially but loses it gradually over a period of time. The hybrid of LDPE and Polypropylene also exhibits good shape memory but has very low strength so less durable. Vinyl and PVC has not exhibited any crease holding capabilities, so they failed to transform into Miura-ori pattern. Polypropylene and LDPE were successful at meeting the set considerations and were further tested.

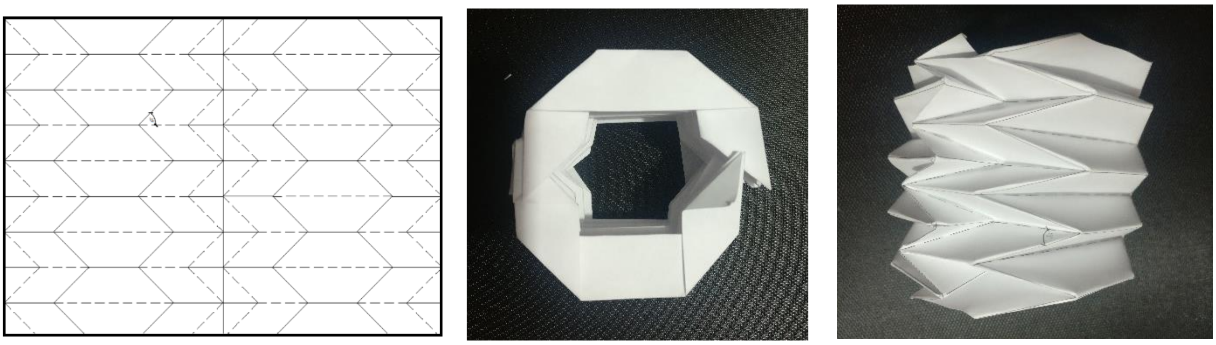


Figure 4 Tachi-miura pattern before and after folding

In the second stage, origami patterns that forms into cylindrical shapes were studied to test the compressibility and durability of materials and also to test whether the they can be transformed into more complex shapes. Three origami patterns made of Kresling fold, Accordion fold and Tachi-Miura polyhedron were selected as they proved to have geometry's predictableness and easiness to control and are have good compressibility ratio.

The first one is Tachi Miura pattern, this is a rigid origami pattern which can be used to form a cylindrical structure but requires exact cross-sectional area at the edges and requires clamping. Clamping or sticking the ends in this pattern is difficult as it created stress in the material as a result the materials failed.

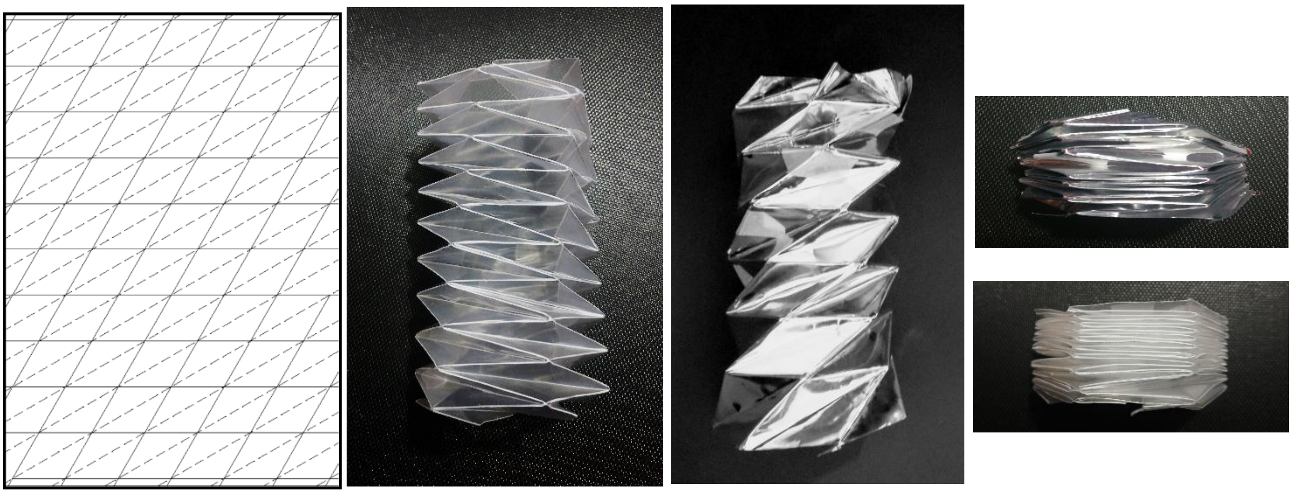


Figure 5 Kresling pattern before folding (left)and after folding using polypropylene (second left) LDPE(middle); after compressed (right- above and below)

The other two patterns are Kresling and Accordion fold patterns. These are non-rigid patterns which means the materials flexes during deployment and contraction. The Kresling pattern is made of either mountains or valleys continuing along any single line throughout its length. This makes it easy during fabrication as the material needs to be folded in only one direction. The Accordion pattern has alternating mountains and valleys along any single line throughout its length, so it is complex compared to the Kresling pattern. This pattern has a greater number of folds and also requires materials to be folded multiple times along any single line of fold during fabrication to achieve the final form. Polypropylene and LDPE were tested in this stage. Both the materials were able to transform into the cylindrical geometry and were able to hold the shape initially. The materials were compressed and deployed for at least 100 cycles. After just 45 cycles of testing, LDPE started to develop fatigue around the vertices and deformed during deployment and contraction. Polypropylene however, managed to withstand the 100 cycles of testing and was further tested with soft robotic actuation.

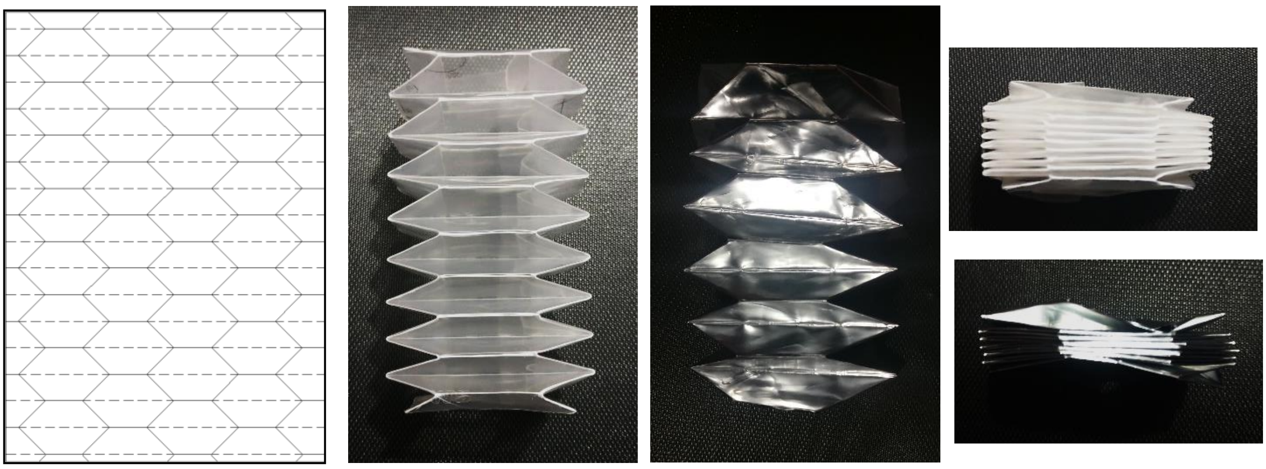


Figure 6 Accordion pattern before folding (left)and after folding using polypropylene (second left) LDPE(middle); after compressed (right- above and below)

In this stage the material was finally tested for soft robotic actuation, where the actuator works on the principle of difference in relative pressure It consists of a vinyl membrane surrounding the origami structure. When the pressure inside is less, the membrane contracts and compresses the origami structure. For this stage, origami patterns that forms into geometrical shapes were studied. Traditional pleated pattern, Muira-ori pattern were considered because of their geometric predictableness, direction of motion during deployment and contraction, and ease of control. Tessellated square and triangular fold patterns were considered because of their geometrical complexity and multi directional movement during deployment and contraction.

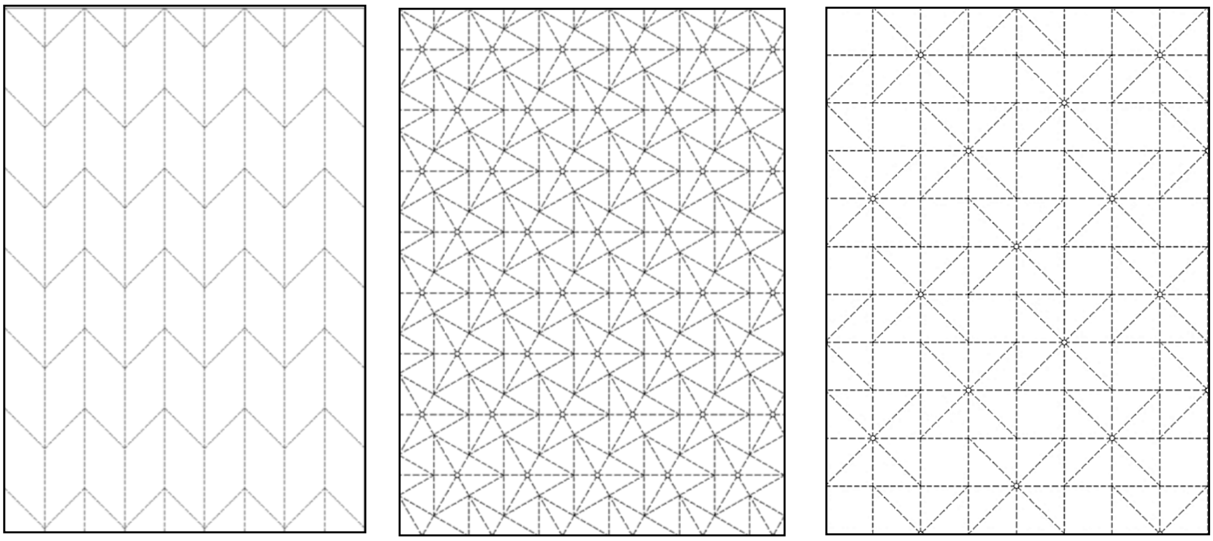


Figure 7 From left to right: Miura-ori pattern, triangular fold and square fold patterns

A vinyl membrane of 0.2mm thickness was used as actuator skin for all the kinetic structures. All the skins were directly sealed by an impulse heat sealer on three sides using proper sealing time. The other end is sealed using a snap lock strip. A high-volume inflator/ deflator air pump was used to regulate the fluid medium inside the actuator skin.

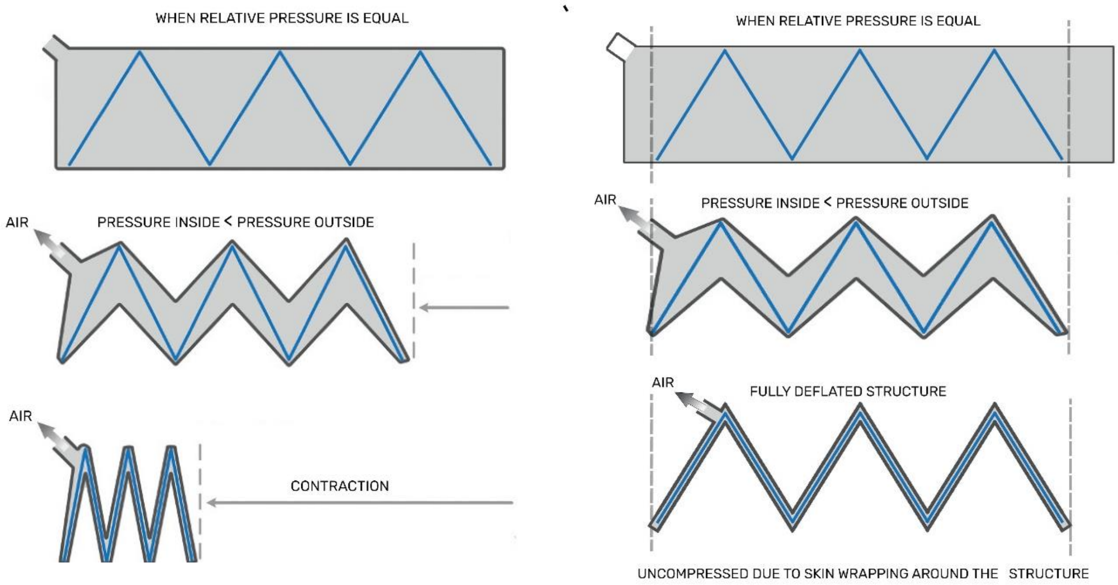


Figure 8 Working of soft robotic actuator

Laser cutter was used to print the origami pattern on polypropylene material and folded manually. Each of these origami pattern forms the compressible solid skeleton of the soft robotic actuators. Air is used as the standard fluid medium inside the all the actuators.

Traditional pleated pattern made of alternating mountains and valleys was placed in the actuator skin and tested for actuation by deflating the air inside. As the pressure inside decreases the skin contracts and compresses the origami structure to form equilibrium. The contraction achieved by this pattern is in horizontal direction. Similarly, Miura-ori pattern displayed the predicted horizontal motion during actuation. The material successfully passed in achieving motion in single direction using these the two patterns.

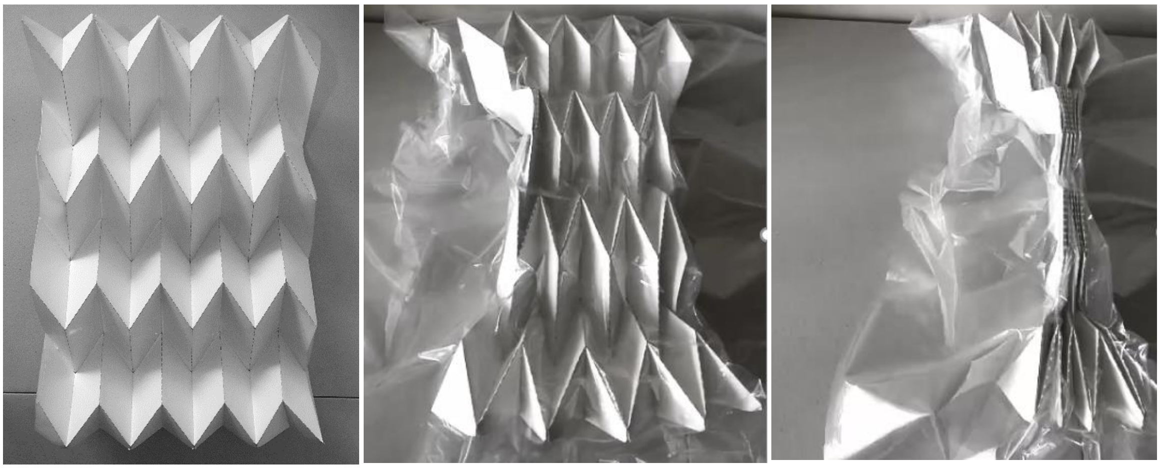
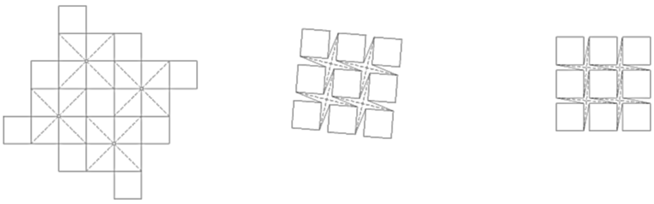


Figure 9 Images showing the deployment and contraction of Muira-ori fold

More complex patterns of square and triangular tessellations were tested using the actuation for observing the bidirectionality in folding. The square pattern succeeded when actuated by displaying compression in both horizontal and vertical directions. However, the triangular pattern failed to compress as the material could not fold and deformed at the corners of the sheet when actuated.



Folding sequence of Square fold pattern

Figure 10 Images showing the deployment and contraction of Square fold pattern

The fundamental shape from both square and triangular tessellation patterns were tested at large scale but both of them failed as the skin of the actuator wrapped around the sides of the compressible origami structure. A further test was conducted by adding four faces around the foldable square form for added stability during actuation. These flat faces prevented the material wrapping and the structure was successfully contracted when actuated.

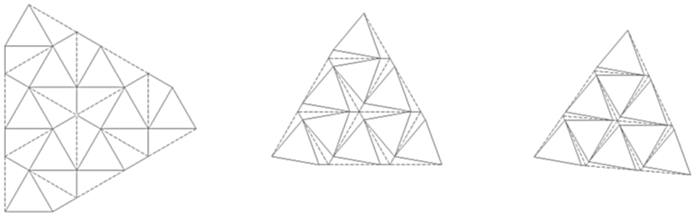


Figure 11 Folding sequence of Triangular fold pattern

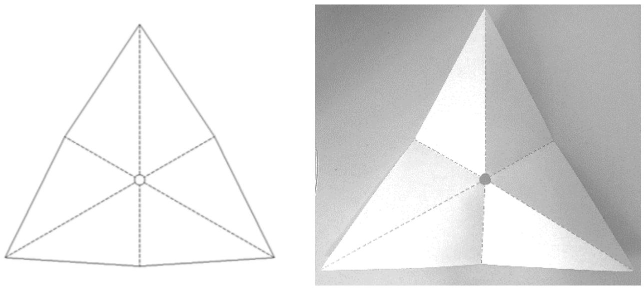


Figure 12 Fundamental fold in triangular pattern

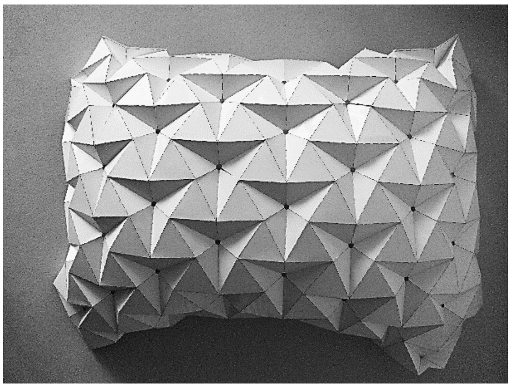


Figure 13 Deployed polypropylene model

Through all the stages of this research, only polypropylene was successfully passed the criteria and demonstrated the properties of holding the crease, shape memory similar to that of paper. However, the compressibility varied as it depended on the thickness of the material and polypropylene has demonstrated less fatigue, hence less deformation under repeated compression and deployment cycles. This research also demonstrates that the hybrid method of origami geometries combined with soft robotic actuators were able to achieve desired controlled movements.

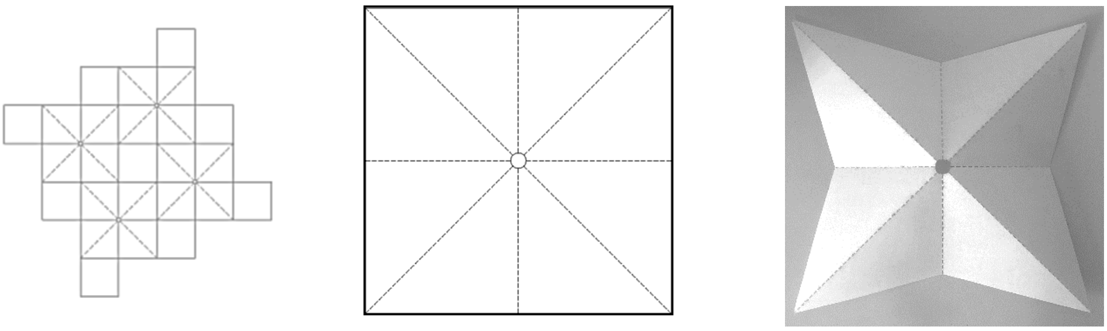


Figure 14 Fundamental fold in Square pattern made with polypropylene

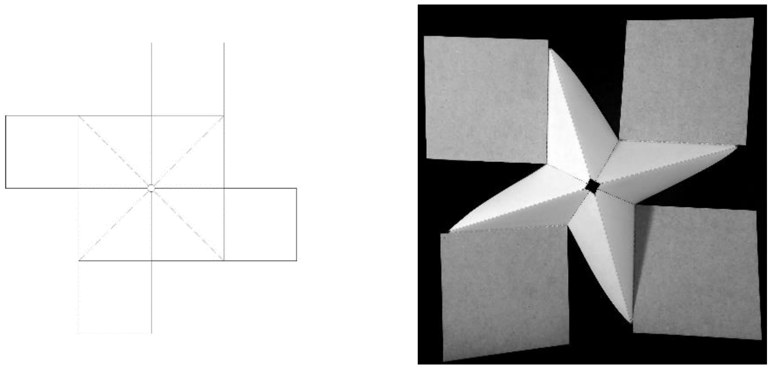


Figure 15 Fundamental fold of square pattern with adjacent four faces

7. Significance of Research

This research explores the idea of developing an alternative mechanism to assist architects and designers to have a better understanding of using them as while designing light weight kinetic structures in built environment. Instead of focusing on digital analysis tools this research focused on developing and evaluating physical iterations of various materials made from polymers and tested using origami geometries combined with soft robotic actuators. The three stages of research showed the versatility of the origami-adapted design process. All three stages of iteration testing followed the four main steps: define criteria, origami solution, modify fold pattern, and analyse. The robotic actuators can be programmed to produce not only a single contraction but also complex multidirectional actuation, and even controllable motion with multiple degrees of freedom. Moreover, a wide variety of materials and fabrication processes can be used to build the soft robotic actuators with other functions beyond basic actuation. The modelling methods demonstrated in this research can also be used with other origami geometries and materials to achieve desired controlled motion. These methods could be advantageous when light weight kinetic structures with desired movement are required and where traditional complex systems are not feasible. Different materials tested in this research are durable and has the potential to be used for a range of applications.

[FIGURE]

Figure 1. Figure caption.

8. Evaluation of research project

The research involved in this project is based on different stages of testing to find the materials that has properties close to the foldable and flexible properties of paper, having tested with materials made from polymers, different materials can also be chosen and tested using this workflow. Not all the steps carried out in the case study process were necessary for each of the designs, but instead the design and testing process adjusts to fit the needs of the project.

The iterations were fabricated either manually or by using digital technologies like laser cutter. Given the lack of material in single large sheet and limited bed size of laser cutters, only small sections of large-scale iterations were fabricated and tested. As an alternative to monolithic fabrication, large kinetic structures would likely require assembly by joining multiple discrete parts. More compressive power would be required when either the materials are scaled up or the thickness of materials increased as the material resistance increases. Logically, the materials that passed through these test stages should be able to be applied to the various scenarios and work in built environment, however given that they are still relatively less used materials with little to no real-world testing, it is difficult to predict a definite outcome on how they will perform.

Given the limited time span, lack of specialist knowledge and accessibility of materials for this project, detailed performance testing was not possible. Though there is potential for this method, given more time, this requires further analysis to explore the difficulty to produce at larger scale.

9. Conclusion

This research explores the potential of origami methods coupled with soft robotic actuators to achieve desired controlled movements. This research demonstrated the versatility of the origami-adapted design process and the robotic actuators which can be programmed to produce not only a single contraction but also complex multidirectional actuation and even controllable motion with multiple degrees of freedom. Different materials made of polymers were physically iterated and tested through three different stages. Only polypropylene was successful in demonstrating the foldable and flexible properties close to that of paper. Moreover, a wide variety of materials and fabrication processes can be used to build the kinetic structures with other functions beyond basic actuation. The modelling methods demonstrated in this research can also be used with other origami geometries and materials to achieve desired controlled motion. Different materials tested in this research are durable and has the potential to be used for a range of applications.

The potential of these methods could prove to be advantageous for designers when lightweight kinetic structures with desired movements are required and where traditional complex systems are not feasible.

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References

References are in 9 pt, 10 pt leading, unnumbered and in alphabetical order. Please make sure you conform to the following style:

Butler, Jared J. 2017. *Highly Compressible Origami Bellows for Harsh Environments.* <https://scholarsarchive.byu.edu/etd/6657> (accessed 18 October 2018)

Decker, Martina. 2015. *Soft Robotics and Emergent Materials in Architecture* <http://papers.cumincad.org/cgi-bin/works/paper/ecaade2015_178> *(accessed 22 September 2018)*

Guest, S. David., 1996. *Deployable Structures: Concepts and Analysis.* Ph.D. thesis, Cambridge University, Cambridge <http://www2.eng.cam.ac.uk/~sdg/preprint/SDG%20dissertation.pdf> *(accessed 08 October 2018)*

Jackson, Paul. 2011. *Folding techniques for designers from sheet to form,* Laurence King Publishing, London. United Kingdom

Jianguo, Cai. 2015. *Bistable Behavior of the Cylindrical Origami Structure With Kresling Pattern* <http://mechanicaldesign.asmedigitalcollection.asme.org/articleid=2211799> (accessed 22 September 2018)

Li, Shuguang., Vogt, Daniel M., Rus, Daniela., Wood, Robert J., 2017. *Fluid-driven origami-inspired artificial muscles* <http://www.pnas.org/content/114/50/13132> (accessed 10 August 2018)

Mallasi, Zaki. *Integrating Physical and Digital Prototypes Using Parametric Bim in the Pursuit of Kinetic Façade <http://papers.cumincad.org/cgi-bin/works/paper/ascaad2016_018> (accessed 22 September 2018)*

Miura, K. 1980. *Method of Packaging and Deployment of Large Membranes in Space*, Proceedings of 31st Congress of International Astronautics Federation, Tokyo, Japan

Morgan, Jessica. 2015. *An Approach for Designing Origami-Adapted Products with Aerospace Mechanism Examples.* <https://scholarsarchive.byu.edu/etd/5778> (accessed 15 August 2018)

O'BRIEN, R. 1998. *Action Research Methodology*. <http://web.net/~robrien/papers/arfinal.html> (accessed 14th August 2018)