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ASSOCIATIVE DESIGN THROUGH MATERIAL EXPLORATION WITH PAPER A FORM GENERATION APPROACH

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ABSTRACT

The subject matter proposes a multidimensional exploration into the intersections of form generation, material exploration, parametric design, and the traditional form of creased folding. Through a series of iterative design processes, origami techniques are investigated for their potential to inspire novel form-finding and material manipulation approaches. This study focuses on the relationship between traditional craftsmanship and contemporary computer aided designs, which opens up new design possibilities and fabrication methodologies.

The ancient technique of creased folding, has developed fascination for its ability to transform a flat sheet of material into intricate three-dimensional structures. Various paper manipulation techniques which form a valley and mountain-like structure are explored within the context of algorithmic design frameworks using a series of experiments and case studies. Furthermore, unique techniques to incorporate different materials into origami-inspired constructions are investigated. This study emphasizes the synergies between computer aided designs, material science, and traditional craftsmanship, illustrating how the integration of these disciplines may result in novel design. The findings provide light on the transformational potential of origami-inspired techniques across a wide range of areas.

1. INTRODUCTION and BACKGROUND

The divergence of curved crease origami represents a significant dissolve from traditional paper folding paradigms that depended on angular, planar arrangements. Curved creases introduce non-linear flexibility, allowing the material to display a broader range of three-dimensional forms that embody both complexity and greater creative freedom. The pursuit of doubly curved surfaces with Gaussian curvature is the pinnacle of this intricacy. These surfaces are well-known for their structural efficacy, which represents an ideal blend of material economy and mechanical durability. Mastering such forms through the lens of curved crease origami has far-reaching consequences, opening up new avenues for architectural designs, deployable structures, and even adaptable materials that can respond to environmental stimuli. Developable surfaces form naturally when three-dimensional objects are made from flat sheets of material without stretching or tearing, as seen in paper models such as origami art. A famous example of this aesthetic is the folding of paper models by artists such as David Huffman. The elegance of these models comes from creases known as curved folds, which can be produced with a single flat sheet. Huffman pioneered early research on curved folds, and computational

geometers have lately investigated folding difficulties and computational origami. Demaine and O'Rourke state that their concentration has been on piecewise linear structures, with inadequate
understanding of curved folds in particular. While industrial designers have recently started exploring the technique of curved folding, existing geometric modelling systems provide no assistance for such a design process. As a result, Frank O. Gehry, who favours developable shapes in many of his architectural projects, has directed his technology company to develop a CAD module for developable surfaces. To the best of our knowledge, that module also lacks curved folding. Motivated by the possibility and interest in using curved folding for diverse geometric design goals, we examine this topic via the lens of geometric modelling. (Martin Kilian, Simon Flory, Zhonggui Chen, Niloy J. Mitra, Alla Sheffer, Helmut Pottmann)

Origami, or paper folding, is not only an excellent source of inspiration in architectural design, but it is also an effective medium for structural form development since origami's developability and foldability properties are useful for constructing shells and folding/unfolding deployable structures. Straight creases are most commonly used in traditional paper folding. We name this sort of origami prismatic origami because straight creases surround planar facets and form a polyhedral surface. By changing the crease to a curved folding, the surface transforms into a complicated three-dimensional structure that cannot be simply described using simple parameters such as vertex coordinates. When using sheet materials to create a 3D surface, the hybrid trait of curved folding is advantageous. When we try to build a surface using pure bending, the shapes are confined to simple geometries like cones, cylinders, and tangent surfaces. Prismatic origami, on the other hand, is more design-friendly, but it cannot depict a smoothly curved surface until the resolution is increased by a significant number of creases. Such creases provide a high number of vertices where the material deforms primarily in-plane. (Erik D. DEMAINE, Martin
L. DEMAINE, Duks KOSCHITZ, Tomohiro TACHI)

2. HYPOTHESIS & RESEARCH QUESTION

This research is based on the hypothesis that a deliberate and sophisticated utilization of curved crease patterns may aid in the precise generation and manipulation of doubly curved surfaces in origami-based structures. It proposes that the inherent characteristics of paper or other foldable materials can be strategically used to reveal a variety of complicated shapes. These geometries, in turn, are seen to have potential for improving the structural integrity, aesthetic appeal, and functional versatility of origami creations, increasing their application across an assortment of fields. At the heart of this research is the question: How can the principles of curved crease origami be employed to consistently produce and control doubly curved surfaces, and what implications do these advanced geometrical configurations have for practical applications in contemporary design, engineering, and technology?

3. OBJECTIVES

To gain insight into the given topic and rigorously evaluate the stated hypothesis, the study defines various targeted objectives:

Comprehensive Theoretical Review: Conduct a thorough investigation of the geometrical and mathematical underpinnings that support curved crease origami, particularly in the context of producing doubly curved surfaces. This review seeks to synthesize existing information and identify theoretical gaps that the experimental component of this study could address.

Innovative Design Experimentation: Employ a methodical method to designing, folding, and analysing an assortment of origami models with curved creases, with a specific objective of generating diverse doubly curved surfaces. This phase comprises both traditional origami techniques and cutting-edge computational tools to iteratively refine and optimise folding patterns.

4. METHODOLOGY

Each experiment within this research project adhered to a stringent selection of materials and constants to ensure methodological rigor and reproducibility. The subsequent materials were meticulously chosen for their distinctive characteristics and applications for origami experimentation:

Ivory Paper Sheets (210 gsm): Ivory paper sheets weighing 210 grammes per square metre (gsm) were used as the primary substrate for origami folding. This option provides an ideal balance of rigidity and malleability, allowing for delicate crease patterns while maintaining structural integrity.

Cardstock and Cartridge Sheets (180 gsm): In addition to ivory paper, differences in stiffness and texture were investigated with cardstock and cartridge sheets. These materials gave significant insight into how varied paper characteristics affect the folding process and the resulting geometrical forms, expanding the scope of the experiment.

RESOURCES AND TECHNIQUES USED FOR EXPLORATIONS

The study of curved crease origami relied on a wide range of resources and techniques, combining traditional craftsmanship with cutting-edge technologies to generate novel results:

- **Software-Assisted Design Exploration:** Advanced computational tools were employed to explore and manipulate various curve types preceding physical fabrication.
  We have used these software tools to visualise complex geometries, analyse folding patterns, and reiterate designs, establishing the framework for precision origami experimentation.
- **Laser Cutting Technology**: Laser cutting has evolved as a pivotal tool to generate complicated curved creases with distinct precision. By partially cutting the paper along preset routes, laser cutting technology made it more accessible to generate uniform crease patterns, enhancing reproducibility and permitting the investigation of intricate geometries that would be difficult to do manually. The experimental approach involved a precise sequence of processes that transformed laser-cut paper into exceptional origami forms. Following laser cutting, the paper was carefully folded and shaped along predetermined crease lines, while using a methodical technique to assure accuracy and consistency in the construction of doubly curved surfaces.
- **Data Analysis and Interpretation**: Comprehensive data analysis was required to acquire applicable conclusions from experiment results. Scrupulous documentation of the observations on structural stability, aesthetic appeal, and geometric accuracy, using qualitative and quantitative analyses to inspire iterative design changes and develop the study technique are done.

5. PROCEDURE

The experimental procedure was distinguished by its methodical approach, which included numerous stages to assure scientific rigour and thorough investigation:

Paper Preparation: Paper sheets were rigorously prepped before laser cutting to ensure their suitability for origami experiments. It is to be taken under consideration that the paper is precisely sized and aligned with the specified crease patterns, so reducing errors and increasing reproducibility.

Laser cutting was done with rigorous attention to detail, with parameters including speed, power, and focal length precisely adjusted to the thickness and qualities of the paper. Accurate cuts along established routes, creating regularly spaced and defined creases that serves as the foundation for later folding and shaping are to be made.

6. EVALUATION AND ITERATION

The generated origami structures were thoroughly evaluated using predetermined criteria such as structural integrity, aesthetic appeal, and conformance to design specifications. Feedback from the evaluation process was rigorously documented and utilised to inspire iterative changes to crease patterns, folding processes, and material selection for future experiments.

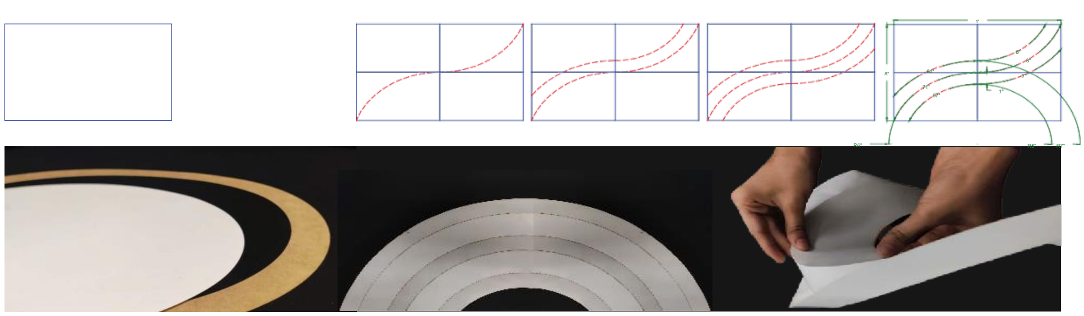


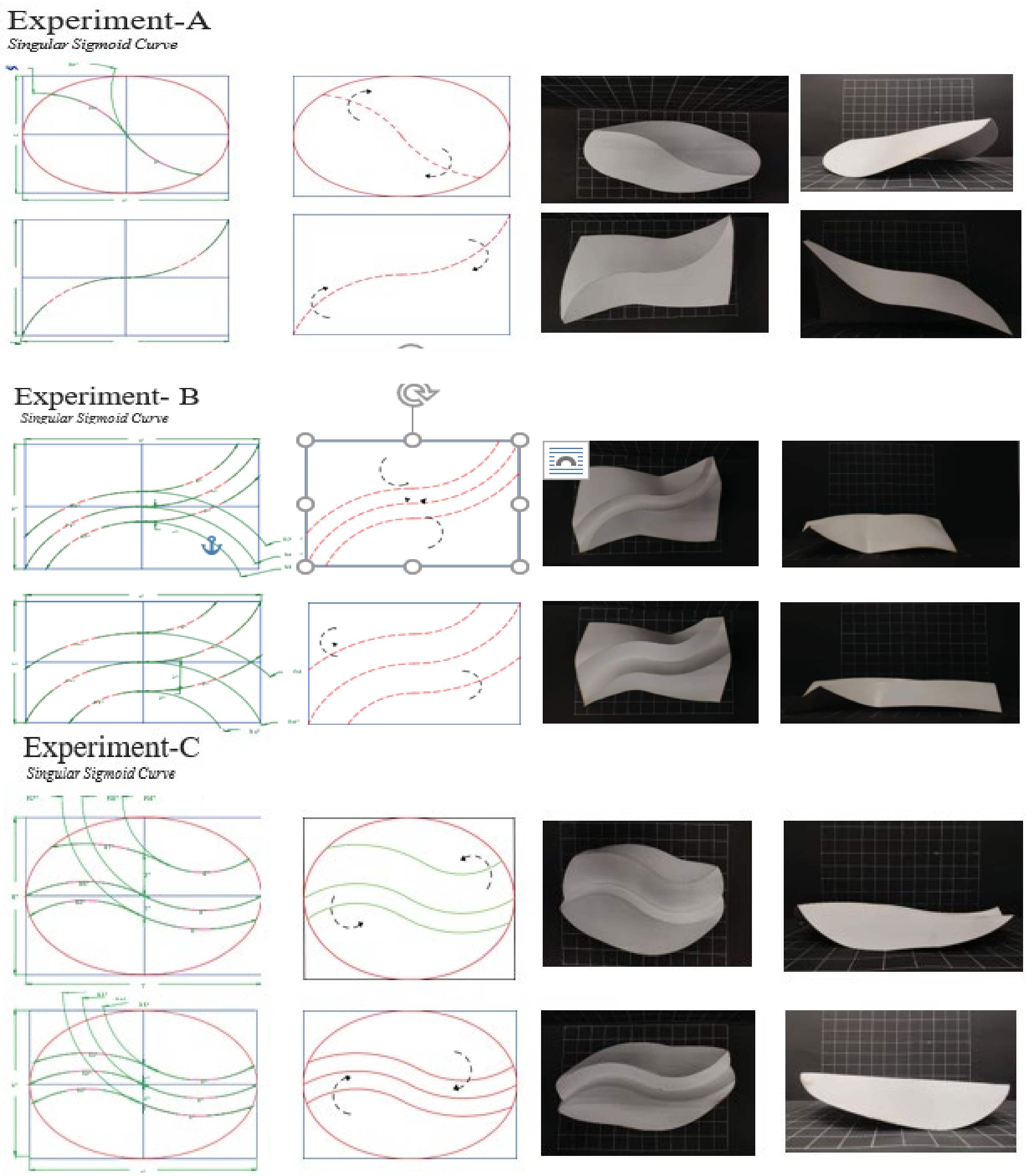
Figure 1, the top illustration demonstrates the step-by-step technical formation of the exploration. Below, the images depict the materials utilized, the resulting crease formations, and the folding processes employed during theexplorations.

7. RESULTS

Aim: The aim is to achieve dynamic form by incorporating variations in height, surface area, volume, and other parameters.

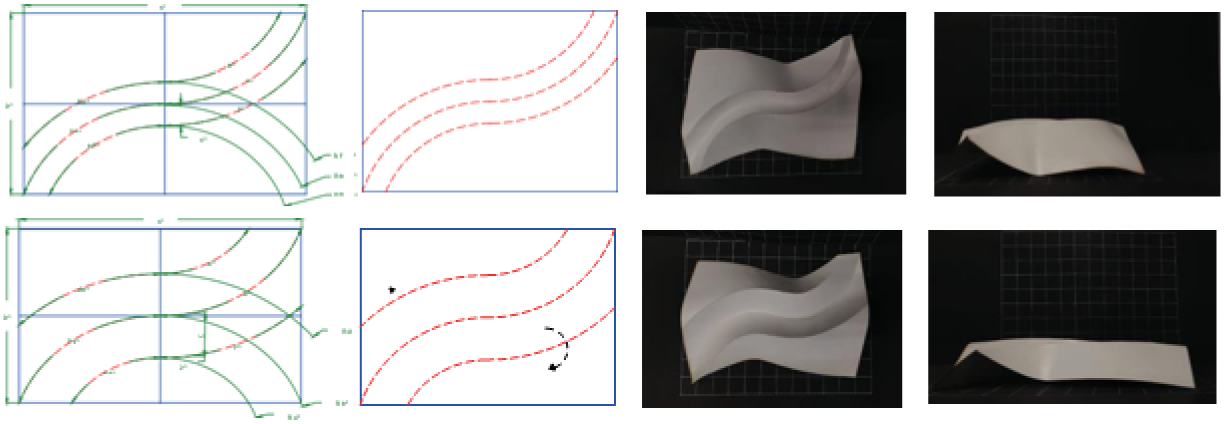
Variable: The variable being explored in each experiment is the difference in units between the distances of two curves.

Constant: Each exploration maintains consistent concentric arrangements, and the size of the sheet remains constant throughout.



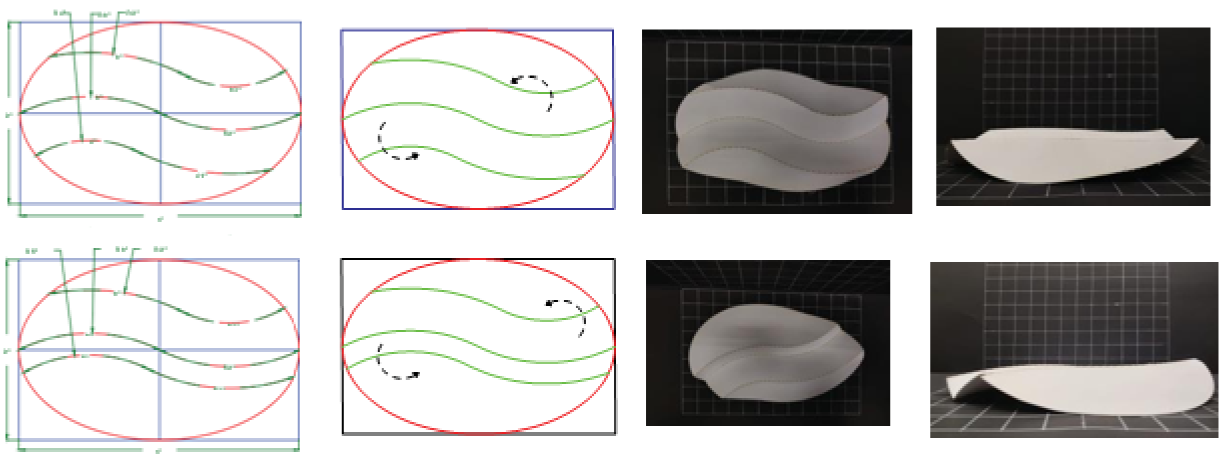
Experiment- D

Singular Sigmoid Curve



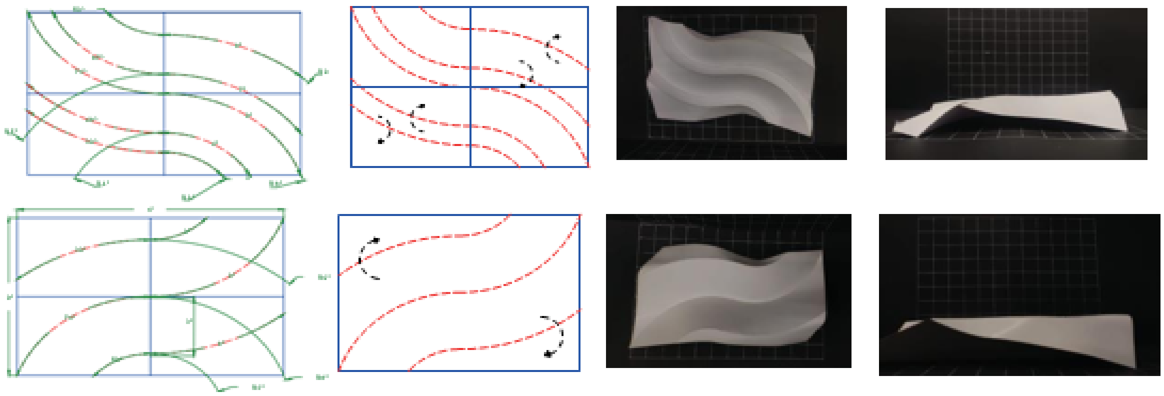
Experiment- E

Singular Sigmoid Curve



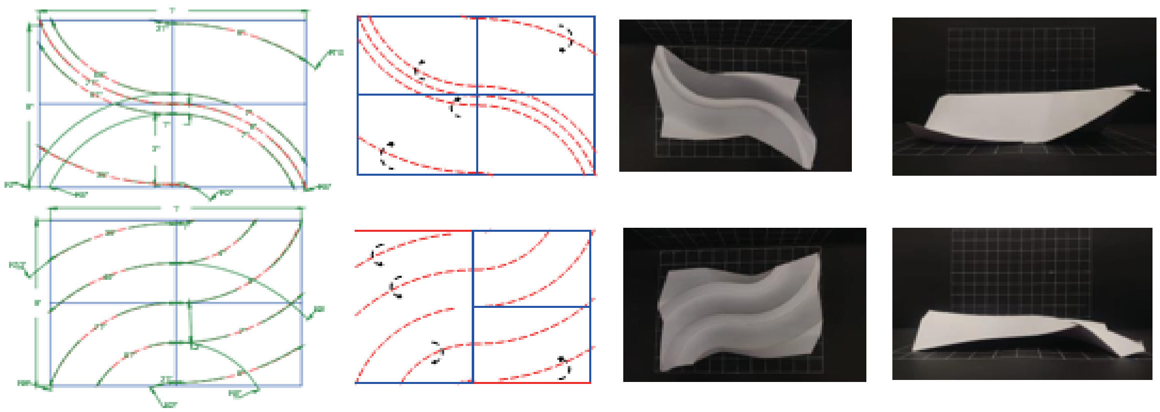
Experiment- F

Multiple Sigmoid Curve



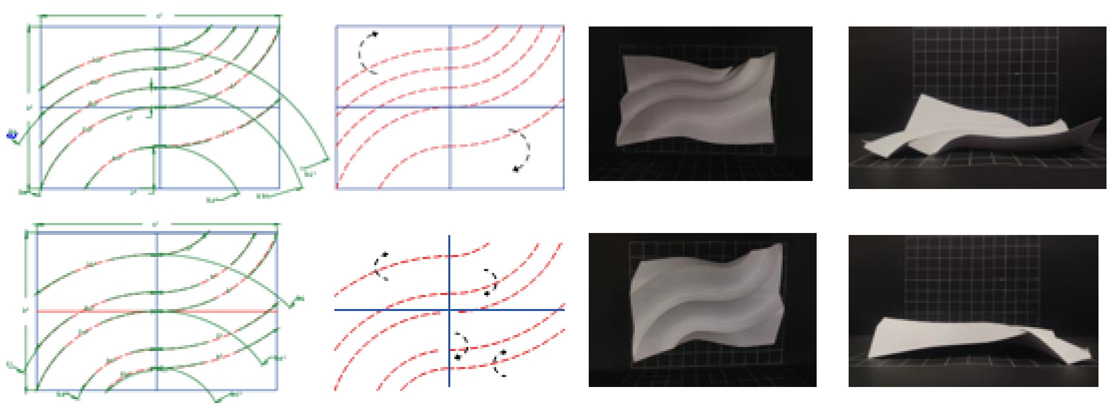
Experiment- G

Multiple Sigmoid Curve

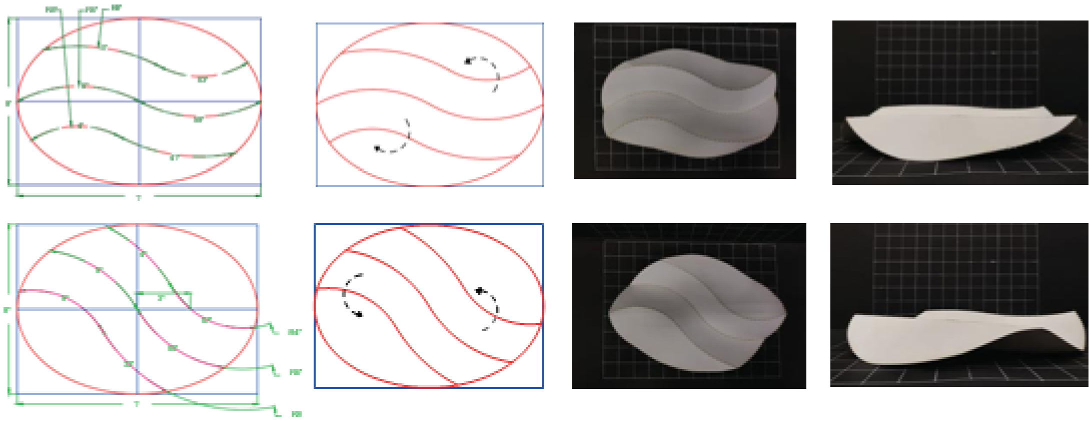


Experiment- H

Multiple Sigmoid Curve



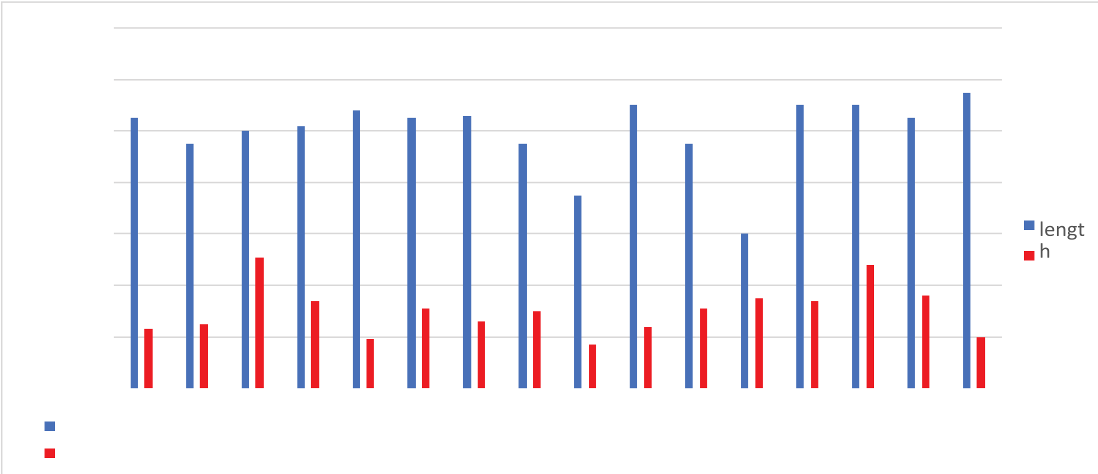
Experiment- I
Triple Sigmoid Curve



All figures illustrate the CAD drawings on the left side, depicting the initial exploration, while the outcomes of the explored forms, measured on grid paper, are presented on the right side.

The dimension of the sigmoid curves are mirrored and reciprocal of each other from opposite direction. The folding of the concentric curves will follow a continuous pattern of downward fold followed by upward. It is recommended to start folding from the outer curve which will be downwards. This exploration is done using an ivory paper sheet. The curves are then half laser cut at the speed of 100 and power 25. The size of the dashed line is 3mm and so is the distance between two dashed lines.

Experiment A Singular Sigmoid Curve				Experiment B Triple Sigmoid Curve			
Height	5.1”	Height	5.9”	Height	3.5”	Height	2”
Length	10”	Length	11”	Length	2”	Length	11”
Experiment C Triple Sigmoid Curve				Experiment D Triple Sigmoid Curve			
Height	3”	Height	3.1”	Height	2.6”	Height	3.1”
Length	9.5”	Length	10.5”	Length	10.6”	Length	9.5”
Experiment E Multiple Sigmoid Curve				Experiment F Multiple Sigmoid Curve			
Height	2.5”	Height	9.5”	Height	3.5”	Height	2.0”
Length	1.9”	Length	10.8”	Length	11”	Length	11”
Experiment G Multiple Sigmoid Curve				Experiment H Multiple Sigmoid Curve			
Height	3.6”	Height	1”	Height	1.5”	Height	1”
Length	10.5”	Length	10.5”	Length	11”	Length	11”
Experiment I Triple Sigmoid Curve				Experiment J Multiple Sigmoid Curve			
Height	1”	Height	1.5”	Height	3”	Height	1.5”
Length	1.5”	Length	10”	Length	9.5”	Length	7.5”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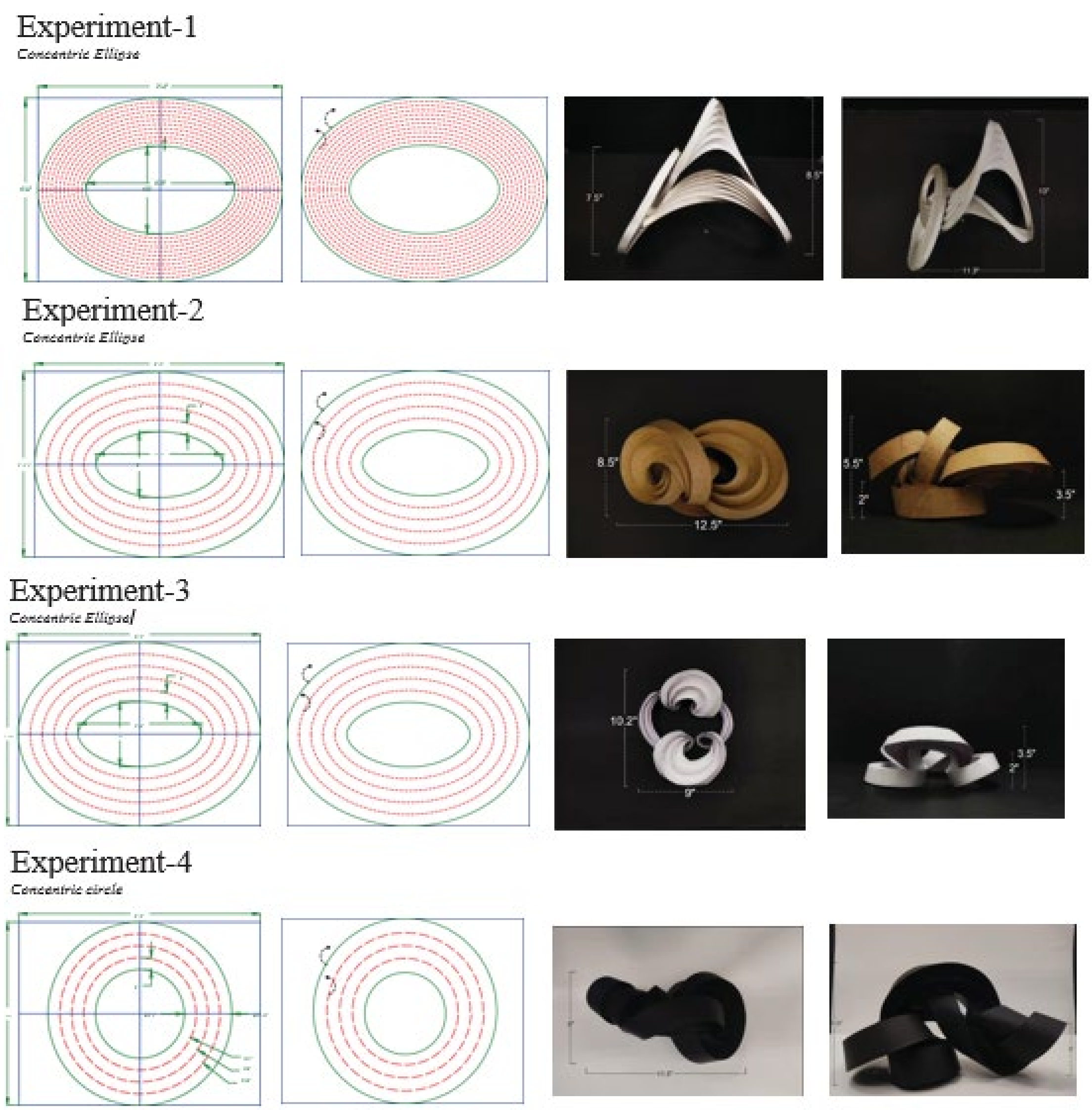
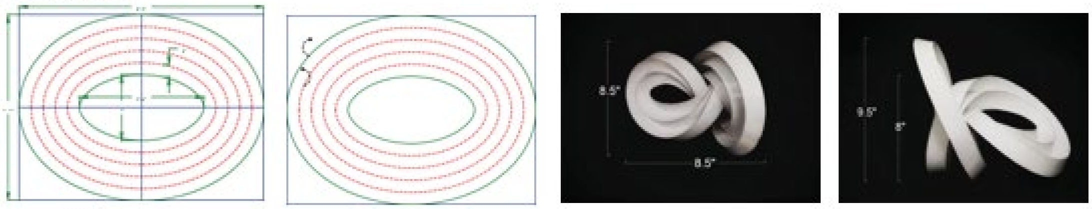

Experiment-1
Concentric Ellipse
Experiment-2
Concentric Ellipse
8.5"
12.5"
5.5"
2"
3.5"
Experiment-3
Concentric Ellipse/
10.2"
9"
3.5"
2"
Experiment-4
Concentric circle

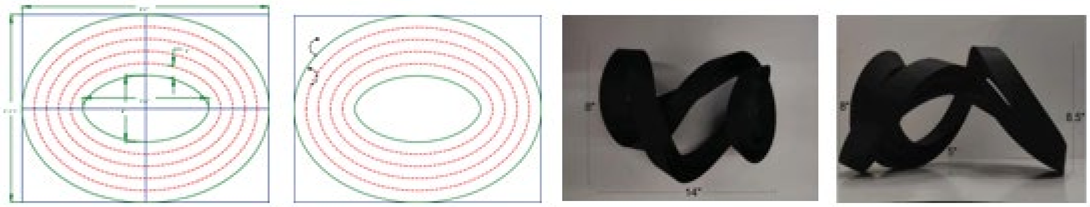
Experiment-5

Concentric Ellipse



Experiment-6

Concentric Ellipse



All figures illustrate the CAD drawings on the left side depicting the technical works, while the outcomes of the explored forms are presented on the right side.

This exploration is done using a card paper sheet. The rings are then half laser cut at the speed of 100 and power 25. The size of the dashed line is 3mm and so is the distance between two dashed lines. The folding of the concentric circles will follow a continuous pattern of downward fold followed by upward. It is recommended to start folding from the outer ring which will be downwards.

Experiment 1		Experiment 2	
Height	Length	Height	Length
Total: 8.5” L.H.S : 5.5” R.H.S : 3.5”	Total: 11.3”	Total: 8.5” L.H.S : 5.5” R.H.S : 3.5”	Total: 12.5”
Experiment 3		Experiment 4	
Height	Length	Height	Length
Total: 3.5” L.H.S : 2” R.H.S: 2”	Total: 10.2”	Total: 11.5” L.H.S : 11.5” R.H.S: 6”	Total: 11.5”
Experiment 5		Experiment 6	
Height	Length	Height	Length
Total: 9.5” L.H.S: 8”	Total: 8.5”	Total: 8.5” L.H.S: 8” R.H.S : 8.5”	Total: 14”

The outcomes of the studies conducted in this research study disclose a junction of geometry and aesthetics, demonstrating the impact of curved crease origami on the visual structure of produced objects. Through comprehensive investigation and research, specific visual qualities evolved, revealing a subtle interplay between the arrangement of curved parts and the overall aesthetic of the emerging forms. The findings gathered during the research of forms formed by curved crease origami reveal an interesting phenomenon about the role of the distance between two curved rings in moulding the visual structure. It becomes clear that this distance is a critical variable, with a significant impact on the overall appearance and perceived fluidity of the structure. Specifically, when the distance between two curved rings increases, the resulting structure becomes more fluid and organic in appearance.

This occurrence results from a gradual transition between adjacent curves, which creates an impression of continuity and fluidity across the design. The spacing between curved parts consequently emerges as an important aspect in orchestrating the aesthetic expression of the origami building. Conversely, when the distance between two curved rings is reduced, the form tends to exhibit a more structured height, characterized by sharper angles and defined creases. This effect is particularly pronounced when additional supporting curves are introduced towards the edges of the structure, further accentuating the geometric interplay between adjacentelements. The juxtaposition of closely spaced curves engenders a visually dynamic composition, marked by intricate interlocking patterns and heightened structural complexity.The implications of these observations are profound, underscoring the inherent versatility of curved crease origami in generating a diverse range of visual forms.

Corrugations provide an easy technique to convert thin, lightweight sheets into sturdy structures. Traditional, straight-crease corrugations, on the other hand, produce extremely anisotropic stiffness, resulting in undesired flexibility in certain loading directions. In this study, we investigate the bending stiffness of curved-crease corrugations, which are developable corrugations formed by folding thin sheets around curves with no linerboard covers on top or bottom. The curved-crease corrugations disrupt the pattern's symmetry and can redistribute stiffness to withstand bending deformations in multiple directions. We develop a system for estimating the bending stiffness of any general corrugation using many geometric cues at various scales. We use the framework to develop two predictive approaches that provide useful information about the global stiffness of corrugations without requiring a full investigation. The results of these methods are consistent with experimental three-point bending tests of five corrugation geometries constructed from polyester film. Corrugations with circular or parabolic curved creases that cross with one edge of the pattern perform best in terms of redistributing stiffness in many directions. A parabolic crease pattern has a stiffness of around 2.5 [N/mm] in both directions, whereas a straight crease pattern has about 4 [N/mm] in one direction and 0 [N/mm] in the other. (Steven R. Woodruff ,Evgueni T. Filipov)

8. DISCUSSIONS

Interpreting the findings of research into curved crease origami necessitates a thorough and exhaustive exploration that delves into myriad dimensions, including a deeper understanding of its comparison to traditional origami methodologies, its broad implications across a wide range of disciplines, and a meticulous examination of the inherent limitations that shape its trajectory. This comprehensive discussion aims to illustrate the various significance and complexities inherent in the study of curved crease origami.

Beginning with a comparison between curved crease origami and standard origami techniques, one discovers an array of distinctions and inventions that deviate from the usual paradigm. Traditional origami, characterised by straight folds and crisp creases, has long been associated with geometric precision and structural stiffness. Curved crease origami, on the other hand, adds a new dimension with its fluidity, curvature, and organic form. By introducing curved folds, practitioners break free from typical geometric limits, creating dynamic, lifelike creations that defy preconceived preconceptions about what origami is capable of. The departure from angular rigidity not only broadens artists' creative horizons, but also gives creations a sense of naturalistic movement, grace, and aesthetic attraction.

Curved crease origami has broad repercussions, enriching each area with its own contributions and applications. In architecture, for example, the ability to manage curved folds opens up a world of possibilities for creating structurally durable forms that contradict traditional architectural conventions. Architects and designers use the concepts of curved crease origami to create unique, biomimetic buildings inspired by the complicated geometries found in nature,

a greater integration of art and engineering in architectural design. Curved crease origami also provides fertile ground for biomimicry and bioinspired design, acting as a catalyst for innovation in domains such as robotics, medical device design, and adaptive materials.

Researchers push the bounds of technology by imitating natural systems' complex shapes and capabilities, resulting in creative solutions to pressing real-world situations. Deployable constructions and space exploration technologies, for example, use curved crease origami to provide small, lightweight solutions for usage in harsh situations, demonstrating the ancient art form's versatility and adaptability as a tool for creativity and problem solving.

However, it is critical to recognise the limits associated with the study and implementation of curved crease origami. The computational complexity of modelling and simulating the behaviour of curved folds, especially in multi-layered structures, is the most significant of these issues. The intricate interplay of geometric parameters and material qualities creates daunting challenges for precisely forecasting the behaviour of curved crease origami designs, demanding the development of advanced mathematical methodologies and computer tools.

Furthermore, the practical constraints of production and assembly present further obstacles, as obtaining accurate curvature and alignment necessitates a high level of artistry and specialised manufacturing methods. While curved crease origami provides novel solutions for design exploration and prototyping, its scalability and cost-effectiveness in mass production and commercial contexts are still important factors that may limit its wider usage.

9. CONCLUSION

Curved crease origami is a departure from standard techniques, bringing fluidity and curve to the ancient craft. Origami, based on painstaking paper folding, combines simplicity and complexity. While traditional origami focuses on linear folds and sharp creases for geometric precision, curved crease origami challenges this paradigm by including dynamic curvature and organic forms. This revolution sparks innovation, breaking down old boundaries and encouraging interdisciplinary collaboration.

Curved crease origami has applications far beyond aesthetics, including building, robotics, and space exploration. In architecture, it drives creativity, resulting in biomimetic forms inspired by nature's geometry. In robotics, it provides adaptive, morphing structures, which have applications in soft robotics and biomedical devices. Furthermore, its application in space exploration offers compact, lightweight solutions for deployable structures and spaceship architecture, potentially revolutionising extraterrestrial habitats and interplanetary exploration.

Moving forward, breakthroughs in computational modelling and interdisciplinary collaboration will fuel innovation. The mysteries of curved folds will be revealed through precise design and fabrication procedures. Ethical considerations will guide our efforts, assuring both societal benefit and environmental sustainability.

In conclusion, curved crease origami represents human innovation and ingenuity. Its relevance extends beyond art, providing a gateway to innovation and discovery. By embracing its revolutionary power, we can create a more sustainable and brighter future.

CONFLICT OF INTERESTS

None

ACKNOWLEDGMENTS

None

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