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**Publication date**

2023

**Document Version**

Final published version

**Published in**

Proceedings of the International Astronautical Congress, IAC

**Citation (APA)**

Sachithanandan, J., Uriol Balbin, I., & Solano Lopez, P. (2023). Preliminary Design of a CubeSat Demonstrator for an Origami-inspired Deployable Structure. *Proceedings of the International Astronautical Congress, IAC, 2023-October*.

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IAC-23,C2,2,8,x79886

# Preliminary Design of a CubeSat Demonstrator for an Origami-inspired Deployable Structure

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## Abstract

Rising commercialization of the space industry has led to increasing demand for large structures in space, such as habitats and fuel tanks. However, due to the limited payload volume available, the shape of such structures is highly constrained. This calls for a structure that is flexible enough to be stowed during launch but still enough to withstand structural loads.

Origami-inspired structures are an appealing design compromise as they can dynamically change their shape and volume while maintaining structural integrity. They also present the advantage of a high packaging ratio, scalability, can largely maintain their structural properties after repeated deployment, and possess flight heritage with space technology like sunshields and solar arrays. The present work aims to further the knowledge in this field by testing the viability of this concept with a deployment demonstrator fit for a 12U CubeSat mission.

Two potential deployment concepts have been identified: telescopic deployment and inflation. The telescopic solution is reliable and has extensive flight heritage but adds weight and complexity to the structure. Inflation, however, is lightweight, has fewer parts, and provides a directly pressurized structure, but runs the risk of depressurization. Nevertheless, it has been used successfully to deploy origami booms and sails in space and other inflatable structures like the BEAM.

Different origami patterns are selected for each of the deployment concepts. The telescopic deployment calls for the Yoshimura pattern due to its straight, non-rotational folding behaviour, and for inflation, the Kresling pattern is considered. The concepts are traded off on the basis of mission-critical criteria.

After identifying a suitable origami pattern and deployment concept, a CAD model representation is created using the Rhino 3D modeling software. The model is then validated using laser-cut paper prototypes, following which it is used to identify an optimal pattern configuration that has a high usable inner volume and low packaging ratio (or folded height).

Next, suitable materials and manufacturing options are traded off to identify a feasible fabrication method and materials. This is followed by a detailed description of the manufacturing process.

Finally, based on the lessons learnt during the design and prototyping stages, some design guidelines are generated. Recommendations for further work are also made.

**Keywords:** deployable structures, engineering origami, cubesats, origami, habitats, 3D printing

## 1 Introduction

Due to the rising commercialisation and privatisation of the space industry[1], access to space is getting more and more affordable. Now more than ever, the interest in not just going up to space, but also living there, has increased manifold. To cater to this demand, over the past two decades, the space industry has been studying the best way to sustain humans in space for the long run. This has resulted in a few fruitful attempts like BEAM, the Bigelow Expandable Activity Module, an inflatable habitat module that is attachable to the ISS [2]. However, there is still a long way to go with regard to optimising the way we take and operate large living and storage modules to space in an economically feasible manner.

While the demand to go to space rises, launch vehicle space is still at a premium. The limited volume available in payload fairings and the massive costs involved call for a solution that takes up as little space as possible[1]. Reducing the size of the habitats is not really a great option because a minimum living space is a must for human life. A potential solution would be to create a deployable module that is compressible down to a small volume for stowage in a launch vehicle, but that has a deployed volume of many times that of its stowage volume.

Deployable structures have widely been used in the past for a multitude of space applications, most commonly, antennas, but also solar arrays, booms, and telescopes. There are several criteria that a deployable module must follow in order to be suitable for long-term use in space and these include deployability, rigidity, structural strength, low mass, high volume, low stowage volume[3][4], among others. A concept that has recently begun to be considered for such an application is Origami, the Japanese art of paper folding[3]. The traditional art form was historically used as a form of recreation or for religious purposes and has only recently, over the past few decades, been of interest for scientific applications. In origami, the structure is folded at pre-defined locations (creases) and variations in origami are defined by unique crease patterns. Due to the ability of origami to dynamically change its structure and structural integrity to suit multiple objectives through geometric transformation, it is of interest in the scientific community, most recently,



Fig. 1: Inflatable Antenna Experiment[5]

in the design of space structures.

Origami has several advantages including its deployability, reconfigurability, ability to self-actuate, tunability, and scalability[3]. These have proved to be very valuable for applications such as minimally invasive surgical equipment[6], adaptive and climate responsive architecture[7], artificial limbs[8], and many others.

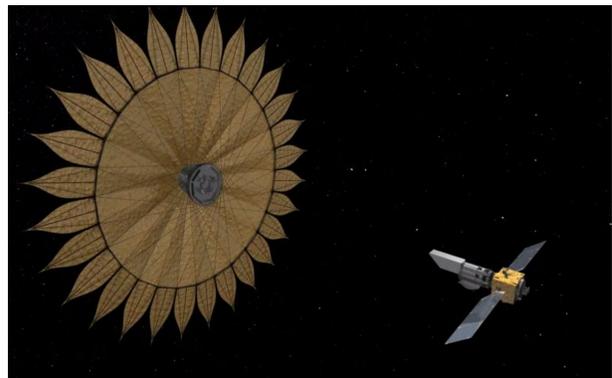


Fig. 2: Starshade Concept Design[9]

These properties of origami have already proven to be an asset to designing for space; they have been used in the past for deployable booms[10][11], Starshade[12], antennas[9] and other applications, primarily as a space-saving mechanism. Researchers have now begun to try to translate the origami concept to much larger space structures. However, designing and testing on such a large scale on ground and in-orbit is not feasible due

to large costs, facility size limitations, gravity effects, and so on[13]. From this project, we see that entire test facilities and new testing approaches had to be developed to test the structure and there were still many unavoidable constraints and implications.

Designing and prototyping a demonstrator that would fit in a CubeSat is an ideal way not just to test the deployment concept and origami pattern suitability on ground at a feasible cost but also to deploy it in orbit and monitor its performance. Since origami is largely scalable[3], this would allow us to translate the lessons learnt to a larger scale model with confidence in its capabilities.

This paper delves into the design process of an origami-inspired deployable structure that can fit in a 12U CubeSat. First, a set of requirements are defined based on the mission, constraints, and design goals. Feasible design concepts are described and traded off based on mission-critical criteria. The concept is then represented digitally via a CAD model made using the Rhino 3D modeling software. The model is validated with paper prototypes after which it is used to generate an optimal pattern configuration with maximum usable inner volume and low packaging ratio. Next, a suitable material and manufacturing option is chosen and the fabrication process is described. Finally, design guidelines based on the CAD model and paper prototypes are generated and recommendations are made for future work.

## 2 Requirements

For any engineering design process, a set of requirements is crucial to drive and constrain the design. The following requirements are generated based on performance, mission constraints, and non-negotiable factors.

1. **Structural performance:** The deployable structure must withstand folding and deployment loads
2. **Repeatable deployment:** Must withstand multiple deployment cycles without damage
3. **Volume  $\leq 100 \times 100 \times 150 \text{ mm}^3$ :** Defined by CubeSat dimensions, accounting for tolerances[14]
4. **Weight  $\leq 10 \text{ kg}$ :** 41% of 12U CubeSat weight, according to SE guidelines[15]

5. **Deployed height  $\geq 2 \times$  folded height:** Low packaging ratio is required so that a large structure can be stowed as compactly as possible. The packaging is ratio is defined as follows.

$$\eta = \frac{\text{Folded Height}}{\text{Deployed Height}}$$

6. **Rigidity after deployment:** Must maintain its deployed configuration
7. **Availability:** Materials and manufacturing equipment must be easily available at a low cost and usable without extensive training

## 3 Design Concepts

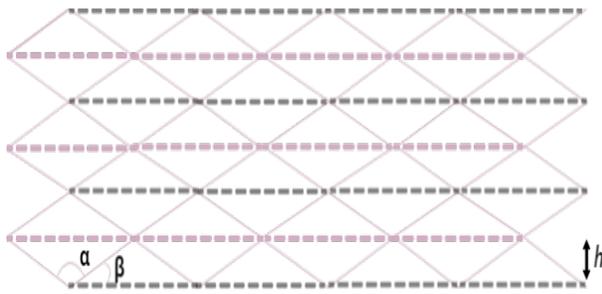
With the aforementioned requirements in mind, two design concepts are developed: a Yoshimura cylinder deployed via telescopic deployment and a Kresling cylinder deployed via inflation. Before delving into the design concepts, each origami pattern and deployment method is described individually.

### 3.1 Origami Patterns

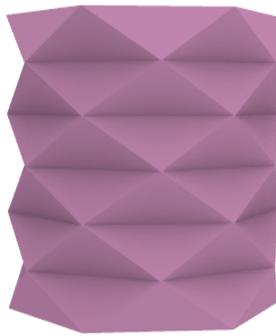
#### 3.1.1 Yoshimura Pattern

The Yoshimura pattern is a triangular mesh buckling pattern that was first observed when a thin cylinder was subjected to axial compression[16]. It is made of repeating diamonds i.e., triangles sharing a single edge, as shown in Figures 3a and 3b.

A cylinder with this pattern is extremely stiff in the axial direction, which is ideal for deployable structures like antennas and booms. However, the pattern is not rigid-foldable, so, on compression, it experiences increasingly larger strains on its facets and creases, thus being unable to maintain its internal envelope and axis. Senda et al.[17] studied the deployment characteristics of a Yoshimura-based boom, and it was found to have much worse straight-line deployment than a Miura-ori boom.



(a) Yoshimura flat pattern



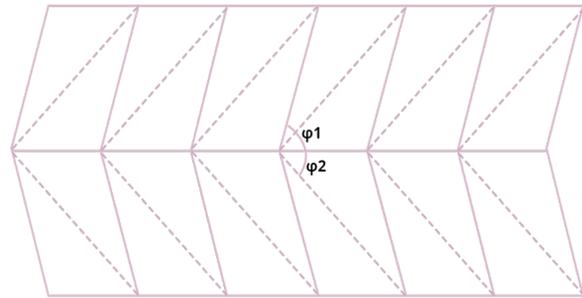
(b) Yoshimura Cylinder

**Fig. 3:** Yoshimura Pattern and Parameters[16]

### 3.1.2 Kresling Pattern

When a thin-walled cylinder is subjected to axial twisting, it gives rise to the Kresling buckling pattern, characterised by alternating mountain and valley folds angled in the direction of the applied twist[18]. It is not rigidly foldable, however, it may be bistable in some configurations. This means it will not require extensive facet deformation to fold down to its fully stowed state. The Kresling flat pattern is shown in Figure 4a, which is folded into its cylindrical form, as seen in Figure 4b.

Studies have shown that the Kresling pattern exhibits tuneable stiffness and bistability and can bear large loads by exploiting a mechanical diode-like effect to lock into a deployed state[19]. Kidambi et al.[20] found that the Kresling pattern is not always bistable but can have its geometrical parameters tuned to fluctuate between mono-, bi-, and multistability, also confirmed in a compression test by Lee et al.[21]. These conditions can be suitable for different deployment strategies depending on the



(a) Kresling flat pattern



(b) Kresling Cylinder

**Fig. 4:** Kresling Pattern and Parameters[18]

deployment accuracy needed and the forces available to compress the cylinder to a compact state. It is to be noted that changing between mono-, bi-, and multistability does not depend on the material of the structure, which is an advantage as any material can be used for its construction.

## 3.2 Deployment Techniques

### 3.2.1 Telescopic Deployment

Telescopic structures consist of cylindrical or rectangular sections that fit inside one another. They have been used in telescopic masts that are deployed either sequentially using a spindle and nut mechanism or simultaneously using cables and pulleys. Some applications also use pneumatic deployment of telescopic sections, which reduces the mechanical complexity and the number of moving parts in the system.

While telescopic deployment might be an option to consider for the origami structure inside a CubeSat, the length and volume limitations could be a problem when

scaled up to a larger structure such as a habitat or storage unit.

### 3.2.2 Inflation

Inflatable structures are those that are either air-inflated or air-supported. This deployment method has low stowed volume and few mechanical parts, reducing complexity. However, it does require gas to be carried on board for inflation and supplementary gas to hold it in its deployed configuration, thereby adding to the mass of the spacecraft. Inflation is a particularly attractive option due to the above advantages and because it has already been studied alongside origami, which may be a viable method of folding for inflatable structures[11].

Inflatable structures have considerable spaceflight heritage—they have typically been used for antennas, booms for solar arrays and sails, and, less commonly, for bases and research modules such as the Bigelow Expandable Activity Module(BEAM). Other examples are the ECHO balloons launched by NASA in the 1960s[22] and the Inflatable Antenna Experiment[5].

Conventionally, a pressurised gas system is used to inflate a structure in space, but this is very heavy and complex, with a possibility of leakage. In the recent past, a Dutch research institute, TNO, developed Cool Gas Generators(CGGs) as an alternative to other forms of inflation and propulsion[23]. A cool gas generator uses a solid propellant charge in which the gas is chemically stored. On initiation, the gas is released at an ambient temperature and the rest of the propellant stays in the generator as slack. These generators are compact, have a long storage time, and since cool gases are used, no thermal problems will arise.

## 3.3 Design Option Tradeoff

### 3.3.1 Telescopically deployed Yoshimura structure

The Yoshimura pattern only compresses axially and does not rotate. Therefore, it is considered suitable for telescopic deployment as it can be deployed linearly.

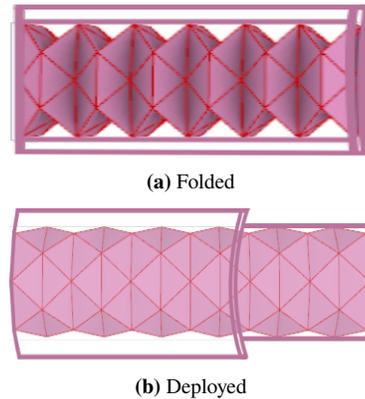


Fig. 5: Telescopically deployed Yoshimura

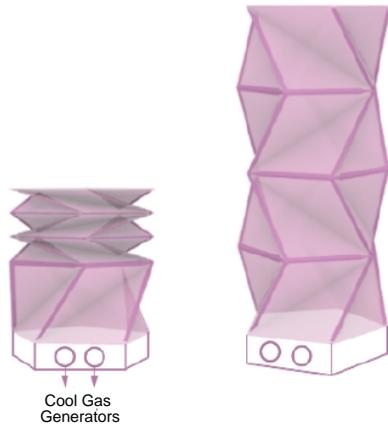
The mechanism consists of a tube contained within another tube of larger circumference. The origami structure is mechanically attached to the rim of the inner tube such that it can be unfolded while the tube is deployed. Guide rails along the inside of the larger tube allow for smooth deployment and add stiffness to the structure. To lock the structure in place, ball pins or latches on the smaller tube latch onto tapered holes or latches on the rim of the large tube.

It is a simple, retractable mechanism with considerable flight heritage. However, it poses a length and volume limitation due to the tubes being nested within each other.

### 3.3.2 Kresling structure deployed via inflation

The Kresling pattern is chosen due to its tunable bistability[19], and relative ease of folding in comparison to the Yoshimura pattern, which is stiff in the axial direction. Additionally, each layer of the Kresling structure can be made bistable, so they can be deployed and collapsed independently of one another.

Cool gas generators(CGGs) placed beneath the structure can be used to deploy it as well as pressurise it to maintain the deployed configuration if required. CGGs are chosen as they are compact, lightweight, and store gas at an ambient temperature.



**Fig. 6:** Kresling deployment via inflation

Since there are no additional mechanical parts, the stowed volume is much lower than other solutions. The gas is maintained at an ambient temperature, so there is no risk of thermal problems.

### 3.4 Tradeoff

Next, the two design concepts are traded off on a qualitative basis. The tradeoff criteria chosen are as follows.

- **Weight:** Lightweight systems are desired to reduce launch costs. The telescopic deployment setup is heavier than the inflation. The majority of its weight comes from the multiple tubes whereas, for the inflation system, the CGGs are lightweight, in the order of 10 grams.
- **Usable Inner Volume:** The demonstrator is intended to be scaled up for use in applications like fuel tanks and habitats where maximum space is desired inside the deployable structure.

The telescopic system consists of multiple tubes nested in each other, occupying considerable space, thereby not leaving much volume available for the actual intended application of the structure. The inflation system does not have any obstructive elements within the volume of the structure; the CGGs are only placed below it. Therefore, the inflation deployment system performs better in terms of available volume for a structure of the same

Tradeoff Criteria	Weight	Usable Inner Volume	Scalability	Deployment Predictability
<b>Design Concepts</b>				
Yoshimura Telescopic Deployment	Yellow	Yellow	Yellow	Green
Kresling Inflation Deployment	Green	Green	Blue	Green

● Excellent ● Meets requirements ● Average

radius.

- **Scalability:** As the current project is a small-scale technology demonstrator to validate the deployment concept, it must also be scalable to the sizes the concept is meant to be used at.

The telescopic system can only be scaled up to a certain extent until the available volume is so low due to the nested tubes that the design concept is not feasible anymore. The inflation system performs better in this regard, having had flight heritage with much larger structures, but could potentially have weight issues with the amount of inflation gas required onboard for a much larger system.

- **Deployment Predictability:** For the intended applications, the deployable structure may be deployed and folded multiple times during testing, transportation, and operation. Exhibiting predictable behaviour across multiple deployment cycles is crucial to building a reliable system.

Both forms of deployment, the telescope and inflation, perform similarly in terms of predictability. The telescopic option provides guided deployment, whereas the predictability of an inflation system depends on the origami pattern used. In this trade-off, the Kresling pattern is chosen, which can exhibit predictable straight-line deployment, given a controlled source of air[17].

From the trade-off table, it is evident that the most favourable design concept is the Kresling structure deployed via inflation. It performs similar to or better than

the telescopic deployment in every criterion and is, therefore, the concept that is chosen for further detailed design.

#### 4 Modeling

To model the origami structure, the Rhinoceros 3D CAD modelling software is used in conjunction with the Grasshopper plug-in. Using this software, the cylinder-like deployable origami structure is generated, starting from a base polygon with user-defined geometric parameters.

The inputs given to the Grasshopper algorithm to generate the structure are:

- **Radius of the base polygon**
- **Number of polygon sides**
- **Deployed height of the cylinder**
- **Number of origami layers**

With these inputs, the 3D geometry shown in Figure 7 is generated. The Kangaroo physics solver enables the folding of the structure, allowing extraction of outputs in the folded configuration. Hence, the following outputs are obtained.

- **Outer Volume:** The cylindrical volume occupied by the origami structure
- **Total Inner Volume:** The complete inner volume of the origami structure
- **Usable Inner Volume:** The inner volume of the origami structure, neglecting the volume between the folds
- **Stowed Height:** The folded height of the structure
- **Flat pattern parameters for manufacturing**

For validation of the model, laser-cut paper prototypes are created and the measurements are compared with those output by the Rhino model. A maximum discrepancy of 10% was found for the usable inner volume which is attributed to the assumption made about the twist angle in the CAD model. However, the model is still considered fit for use to understand the behaviour of the origami structure in response to varying geometric parameters and observe trends.

#### 5 Optimisation

The model has now been validated and can be used to identify an optimal pattern configuration that provides maximum usable inner volume and a low packaging ratio.

For the optimisation process, the Galapagos solver module is added to the Rhino-Grasshopper model, which works on the basis of evolutionary algorithms. Galapagos facilitates optimisation and exploration of design solutions by iteratively evolving a population of potential solutions based on defined fitness criteria. By defining variables and objectives, Galapagos automatically generates and evaluates multiple design alternatives, iteratively refining them towards the desired outcome.

The solver takes a fitness function as input which is the value to be maximised i.e., the usable inner volume. It also accepts "genomes" which are the parameters that affect the fitness function. These are the number of polygon sides, number of origami layers, and total height of the deployed origami structure. The radius is fixed at 5 cm, according to CubeSat dimensions.

On running the solver, the following outputs are obtained.

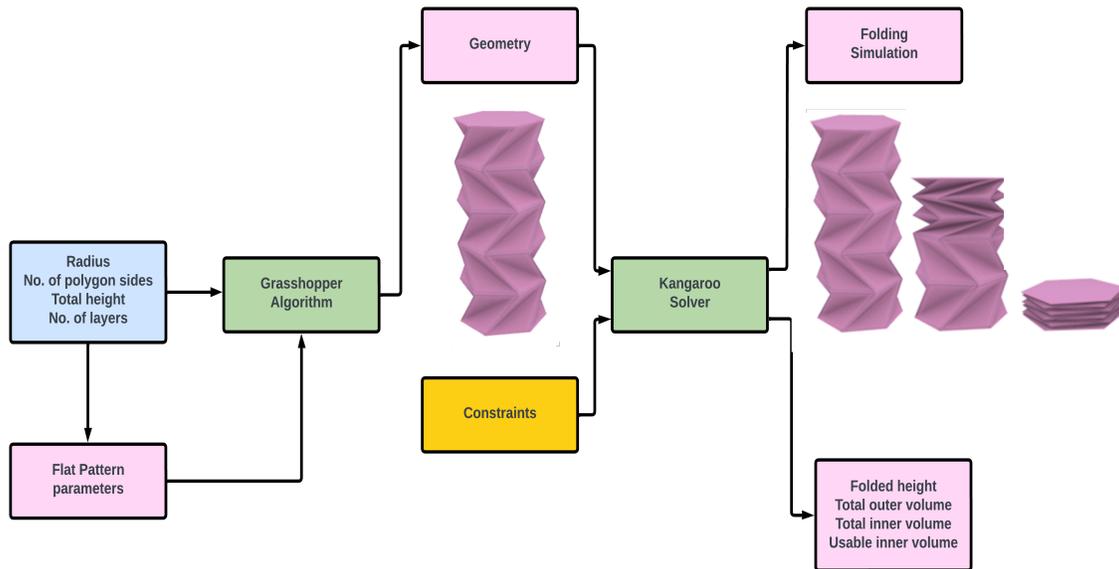
**Table 1:** Optimised Parameters

Optimised Parameters	
<b>No. of sides</b>	14
<b>No. of layers</b>	11
<b>Total height(cm)</b>	39.2

**Table 2:** Optimal Outputs

Outputs	
<b>Stowed Outer Volume(cm<sup>3</sup>)</b>	314.15
<b>Usable Inner Volume(cm<sup>3</sup>)</b>	2265
<b>Packaging Ratio</b>	0.102
<b>Deployment Ratio</b>	9.72

The deployment ratio is calculated as the ratio of the deployed height to the folded height and is found to be  $9.72 \approx 10$  i.e., the structure can be folded down to about one-tenth of its deployed height. However, it should be noted that this value could vary for a physical model



**Fig. 7: Rhino-Grasshopper Model**

because, in reality, some sections are twice as thick as the rest due to additional flaps used to join two halves of the structure.

Additionally, while this configuration is optimal in terms of geometry, it is yet to be seen if it can be manufactured feasibly.

## 6 Prototyping

The next step is to translate the design concept into a real-life prototype. To do this, various materials and manufacturing options are considered. Two options—hand fabrication of dual matrix composites and 3D printing thermoplastics—are chosen for a final tradeoff.

### 6.1 Prototyping Options

#### 6.1.1 Dual Matrix Composites

Dual matrix composites are a subset of High Strain Composites(HSCs). Dual Matrix Composites(DMCs) utilise the high flexibility of a soft matrix alongside a stiffer polymer matrix to create localised flexible hinge regions within the composite resulting in a stiff composite in the load-bearing sections and a softer composite at the folding regions. These composites have garnered

considerable interest in the field of deployable space structures but are yet to be flown[24][25].

One caveat with these composites is that a reliable manufacturing method has not yet been established. Hand fabrication can be done but is a painstaking task, requires extreme precision and is not a viable option if a product is being developed for mass production[26].

#### 6.1.2 3D Printing

Additive manufacturing(AM) or 3D printing is the manufacturing of a 3D object layer by layer from a digital design. Thermoplastic filament is softened, extruded from a nozzle, and deposited in layers. FDM is especially ideal for applications that do not require high resolution and surface finish, such as for early-stage prototypes and proof-of-concept models.

For the origami, ideally, a two-material structure is desired—a rigid material for the origami faces and a soft, flexible material for the crease lines. This can be manufactured using multi-material 3D printing, which allows for a range of mechanical properties within a single part, reducing manufacturing and assembly time and costs.

For the materials, polylactic acid(PLA) for the rigid parts and thermoplastic polyurethane(TPU) for the flexible parts are proposed. PLA is stiff with a glass transition temperature of 60-70° C and a melting point of 170-180° C. So, it does not lose plasticity or toughness with use[27]. TPU is characterised by a low elastic modulus and high toughness, and is often used in applications that require mechanical strength while also being flexible, such as automobile interiors and industrial tools, providing high resistance to impact, fatigue, and stress.

Given the rigidity of PLA and the flexibility of TPU, combining these two materials to form origami structures is desirable.

**Table 3:** Material Properties

Materials	TPU	PLA
<b>Properties</b>		
<b>Young's Modulus(MPa)</b>	26	2346.5
<b>Tensile Modulus(MPa)</b>	8.6	49.5
<b>Elongation at break(%)</b>	580	5.2
<b>Poisson's Ratio(-)</b>	.45	.35

### 6.2 Tradeoff

The two prototyping options are traded off based on the following criteria.

- **Resource Availability:** Keeping in mind the available time and budget for the project, it is necessary to consider how easily accessible the required materials are. Additionally, they must be manufacturable with the facilities available at the site of the project, i.e., the university or in its vicinity.

3D printing with thermoplastics performs very well in this regard as there is a dedicated additive manufacturing lab at the TU Delft Department of Aerospace Engineering with commonly used materials already available. Composites are a little harder to procure and require more training from technicians to start fabrication, which adds extra time to the project.

- **Manufacturing Time:** A fast turnaround time is desired so multiple iterations can be done to achieve

the optimal manufacturing parameters.

DMCs require manual effort and have time-consuming curing processes. For a structure of similar dimensions, 3D printing takes far less time and does not require hands-on work; it is almost entirely computerised.

- **Novelty of Approach:** With the current research, it is expected to contribute to the existing body of knowledge with a novel design concept in the field of large deployable space structures. This novelty can be brought about by the prototyping options chosen, in addition to the concept of origami in space.

DMCs and 3D-printed structures have promising capabilities but are less explored in the space industry. Therefore, both options perform similarly in this regard.

**Table 4:** Prototyping Options Tradeoff

Tradeoff Criteria	Resource Availability	Manufacturing Time	Novelty of Approach
<b>Prototyping Options</b>			
<b>Dual Matrix Composites</b>	Meets requirements	Average	Excellent
<b>Hand Fabrication</b>			
<b>Thermoplastics</b>	Excellent	Excellent	Excellent
<b>3D Printing</b>	Excellent	Excellent	Excellent



### 6.3 Manufacturing Process

To manufacture the origami structure, the dual extrusion 3D printing technique is used. The structure is printed flat and later formed into its 3D configuration.

First, the flat pattern parameters obtained from the Rhino model are used to draw the flat pattern on Solidworks Assembly. The assembly is exported as STL files to Cura, the 3D printing slicing software. In Cura, the imported STLs are "merged" to assemble them in the correct position. This model is sliced and a G-code file is generated to send to the printer(Ultimaker 3+).

The pattern is printed at 100% infill density with an initial layer thickness of 0.2 mm. Mesh overlap is set

to 2 mm, which creates an overlap (and hence, a bond) between the PLA and TPU segments in each layer. The entire structure is printed at a thickness of 0.3 mm to accommodate folding.

The flat structure is joined with plastic welding and formed into the cylindrical structure shown in Figure 8. Lastly, to enable load application on the top surface, a hexagonal cover is printed and welded.

The deployment ratio for the 3D printed prototype is 7.7, i.e., it can be deployed to a height that is 7.7 times its folded height. This is slightly lower than that observed in the Rhino optimal configuration in Section 5, possibly due to the added thickness of the folding tabs.

A shortcoming to note with the 3D printed prototype is that the bistability that the Kresling pattern is known for is not observed in this prototype even though, for the exact dimensions, it was exhibited in the laser-cut paper prototypes made for the Rhino model validation. This could possibly be due to the larger creases and consequent imprecise folding in the printed prototype (as compared to the precise, uniform creases on the paper prototype) that affect the geometric parameters of the structure. Further work is required to understand this relationship.

## 7 Design Guidelines

Finally, with the lessons learnt and observations made during this design process, some design guidelines are created to help future researchers work with Kresling origami structures. These guidelines were derived from Rhino optimisation studies for maximum usable inner volume, prototyping, and its foldability in Rhino and the physical prototype. This is done because, sometimes, the optimal configuration output by Rhino cannot necessarily fold and act as a deployable structure or even be manufacturable (due to very small dimensions). Hence, it is important to define boundaries within which the Rhino results comply with its actual physical behaviour.

The guidelines thus obtained are:

1. Number of layers should not exceed  $(2 \times \text{number of sides}) + 1$ .

2. Layer height should be greater than  $\approx 2.8$  cm. It is found that all models that break upon folding have a layer height lesser than 2.8 cm in the Rhino model and the paper prototype.
3. The maximum feasible number of sides is three times the radius of the base polygon.
4. Fewer the sides, the better the manufacturability. However, it is also found via simulations [28] that a larger number of sides improves the structural performance. Therefore, a balance must be struck between optimising for manufacturability and structural performance.

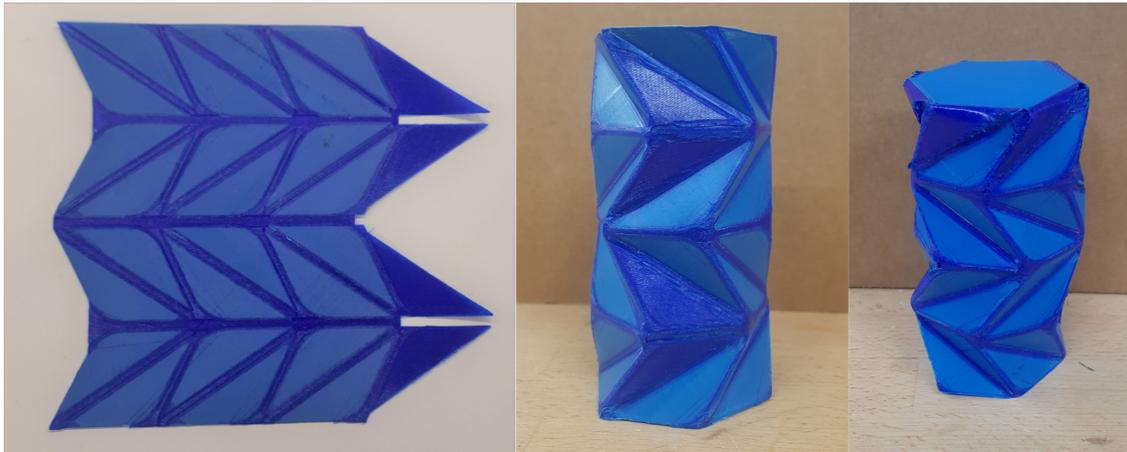
The current guidelines provide a general framework within which an optimal configuration can be identified. These guidelines are valid for Rhino models and paper prototypes of radii 4 cm and 5 cm. However, how well they scale further up or down and whether they are valid for 3D-printed prototypes is yet to be verified. Changes can be made to the guidelines as more knowledge is gained.

## 8 Conclusions

With this paper, one iteration of the design cycle of an origami-inspired deployable structure has been completed.

The process started with a brief look into the most feasible origami pattern and deployment technique combinations. The chosen design concept is the Kresling patterned origami structure deployed via inflation. A CAD model was created on the Rhino 3D modelling software to help visualise the folding of the structure and derive geometric outputs for its deployed and folded configurations. Once the model is validated, the optimal Kresling pattern configuration in terms of high usable inner volume and low packaging ratio was found which is a structure of 14 sides, 11 layers, and a deployed height of 39.2 cm.

Next, the concept was translated into a physical prototype using dual extrusion 3D printing with PLA and TPU for the rigid and flexible sections respectively. It was found that prototypes manufactured this way do not exhibit expected bistability, likely due to imprecise folding and large creases.



**Fig. 8:** 3D printed prototype, from left to right: a) Flat pattern b) 3D structure c) Top covering

Finally, design guidelines are created based on observations made in the Rhino model and the paper prototypes. These serve as a starting point for designing Kresling origami structures based on geometric and manufacturing feasibility.

While the present work provides a foundation for designing Kresling patterned deployable structures, there is still some work to be done to arrive at a refined, functional solution. While 3D printing, it was noted that, though it is suitable for rapid prototyping to test function and manufacturing feasibility, the printed structure is currently incapable of exhibiting bistability for the exact dimensions as the bistable paper prototype, which could be due to an imprecise folding technique. This needs to be studied further. Additionally, the proposed design guidelines can further be refined with knowledge on how they apply to different materials, manufacturing techniques, and scale.

With these action points addressed, the origami deployable demonstrator can achieve a Technology Readiness Level of 4, i.e., tested in the lab, and can proceed further with integration with the CubeSat and testing in a simulated space environment.

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