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EXECUTIVE SUMMARY OF THE THESIS

Origami Engineering: Evaluation of Patterns for Deployable Space Structures

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

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1. Introduction

Spacecraft require relatively large structures to achieve their mission goals. Solar panels, radiators, sunshields, drag and solar sails are typical examples. Their size is expected to grow in the near future as requirements become more demanding. From the dawn of the Space Age, gossamer structures, which are composed by thin membranes, have been tested in space with the aim of introducing lightweight devices characterized by extremely large areas. Origami-folding can help a solution of this kind to improve packing efficiency while adding some interesting properties, like an increased bending stiffness and the ability of tuning the structure properties by controlling the degree of deployment [2]. The aim of the present work is to carry out an initial assessment of crease patterns that could be beneficial for space applications, to study their deployment kinematics and to develop an optimization application useful to design efficient origami-folded space structures.

2. Selected crease patterns

Miura-Ori, Kresling, Yoshimura and Waterbomb are the crease patterns selected for the

study because are composed by a repeated unit cell and exhibit rigid foldability. Another interesting pattern is Flasher but it is excluded from the analysis due to its complex design.

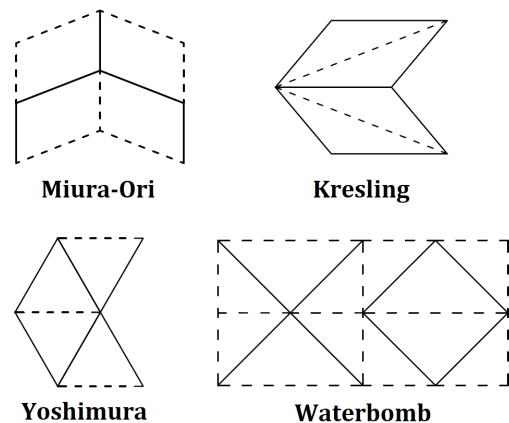


Figure 1: Studied crease patterns.

Their kinematics is studied by modelling single-cell and multi-cell origami on MATLAB[®] (see Figures 2 to 5) to analyze the folding behaviour. The geometrical properties that each crease pattern must possess in order to exhibit a maximized packing efficiency are investigated, while expressions useful to compute deployed area and stored volume of the origami are determined.

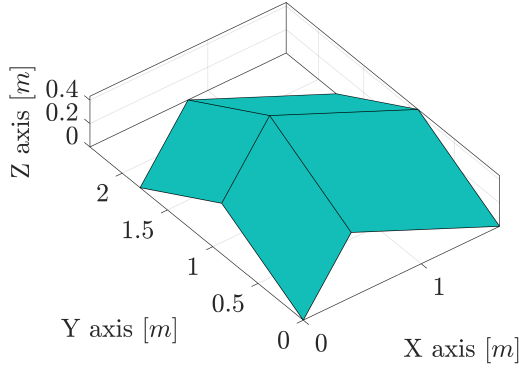


Figure 2: Miura-Ori unit cell.

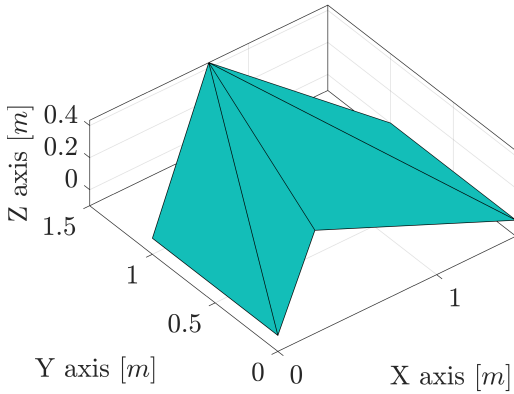


Figure 3: Kresling unit cell.

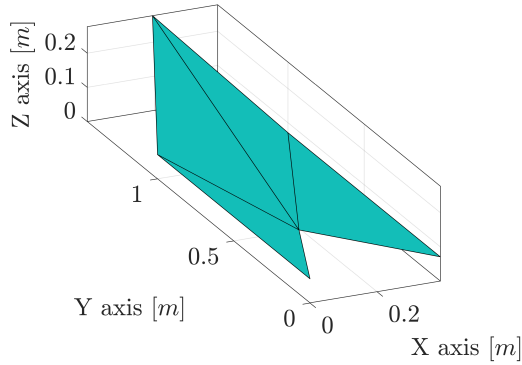


Figure 4: Yoshimura unit cell.

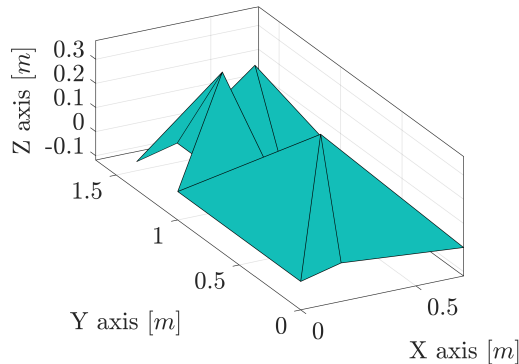


Figure 5: Waterbomb unit cell.

3. Actuation force model

The force required to deploy an origami structure is a fundamental aspect needed to size correctly the actuation system. A preliminary model able to compute it has been developed by Jianjun Zhang et al [3]. The model is analytical and based on the energy that is absorbed by fold lines during deployment. In particular, the force-displacement curve can be obtained by integrating the balance between external work and the sum of each fold line deformation energy:

$$F dD = \sum_{j=1}^{n_c} L_j M_j d\psi_j \quad (1)$$

where F is the force, D the dimension of the origami along traction axis, ψ_j the fold line dihedral angle and L_j the fold line length. M_j is instead the bending moment per unit length that develops inside a given fold line during deployment. The expression required to compute it depends on the regime. Up to a certain value of the dihedral angle the deformation is elastic so the bending moment is found with:

$$M_j = \frac{EI}{R} \quad (2)$$

while once the fold behaviour becomes plastic the expression changes to:

$$M_j = \sigma_y \frac{t^2}{4} \quad (3)$$

These equations are rather simple and require only to know the values of elastic modulus E , yield strength σ_y , radius of curvature R and second moment of inertia I of the fold line.

The exact shape of the curve obtained clearly depends on the material composing the structure and the crease pattern used for folding it. However, a common behaviour that characterizes any origami belonging to the four selected types is shown in Figure 6. Note that term *structure width* is equivalent to *displacement*. It can be observed that, starting from a packed configuration, a structure initially requires a relatively low actuation force that, only in proximity of complete deployment, increases and becomes infinite. This analytical result is only ideal and assumes that origami facets remain rigid during morphing. Geometrical properties of the unit cell and their number inside the origami can

change by several orders of magnitude the result for a given width value, even though the characteristic concave shape of the curve is preserved.

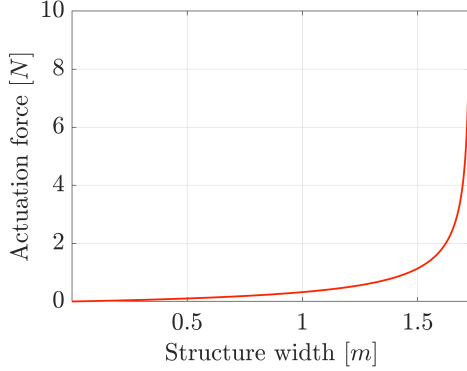


Figure 6: Typical force-displacement curve.

4. Origami optimization

Deployed area and stored volume expressions, which are related to packing efficiency of the origami, together with the analytical model of the force are implemented to program a Graphical User Interface using MATLAB® App Designer. This tool allows to optimize the folding pattern. In particular, packing efficiency is maximized while the energy required for deployment is minimized. The application window is user-friendly as it is possible to easily define constraints on packed and unfurled dimensions, material properties of the film and other requirements to design an optimally folded structure. The code exploits the genetic algorithm function *ga* to find a suitable solution due to its ability to handle non-linear mixed-integer problems.

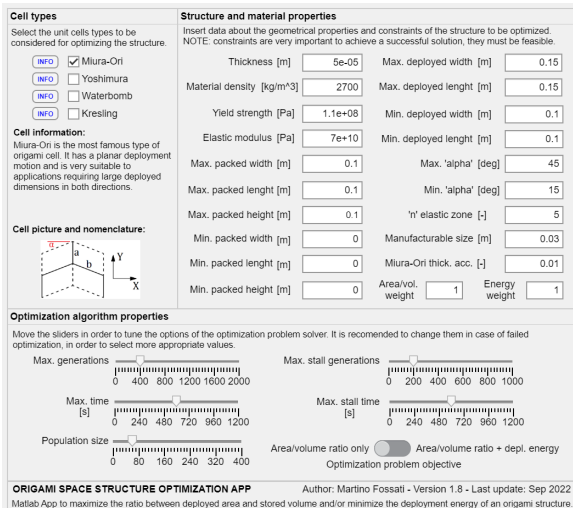


Figure 7: GUI application left-hand side.

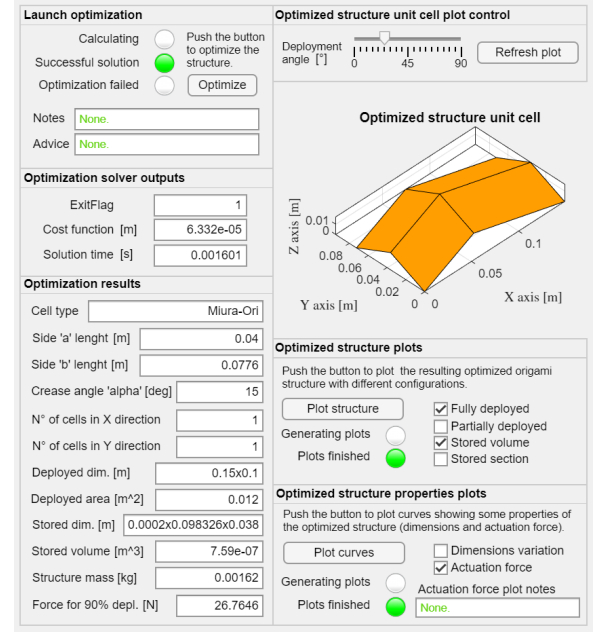


Figure 8: GUI application right-hand side.

If a solution is successfully found by the solver, the geometrical properties of its folding pattern are reported in dedicated displays. Graphical representation of the optimized origami structure in different steps of its deployment and other useful quantities, like required actuation force and structure dimensions during morphing, can be generated in distinct plots. In case of failed optimization, the application reports useful advices to improve the genetic algorithm parameters, which can be tuned using sliders. Results given by the application that aim at maximizing packing efficiency alone are validated using the following theorems:

Theorem 4.1. *Under the assumption of neglecting thickness accommodation effects, the maximum value attained by the ratio of deployed area and stored volume, expressed as the volume of the smallest rectangular cuboid containing the folded configuration, of an origami is equal to the reciprocal of the thickness of the membrane composing the structure.*

Theorem 4.2. *Under the assumption of neglecting thickness accommodation effects, the maximum value attained by the ratio of deployed area and stored volume, expressed as the volume of the smallest rectangular cuboid containing the folded configuration, is achieved when the packed origami assumes the shape of a rectangular cuboid free of empty spaces.*

5. Experimental validation

The force model is an essential tool needed to design an origami structure, so a validation of its predictions is necessary. An experimental activity on several origami specimens was carried out in aerospace laboratories of Politecnico di Milano. Miura-Ori is the simplest among the four selected crease patterns and claims a broad interest in origami literature. Consequently, this tessellation was selected to fold 12 origami samples manufactured with Aluminium 8011 alloy and DuPont™ Kapton® 200HN.

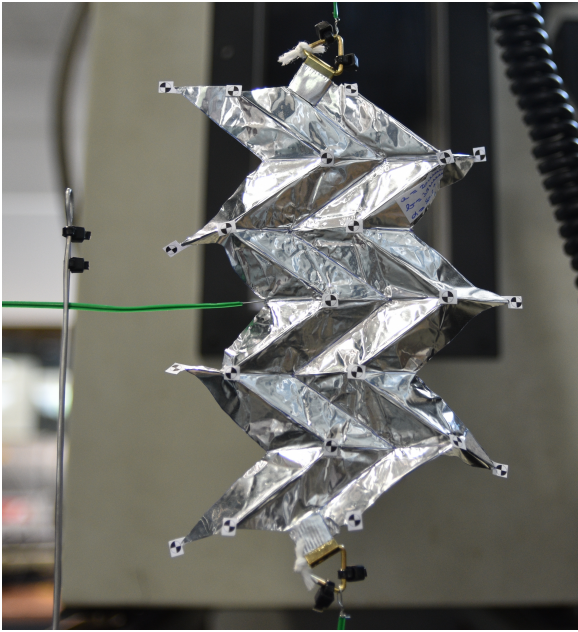


Figure 9: Tensile test on Aluminium 8011.

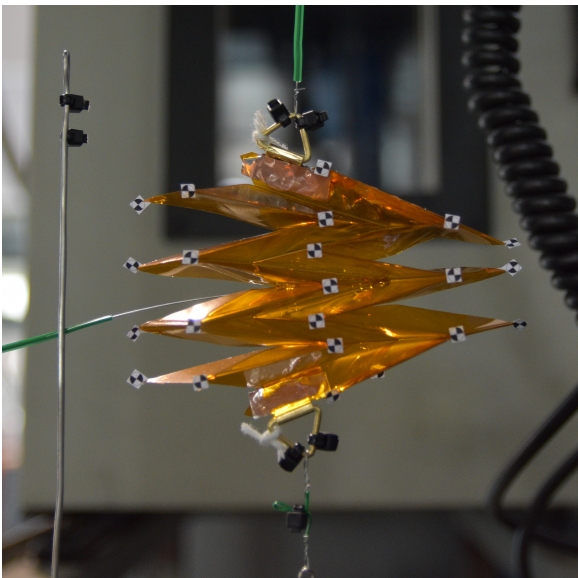


Figure 10: Tensile test on Kapton® 200HN.

Specimens were pulled using an Instron® tensile test machine at different traction speeds for a total of 36 deployment tests, 4 per each unique specimen. Additionally, 6 specimens were fitted with tracking markers to observe vertices trajectories and perform an analysis of their deployment kinematics. Figures 9 and 10 show two origami samples fitted with markers that were tested during the laboratory activity.

The actuation force was measured successfully and an example of result is shown in Figure 11. Some interesting aspects were observed during tests. Specifically, in proximity of full deployment every specimen experienced a bending around traction axis due to partially unconstrained external cells and loss of bending stiffness that characterizes the final flat configuration. In some cases buckling of facets also introduced a discontinuity in the measured force.

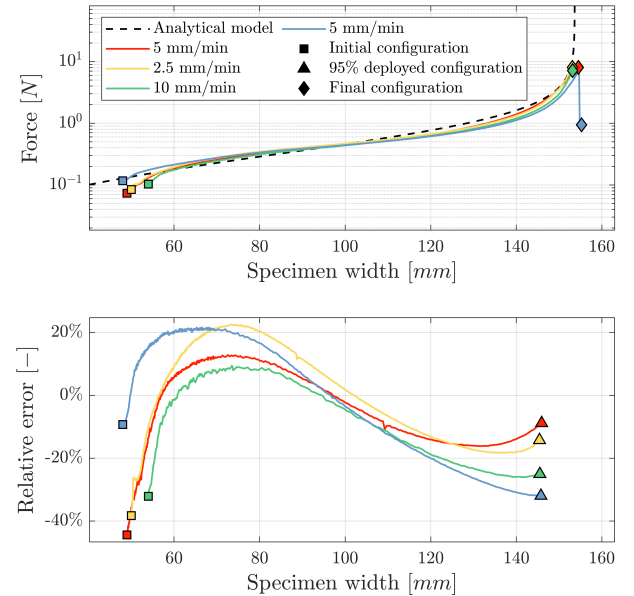


Figure 11: Measured force on Aluminium 8011.

In most cases the maximum relative error between experimental measure and analytical prediction resulted to be smaller than $\pm 100\%$, an acceptable outcome considering that flexibility of facets was omitted. Traction speeds of 2.5, 5 and 10 mm/min were experimented on Aluminium specimens, but without introducing a noticeable effect on the shape of force curves. The contribution of deployment rate is expected to play an important role only in situations where inertial effects become non-negligible.

The following tables summarize the maximum

relative error of every tensile test performed.

Specimen	Maximum percent error
#1	30% – 9% – 22% – 13%
#2	59% – 33% – 24% – 37%
#3	159% – 262% – 212% – 165%
#4	33% – 74% – 78% – 88%
#5	46% – 31% – 27% – 35%
#6	44% – 38% – 32% – 32%

Table 1: Relative errors of Aluminium 8011.

Specimen	Maximum percent error
#7 and #10	92% – 32% – 59% – 38%
#8 and #11	42% – 31% – 45% – 43%
#9 and #12	145% – 36% – 26% – 20%

Table 2: Relative errors of Kapton[®] 200HN.

Also the observation of tracked vertices trajectories and the consequent analysis of unfolding kinematics were accomplished successfully. As previously reported, external regions of specimens experienced large deformations due to bending and buckling that arise near full deployment. This phenomenon confirms the need to introduce flexibility effects in the actuation force model in order to obtain a more refined prediction. Figures 12 and 13 report vertices deviations from their ideal position and the center of mass trajectory. They are referred to the same specimen of Figure 11.

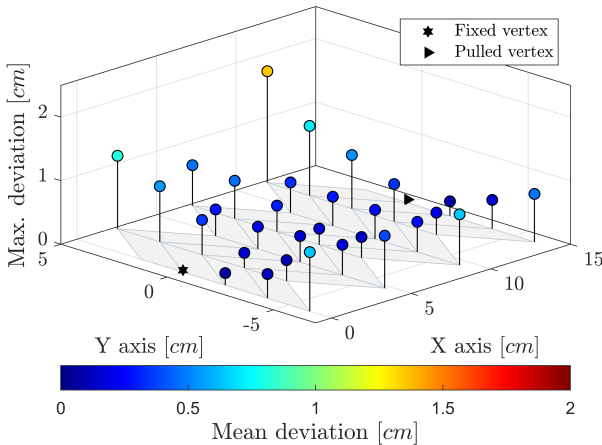


Figure 12: Vertices deviations.

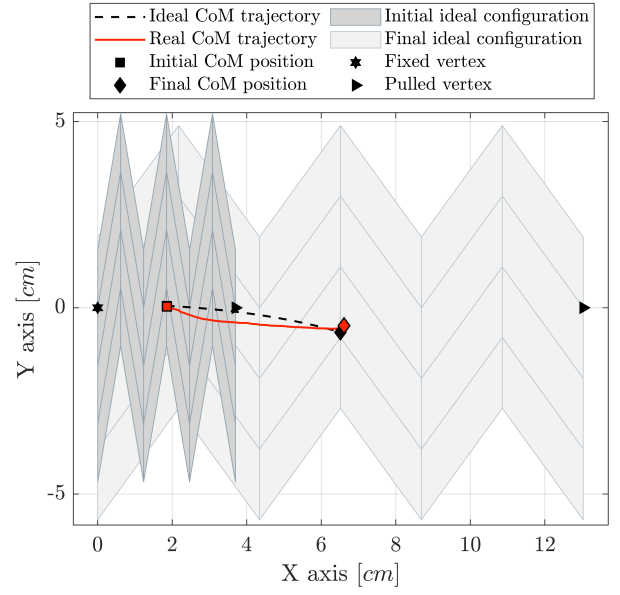


Figure 13: Center of mass trajectory.

In Figure 12 it is evident that vertices located on the origami perimeter are less constrained and so characterized by larger deviations. However, considering that the majority of vertices follows the predicted morphing behaviour, the discrepancy of the center of mass trajectory from its ideal path displays only a small error.

6. Preliminary drag sail design

The initial assessment results and the origami optimization application will be implemented by future expansions of the work and exploited for the design of a space structure based on origami-folding. Drag sails represent the most important devices for the near future. Strategies to decommission safely a spacecraft are expected to become one of the most important aspects of space vehicles design in light of the advent of extremely large megaconstellations and demanding deorbit regulations.

A preparatory design for a drag sail mission is developed in anticipation to future detailed studies. The spacecraft considered is a 3U CubeSat located in a 700 km circular orbit because, according to statistics, represents the most common situation for nanosatellites. Its drag sail is assumed to be planar and characterized by a drag coefficient of 1.034, value that takes into account a tumbling motion [1]. The area required to guarantee a deorbit in 5 years and worst case scenario temperatures are determined. Atmospheric drag is the only contribution considered

for the decay model, while for thermal analysis a steady-state single-node lumped parameter approach is used. Sails are typically aluminized, so surface thermal properties of this material are taken as reference. Solar radiation pressure perturbations are neglected because the definition of precise orbital elements would be required. Table 3 reports the computed drag sail characteristics while Figure 14 shows a preliminary sketch of the 3U CubeSat with the deployed sail.

Property	Value
Decay time	4.997 years
Sail area	0.894 m^2
Sail size	$0.95 \times 0.95 \text{ m}$
Sail material	Kapton [®] HN, Upilex [®] -S
Lowest temp.	-54°C
Highest temp.	$+233^\circ\text{C}$

Table 3: CubeSat drag sail results.

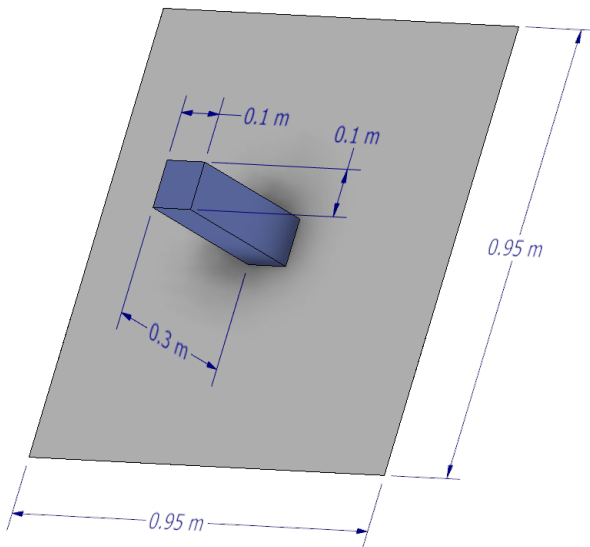


Figure 14: Preliminary sketch of the CubeSat (blue) and its sail in deployed state (grey).

The sail can be packed using a Miura-Ori folding pattern considering that an application of this kind requires a simple solution with low probability of failure, which can be guaranteed by this tessellation scheme. Subsequent advanced design will refine the preliminary results obtained and use the optimization application to design an efficient Miura-Ori pattern for sail storage.

7. Conclusions

The realization of an optimization application and the validation of a simple analytical model for the actuation force have been successfully achieved. Future expansions of the work should attempt the design of an origami structure with its actuation system and the implementation of a finite element model to refine the kinematics prediction. An important outcome of the experimental activity is that a single point traction is not suitable as deployment solution. An efficient actuator should instead be based on shape memory materials or a perimeter truss mechanism given their ability to grant multiple application points and a more uniform unfolding.

8. Nomenclature

Symbol	Description
σ_y	Yield strength
ψ_j	Fold line j dihedral angle
CoM	Center of Mass
D	Origami structure dimension
E	Elastic modulus
F	Actuation force
I	Second moment of inertia
L_j	Fold line j length
M_j	Fold line j bending moment
n_c	Number of fold lines
R	Fold line radius of curvature
t	Film thickness

References

- [1] A. Black and D. A. Spencer. DragSail Systems for Satellite Deorbit and Targeted Reentry. *Journal of Space Safety Engineering*, 7:400, 2020.
- [2] M. Meloni et al. Engineering Origami: A Comprehensive Review of Recent Applications, Design Methods, and Tools. *Advanced Science*, 8:1–26, 2021.
- [3] J. Zhang et al. Quasi-static Large Deformation Compressive Behaviour of Origami-based Metamaterials. *International Journal of Mechanical Sciences*, 153-154:194–197, 2019.