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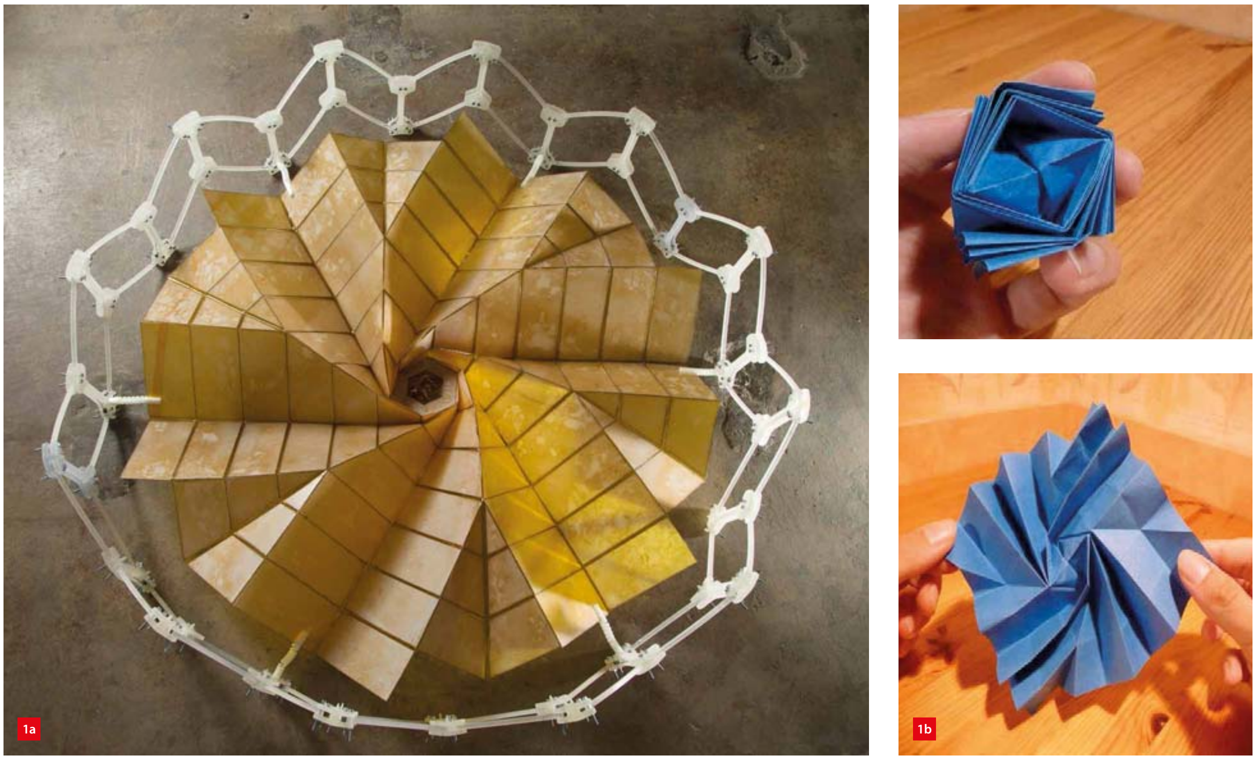
INSPIRATION FROM FOLDING PATTERNS

Origami is generally associated with decorative art, not the engineering world. For some time now, however, engineers have been using the gigantic database of origami folding patterns as inspiration for designing deployable mechanisms that can be fabricated efficiently from a flat sheet material. Most of these mechanisms do not contain springs, because by introducing springs, the advantageous planar properties of the design are lost. Yet there is a trick.

JELLE ROMMERS, GIUSEPPE RADAELLI AND JUST HERDER

Taking inspiration from origami for products is not new. Think about stiff sandwich panels with an origami-inspired core, or the clever way in which a paper roadmap can be unfolded in a single movement by pulling two corners apart. More recently, there has been a growing interest in origami from a mechanism design perspective. Paper is then replaced with more common engineering materials, while in the mechanisms, the often ingenious kinematics of the folding patterns are exploited. The paper models are usually constructed from a flexible material, with the creases becoming ‘hinge lines’, which means they can be categorised as a subset of compliant mechanisms. Compliant mechanisms are popular in precision engineering owing to their highly deterministic behaviour, which is due to the absence of friction and backlash; advantages which also apply to origami mechanisms.

Examples of origami mechanism designs include a solar array that can be stowed in a square satellite and deployed in space (Figure 1), or a stent that can be deployed in the desired place in an artery (Figure 2).



1 An origami-inspired solar array that can be stowed in a square satellite and deployed in space [1].
(a) Design by the Brigham Young University Compliant Mechanisms Research group [2].
(b) Unfolding principle.

AUTHOR’S NOTE

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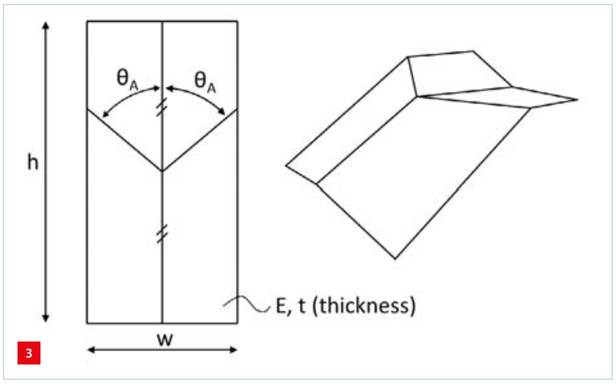
2 *Origami-inspired stent that can be deployed in an artery [3].*



3 *The common 'reverse fold' origami pattern and design variables.*

The main advantages of origami mechanisms are:

- An ability to deploy from a flat state.
- A planar fabrication method, which can reduce fabrication cost. This also makes the mechanisms suitable for the planar fabrication processes in the micro-domain. Additional fabrication steps could be integrated; for example, printing an electrical circuit on the mechanism.
- No assembly step. Again, in the micro-domain where assembly is difficult, this is an important advantage. In this case the term 'responsive origami' is used, where the hinges are designed to react to some external impulse, like heat, and the mechanism then folds itself into the desired state.

Origami mechanisms can be compared to general mechanisms by regarding the facets (panels between the hinge lines) as links or bodies, connected by revolute joints. Viewing the mechanisms in this way, one could argue that origami mechanisms are missing one fundamental attribute: springs. But introducing regular helical springs into an origami mechanism would result in most of the aforementioned advantages resulting from its planar nature being lost. In this regard, it would seem that it is impossible to design origami mechanisms with springs. But there is a trick.

Compliant Facet Origami Mechanisms

In most current origami mechanisms, the facets are designed as very stiff elements, and flexibility is primarily seen as an unwanted side-effect. However, this property can be used to the designer's advantage. Flexible facets can function as springs, without losing the advantages of the planar nature of the origami mechanisms. We call these mechanisms Compliant Facet Origami Mechanisms (COFOMs) [4].

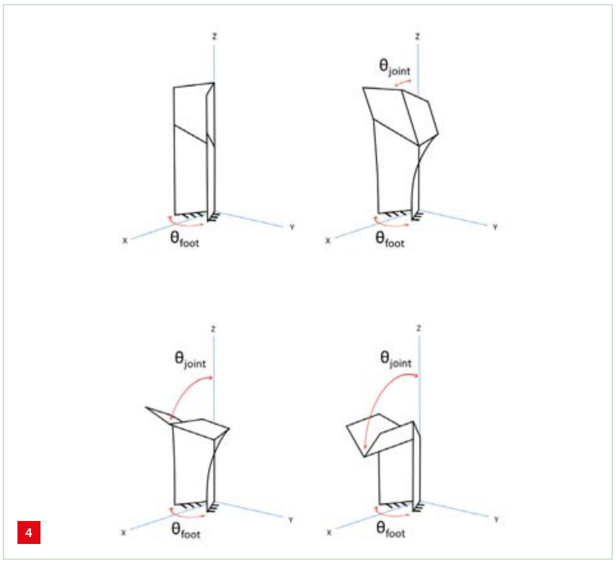
Figure 3 shows a very common origami mechanism segment, called the 'reverse fold' in origami terminology. In Figure 4 this mechanism is shown clamped at the lower facets. When the facets are rigid, the mechanism has zero degrees of freedom (DoFs). But bending the lower facets provides two additional DoFs, allowing movement in the direction θ_{joint} and the y-direction. The bending facets act as springs. In the direction θ_{joint}, this results in a bi-stable behaviour, in which the mechanism snaps to the positions in the top left and bottom right of Figure 4. The mechanism can be viewed as a joint with angle θ_{joint} and a certain reaction moment curve. The main focus of our research is in how this moment curve can be manipulated by changing the design of the mechanism.

Design tool

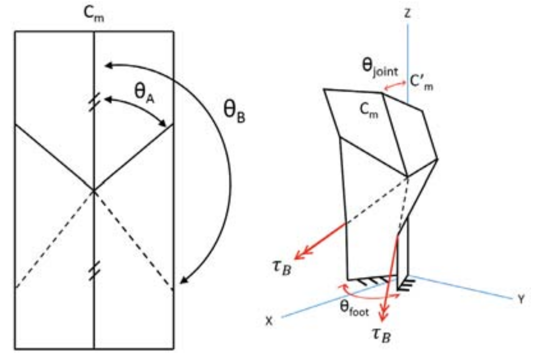
The goal is to create a design tool in which a desired moment curve can be given as an input. The tool will output the values of the design variables (Figure 3), which result in the closest approximation of this desired curve. The challenge here is to come up with a model of the mechanism with a low computational cost. With such a quick model, an optimisation algorithm can be used to select the optimal design by rapidly computing the moment curves of a multitude of designs and selecting the best-performing one.

Model

The main challenge in constructing such a quick model is the large deformation of the lower facets. The solution used is to model a bending facet by dividing it into two rigid ones, introducing a 'virtual hinge line' with a torsion spring, shown dashed in Figure 5. From this model, the moment curve can be calculated using kinematic relations.



4 *The 'reverse fold' mechanisms with the lower facets forced to bend, introducing spring forces.*



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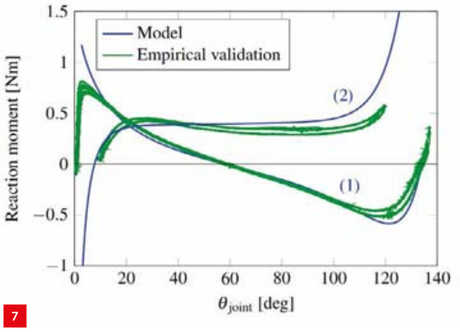

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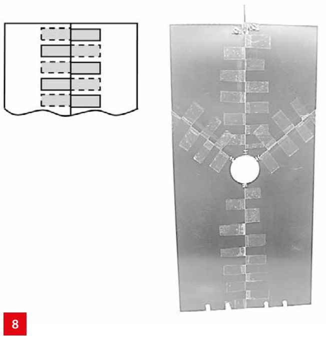

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5 *Modelling the bending of the lower facets.*

6 *The performance of the model is tested by varying design variables from the 'standard design'.*

7 *Moment curves of two example designs; see text for further explanation.*

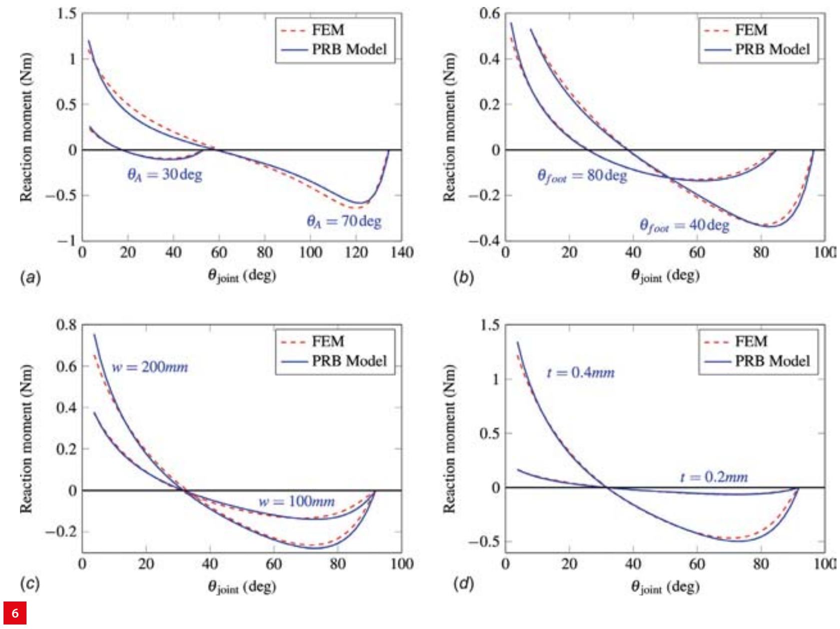
8 *Spring steel mechanism used for empirical validation. Hinge lines are made using alternating Mylar tape. ng forces.*

This model is a semi-spatial version of the Pseudo-Rigid Body (PRB) theory from Howell [5], which is used to approach bending a beam in 2D. Just as in this theory, the position of the virtual hinge line and the stiffness value of the torsion spring are obtained by fitting on existing data, in our case from finite-element analysis and experiments. In order to do this, a 'standard design' of the mechanism is defined. After obtaining the two values, they are fixed, and the model is compared to an (empirically validated) finite-element model (FEM). Figure 6 shows this comparison where the design variables are varied from the standard design.

It is important to note that the model has not been refitted on this data. The model has a good accuracy, given the large variation of the design variables, and is orders of magnitude faster than the finite-element model, due to the fact that it is a closed-form analytical expression. Therefore, it is very suitable for use in an optimisation procedure.

Example designs

Figure 7 shows the moment curves of two example designs. The model output is empirically validated by constructing and measuring the resulting mechanisms using spring steel plates of 0.3 mm thickness, joined by Mylar tape in an alternating pattern to form the hinge lines (Figure 8).



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Curve 1 shows a design with a snap-through behaviour. Around a joint angle of 60°, the mechanism is in an unstable state, where it tends to snap to the first and last position in Figure 4. It exhibits a large range of 'negative stiffness', i.e. the slope of the moment curve is negative. Combining this with normal positive stiffness from other elements (e.g. a bending beam), the force-deflection characteristics can be manipulated to a large extent.

Curve 2 shows a design where the tool was used to create a mechanism that exhibits a constant moment in a certain range. In this mechanism, the stiffness of the real hinge lines is taken into account. The positive stiffness from these hinge lines, combined with the negative stiffness resulting from the bending of the facets, creates the roughly constant moment curve.

Conclusion

Engineering origami is an exciting and still-emerging field. Applications mainly seem to be in the micro-domain due to the planar fabrication process, although spacecraft and medical applications also benefit from its deployable characteristics. Exploiting the flexibility of the facets, a spring-like behaviour can be incorporated in these mechanisms without losing the planar nature that makes these mechanisms so fascinating. ■

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