Carbon Origami

Micromachines 2021 — 1st International Conference on Micromachines and Applications (ICMA2021)

Marc Madou, April 16, 2020

Rodrigo Martinez, Clemson University

Outline

- 01 Origami Folding by Hand (C-MEMS)
- 02 Folding by Elastocapillary of PDMS
- 03 Folding by Elastocapillary of Patterned Photoresists (C-MEMS)
- 04 Self-folding of polymer layers (C-MEMS)
- 05 Applications
- 06 Conclusions/Prospects

01 Origami Folding by Hand (C-MEMS)

- Paper was first invented in China around 105 A.D., and was brought to Japan by monks in the sixth century. Handmade paper was a luxury item only available to a few and strictly for ceremonial purposes.
- By the Edo period (1603–1868), paper folding in Japan had become recreational as well as ceremonial. It came to be regarded as a new form of art that was enabled by the advent of mass-produced paper.
- Europe also has a tradition of paper folding that dates back to the twelfth century or before, when the Moors brought a tradition of mathematically based folding to Spain. The Spanish further developed paper folding into an artistic practice called papiroflexia or pajarita.

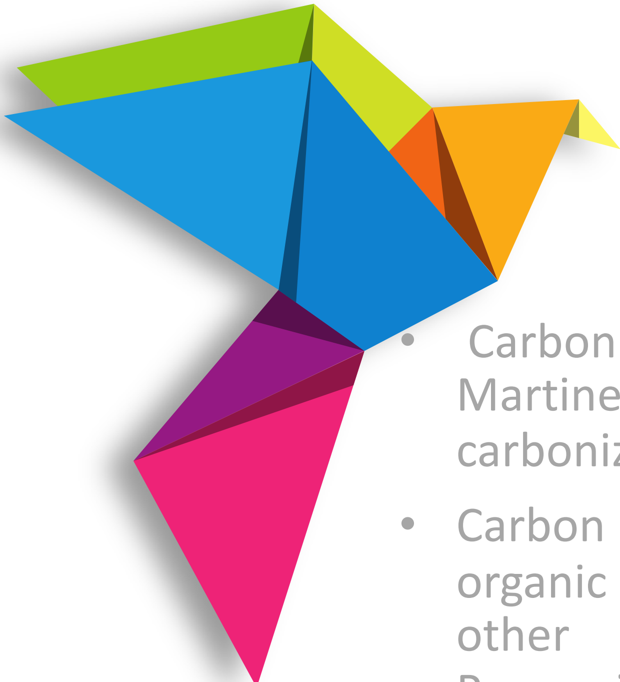
Written instructions for paper folding first appeared in 1797, with Akisato Rito's *Sembazuru Orikata*, or "thousand crane folding"

01 Origami Folding by Hand (C-MEMS)

- Today, origami has expanded to incorporate advanced mathematical theories, as seen in BETWEEN THE FOLDS. Mathematical origami pioneers like Jun Maekawa and Peter Engel designed complex and mathematically based crease patterns prior to folding, which emphasized the puzzle aspect of origami, with the parameters of using one piece of uncut paper. Artistic origami has also enjoyed a recent resurgence, with abstract paper folders such as Jean-Claude Correia (1945-2016).

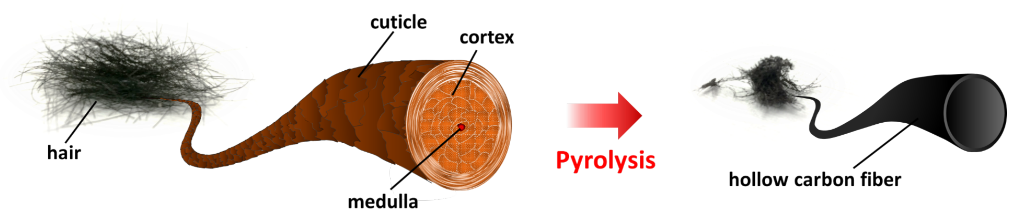
Le Manteau de Moctezuma –by Correia

https://documentaryheaven.com/between-folds-art-of-origami/



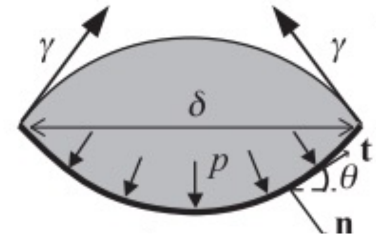
01 Origami Folding by Hand (C-MEMS)

- Carbon and Carbide Origami by Rodrigo Martinez et al at Clemson University. – carbonization of folded paper (inked or blank)
- Carbon 3D shapes derived from natural organic precursors e.g. charcoal from wood other precursors (e.g. hair ...Bidhan Pramanick)



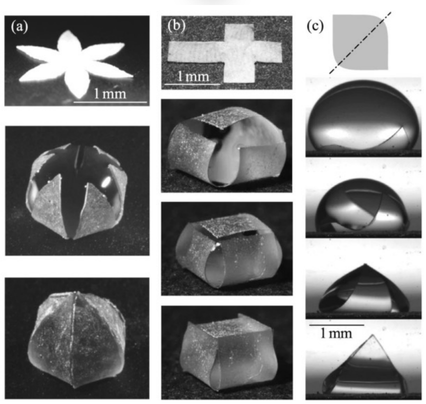
Human hair-derived hollow carbon microfibers for electrochemical sensing
B Pramanick, LB Cadenas, DM Kim, W Lee, YB Shim, SO Martinez-Chapa, ...
Carbon 107, 872-877

02 Folding by Elastocapillary of PDMS

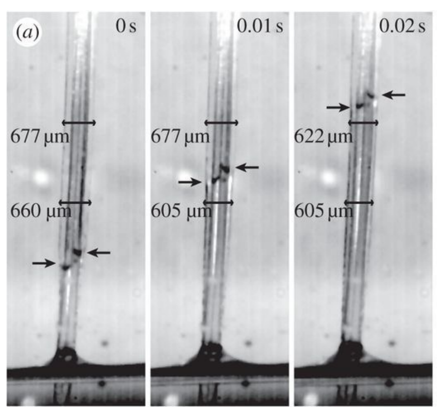


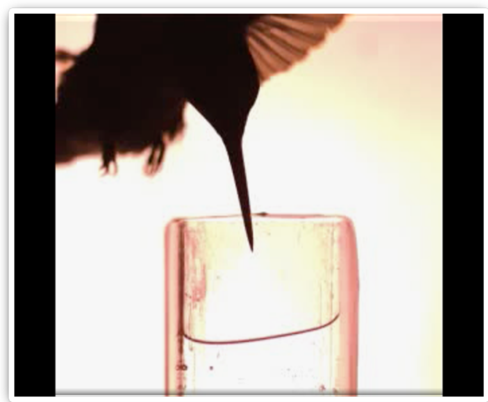
- An elastocapillary-based origami fabrication process based on PDMS and water droplets was adopted by Py et al., 2007*
- Elastocapillary is a two-way interaction between the liquid and the structure driven by the surface tension of the liquid to minimize surface + elastic energy

Capillary origami



Humming bird's tongue





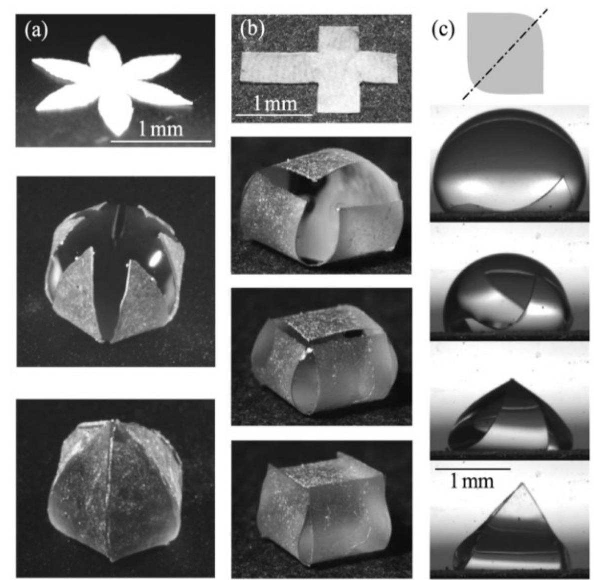
Wet hair

*Capillary Origami: Spontaneous Wrapping of a Droplet with an Elastic Sheet
Charlotte Py, Paul Reverdy, Lionel Doppler, José Bico, Benoît Roman, and Charles N. Baroud
Phys. Rev. Lett. **98**, 156103 – Published 13 April 2007

02 Folding by Elastocapillary of PDMS

1. Difficult to pattern PDMS
2. Difficulty to distinctively design folds and faces with different material properties
3. Not capable of making permanently folded structures
4. Inability to fabricate folded structures on a surface (anchored)
5. Impossible to fabricate rigid structures such as carbon

Capillary origami



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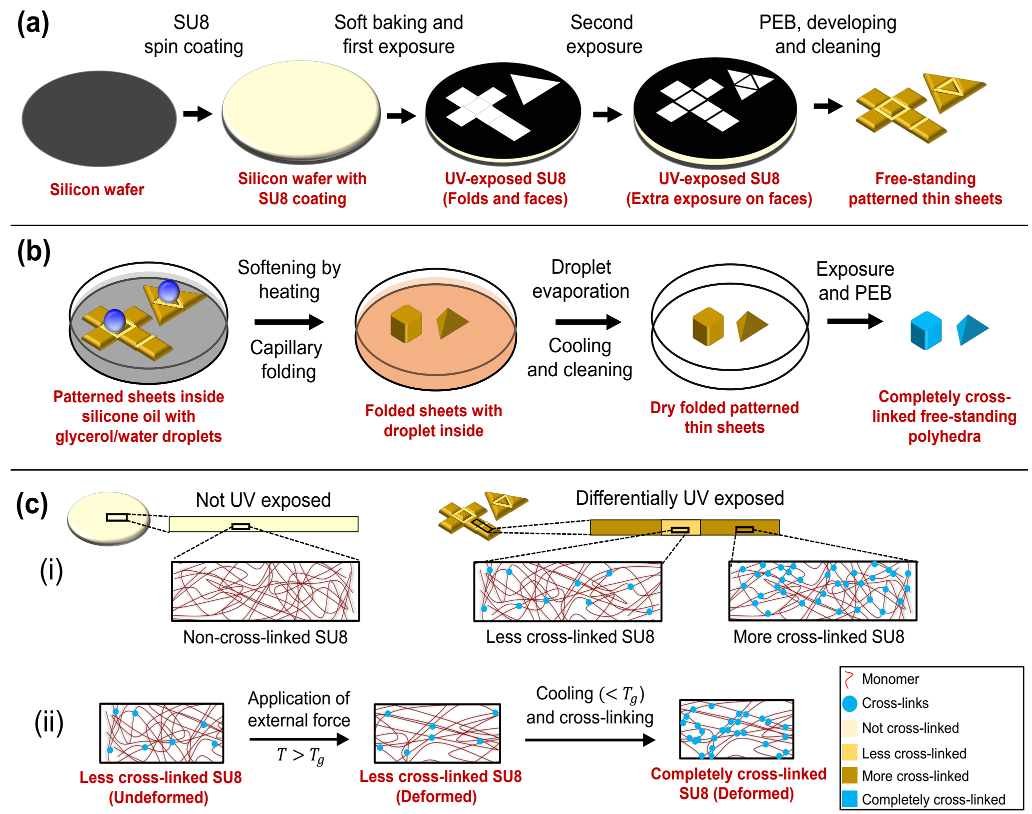
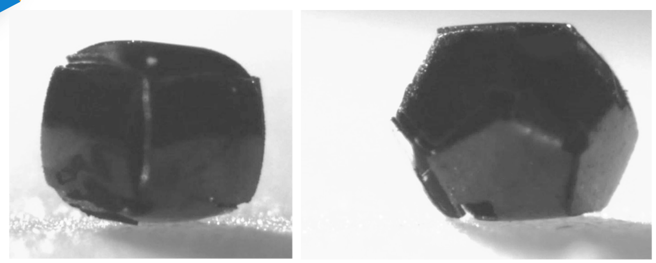
03 Folding by Elastocapillary of Patterned Photoresists (C-MEMS)

1. Expands photoresist application domain
2. Hinges and faces are distinct
3. Both anchored and free 3D photoresist shapes are enabled
4. Faces can be further patterned
5. Free form manufacturing-shapes can be “frozen” at any moment by a quenching UV exposure
6. All these shapes can be converted to carbon

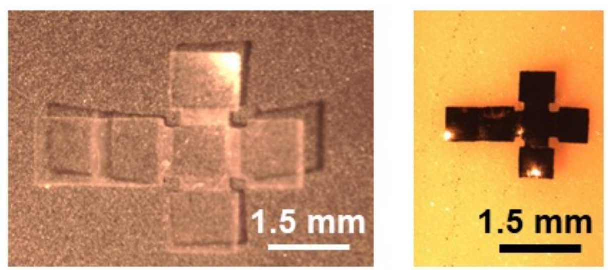


Fabrication of polymer and carbon polyhedra through controlled cross-linking and capillary deformationsD George, EAP Hernandez, RC Lo, M Madou
Soft Matter 15 (45), 9171-9177

03 Folding by Elastocapillary of Patterned Photoresists (C-MEMS)

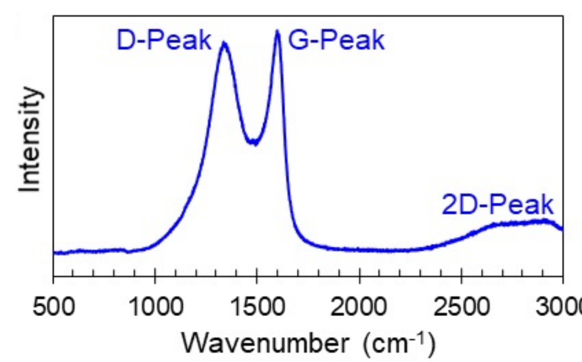


Folded free-standing carbon shapes



Before pyrolysis After pyrolysis

Free-standing patterned precursor polymer and carbon shapes



Raman spectrum of the carbon

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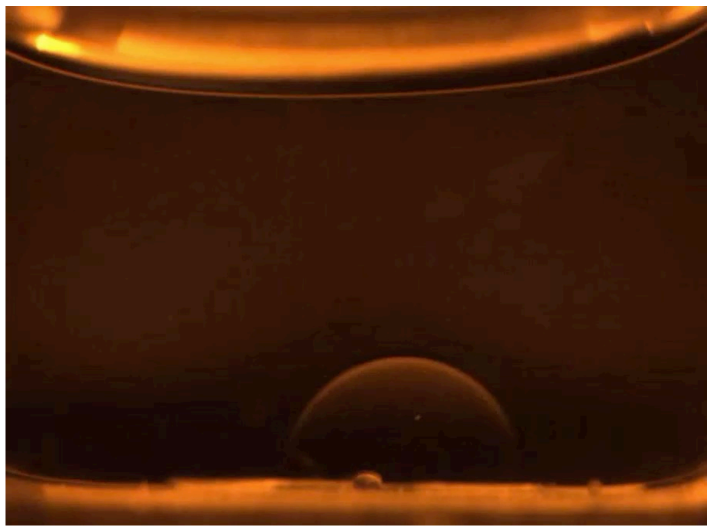

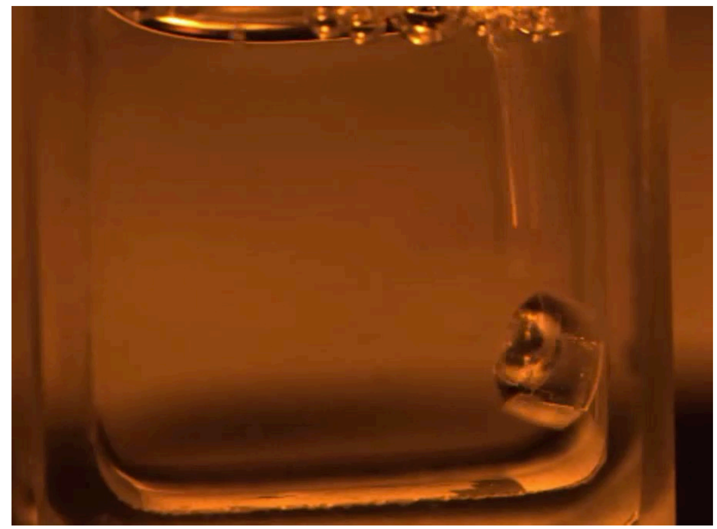

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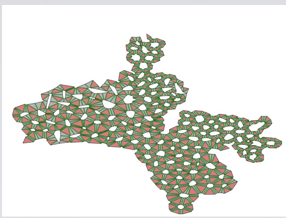
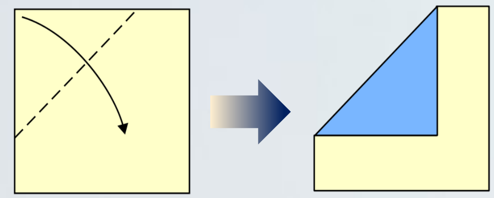
04 Self-folding of polymer layers (C-MEMS)

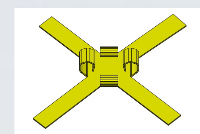


We need origami manufacturing that is :

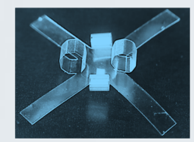
- Scalable in numbers and sizes
- Complex shapes
- Self-folding
- Simple construction
- Freeform
- Minimal materials consumption



Simple construction



Target shape



Polymer structure

Programmable Self-Foldable Films for Origami-based Manufacturing D George, MJ Madou, EAP Hernandez Smart Materials and Structures

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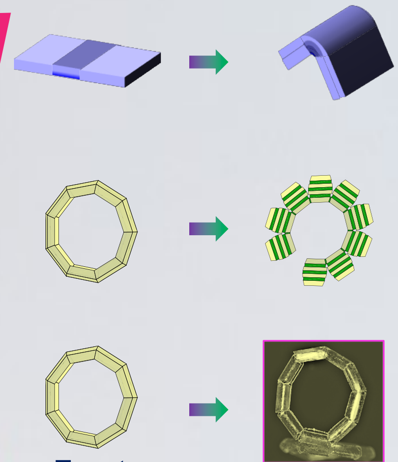
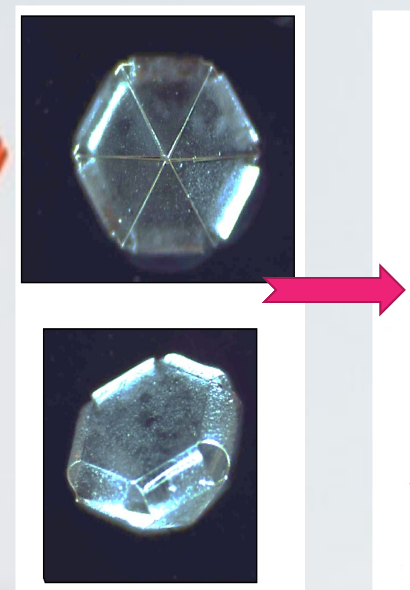
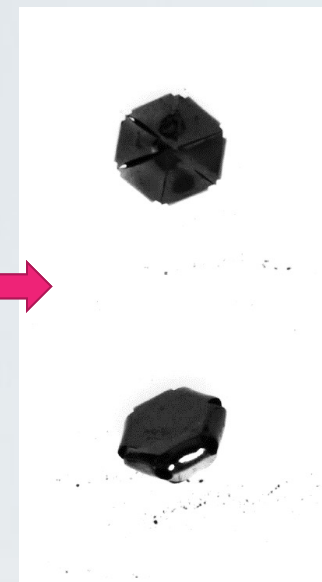


1. **Single layer** photopolymer films as precursors
2. Controlled folding using **programmable films** and **origami design**

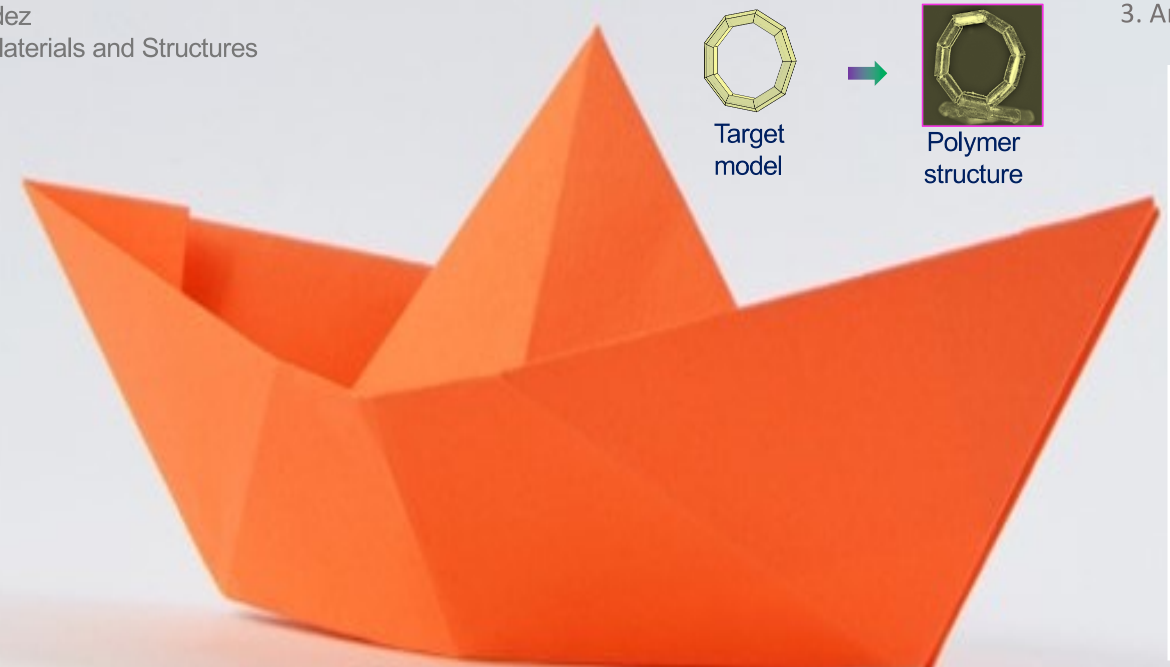
3. An **end-to-end freeform manufacturing** method





Polymer Origami

Carbon Origami



04 Self-folding of Polymer Layers (C-MEMS)

Programmable Self-Foldable Films for Origami-based ManufacturingD George, MJ Madou, EAP Hernandez
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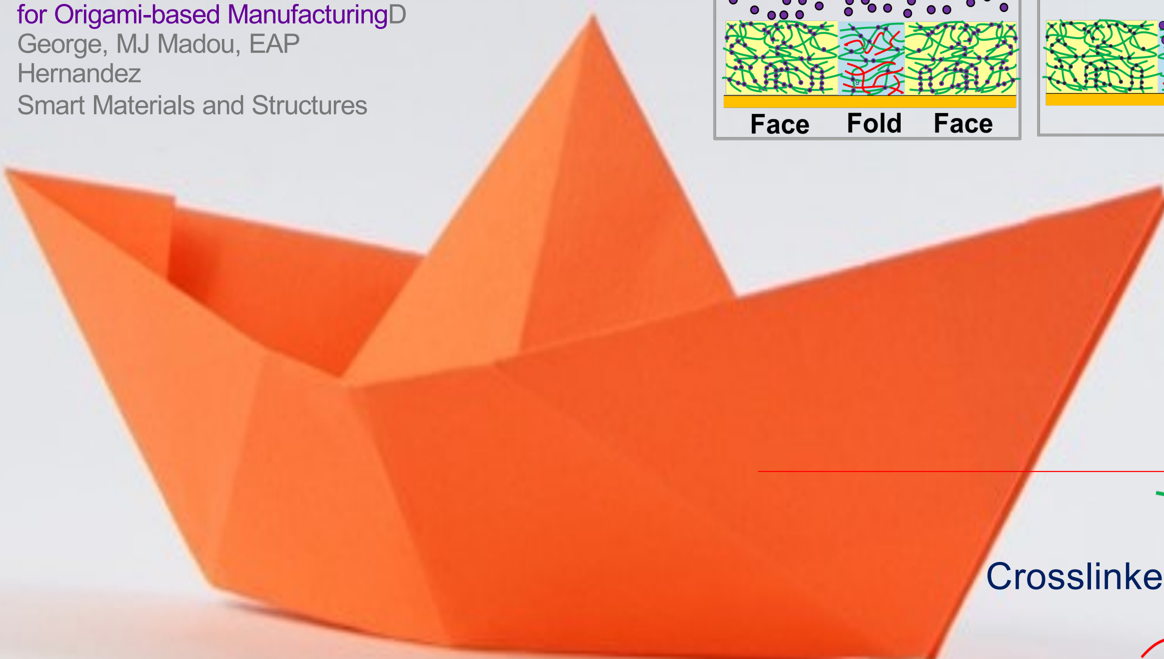
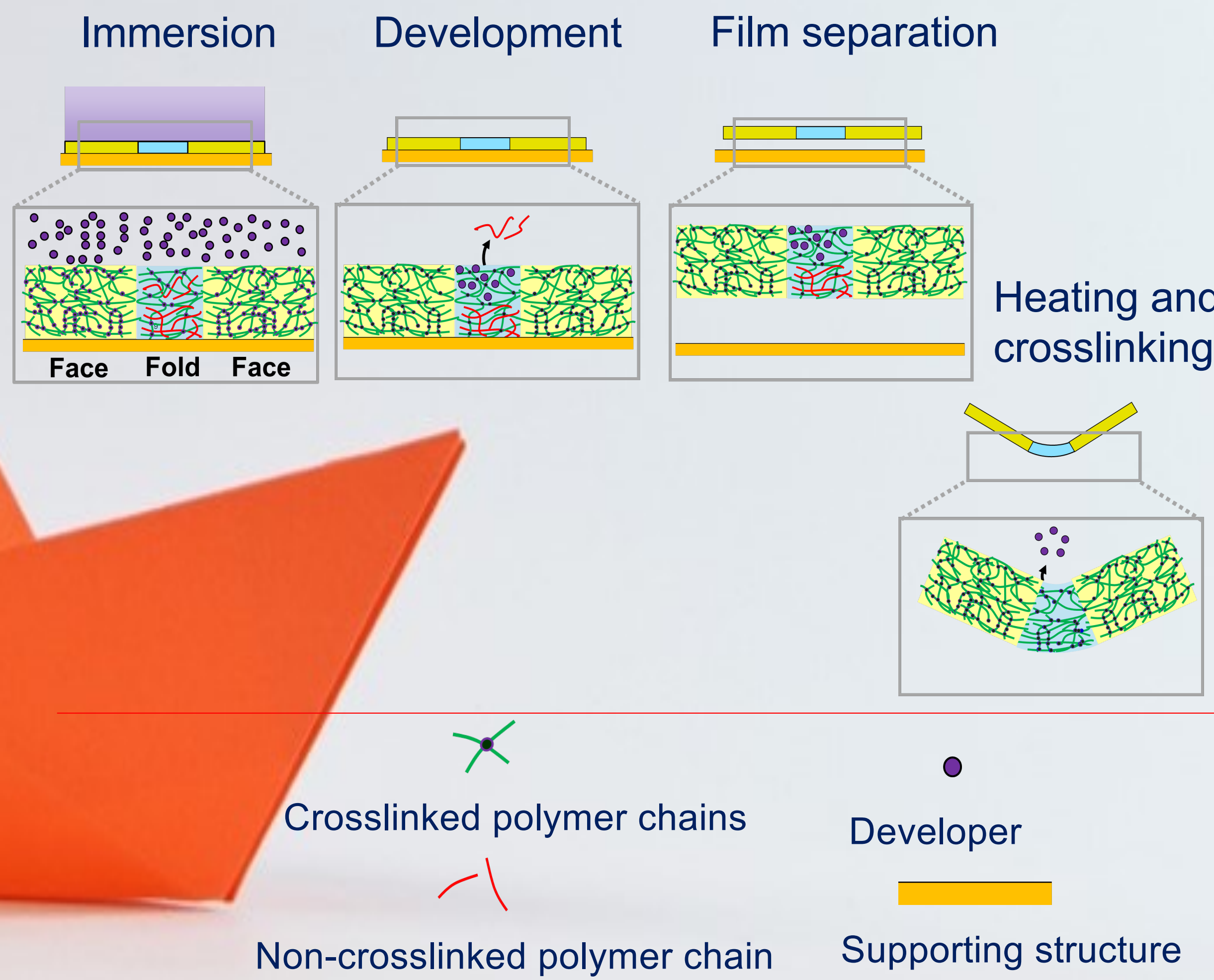
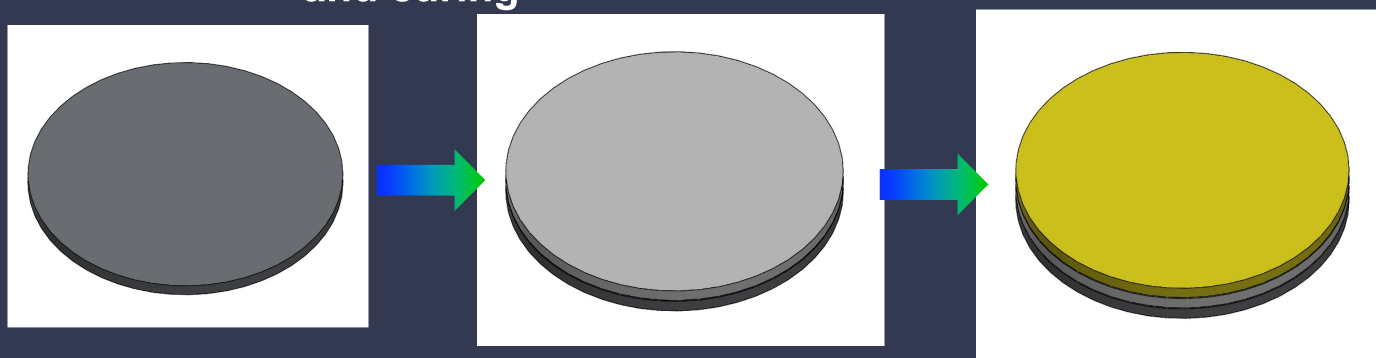


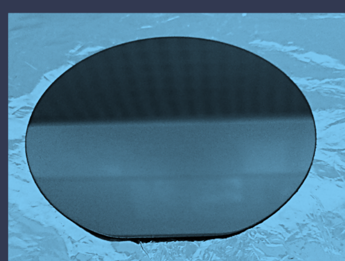


04 **Self-folding of Polymer Layers (C-MEMS)**

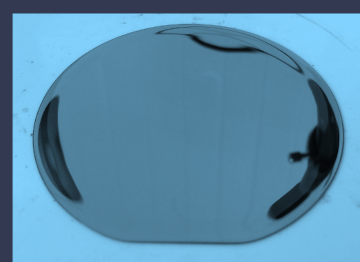
Photolithography Film Preparation

PDMS spin coating and curing **SU8 spin coating**

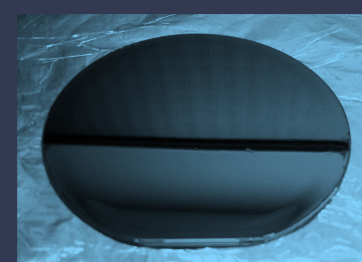




Silicon wafer



Silicon wafer with PDMS coating



Silicon wafer with PDMS and SU8 coatings

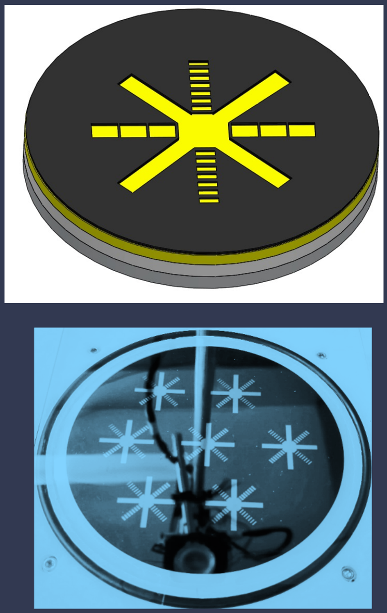
04 Self-folding of Polymer Layers (C-MEMS)

Photolithography Film Patterning

First UV light exposure

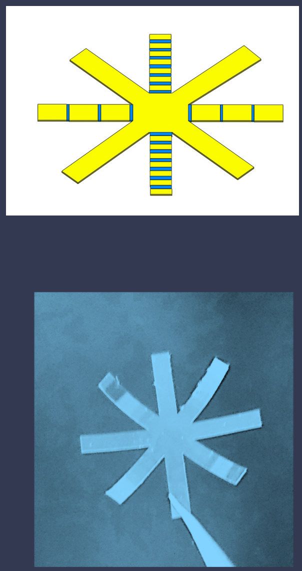
UV-exposed SU8
(Folds and faces)

Second UV light exposure



UV-exposed SU8
(Extra exposure on faces)

PEB, developing and removing



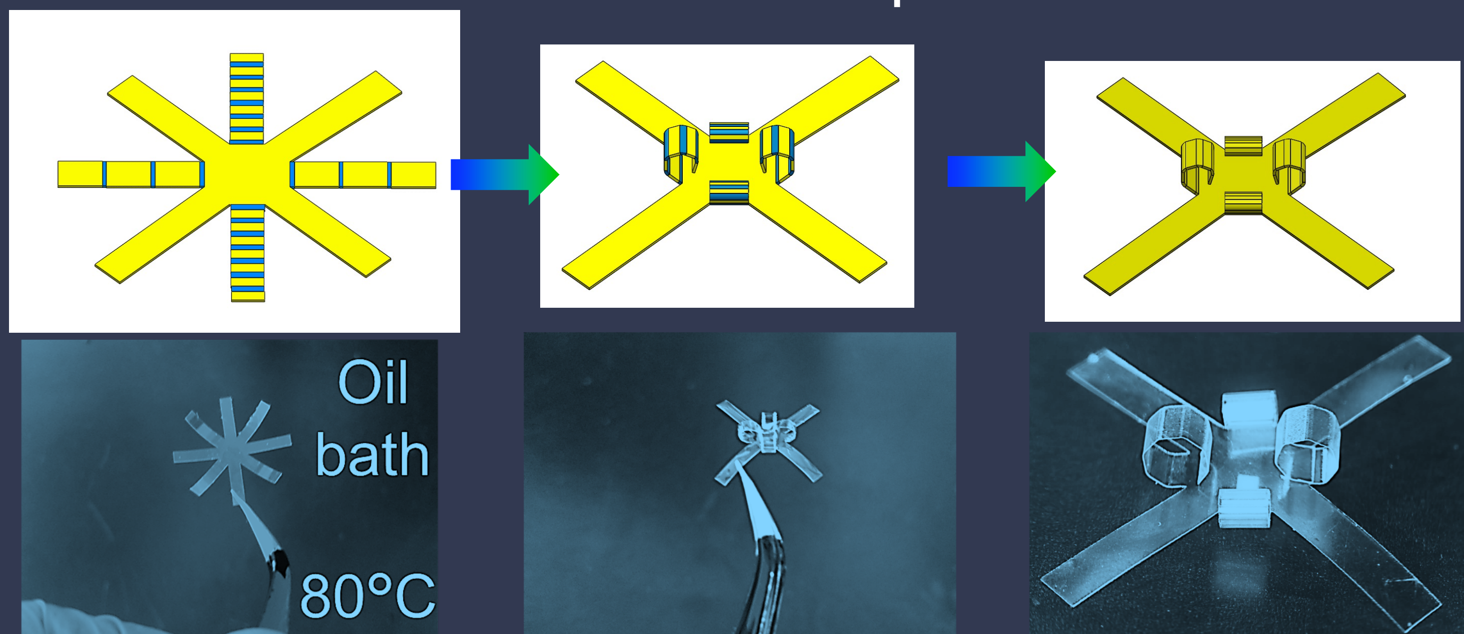
Free-standing patterned thin film

04 **Self-folding of Polymer Layers (C-MEMS)**

Film Folding

Programmable Self-Foldable Films for Origami-based ManufacturingD George, MJ Madou, EAP Hernandez
Smart Materials and Structures

Folding by heating **Exposure and PEB**



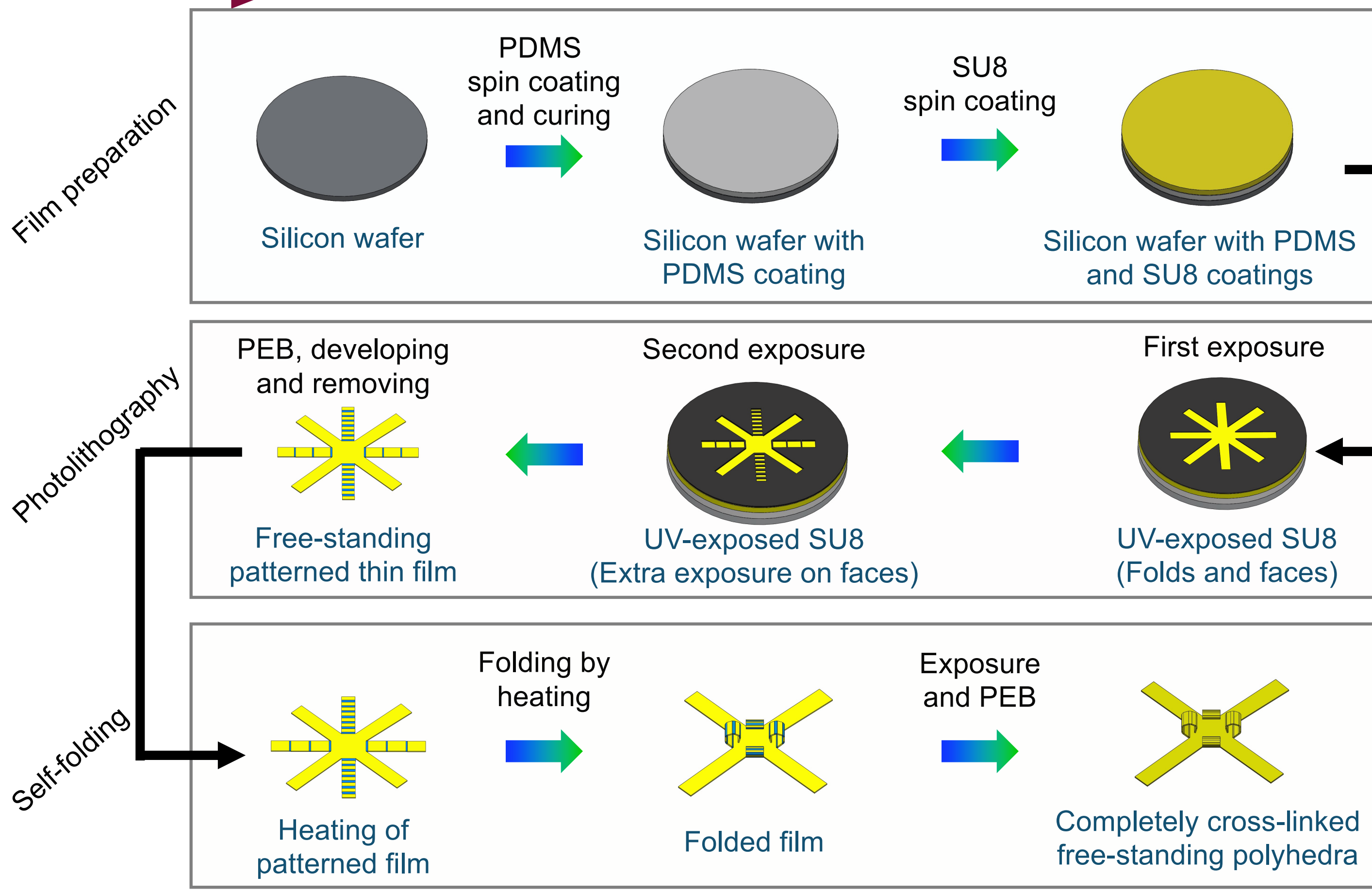
Heating of patterned film

Folded film

Completely cross-linked free-standing structures

04 Self-folding of Polymer Layers (C-MEMS)

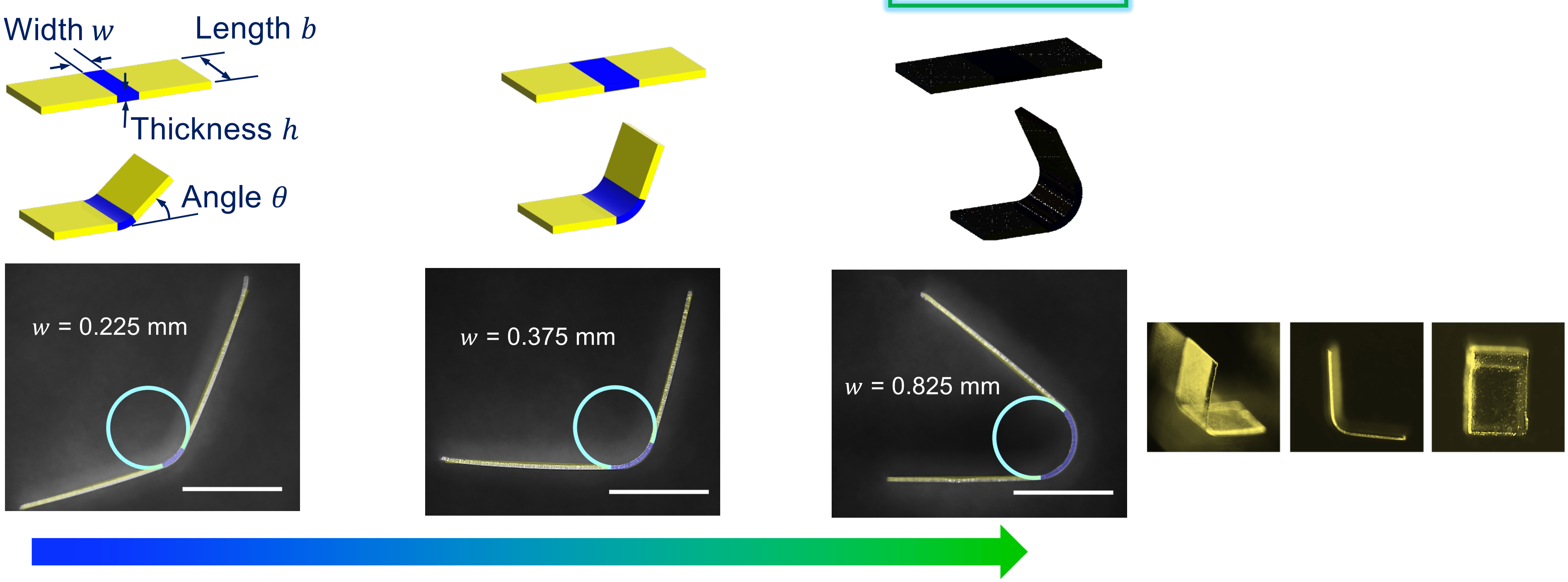
Fabrication - Summary



Fold Angle Programming

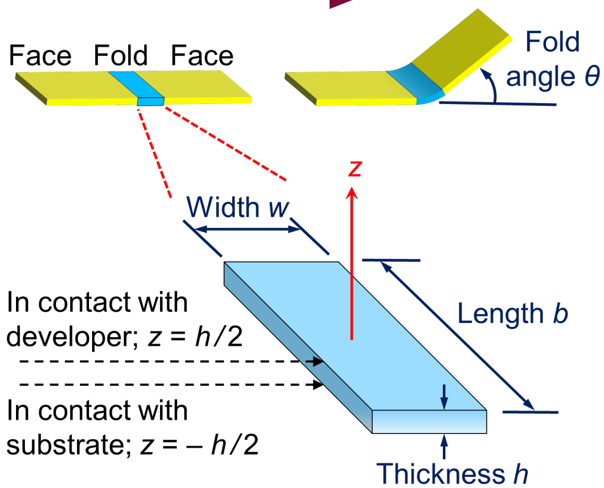
$$\theta = c\frac{w}{h}$$

- **Fold angle** given by **fold width**



04 Self-folding of Polymer Layers (C-MEMS)

Modeling



$\sigma = E.\varepsilon$

where

- σ is stress [Pa]
- ε is strain $= \frac{\Delta L}{L_0}$
- E is the modulus of elasticity [Pa]

Diffusion equation $$D\frac{\partial^2 c(z)}{\partial z^2} = 0$$

Concentration field $$c(z) = C_{c0} + C_{c1}z$$

Actuation strain field $$\varepsilon_a(z) = C_{\varepsilon 0} + C_{\varepsilon 1}z$$

$$\varepsilon_a\left(-\tfrac{h}{2}\right) = 0 \qquad \varepsilon_a\left(\tfrac{h}{2}\right) = -\varepsilon_A$$

$$\varepsilon_a(z) = -\varepsilon_A\left(\frac{1}{2} + \frac{z}{h}\right)$$

Elastic strain field $$\varepsilon_e(z) = -z\kappa - \varepsilon_a(z)$$

Now using $$-b\int_{\frac{-h}{2}}^{\frac{h}{2}} \sigma(z)\, z\, \mathrm{d}z = m = 0$$

where

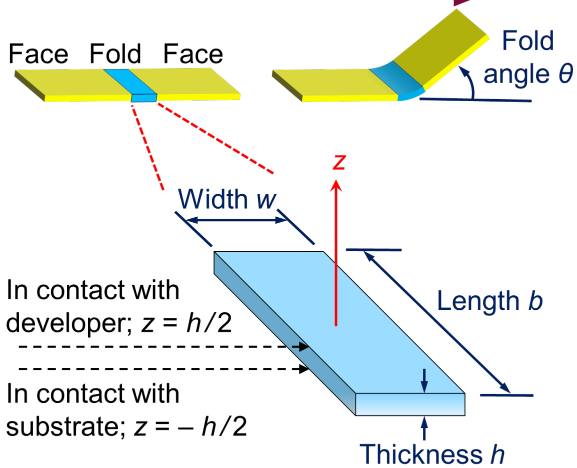
$$\sigma(z) = E\varepsilon_e(z)$$

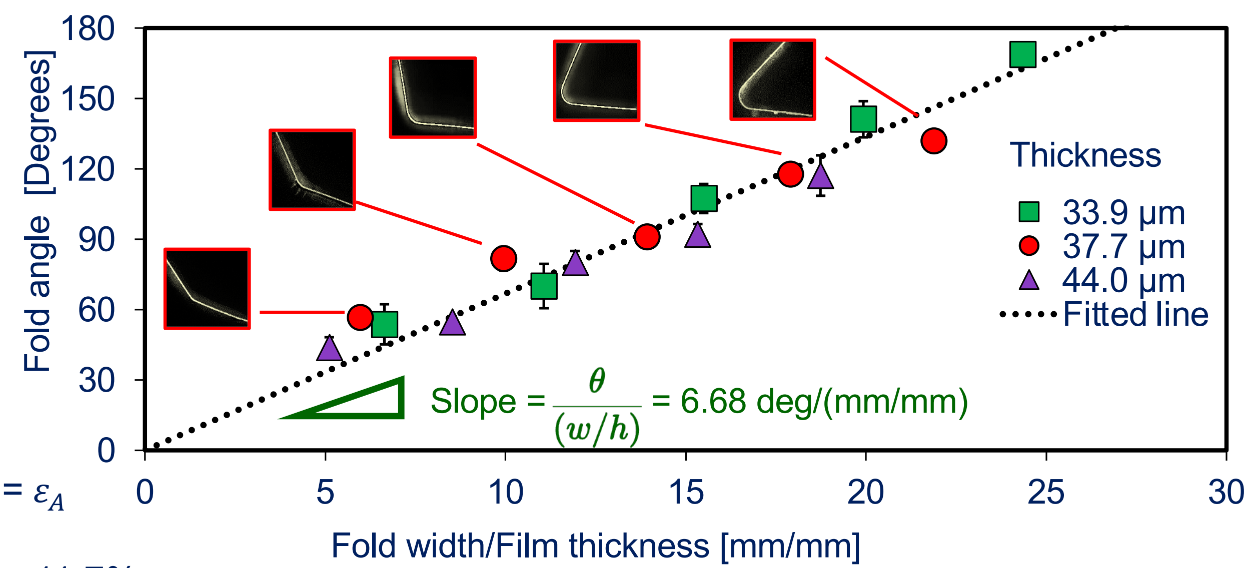
$$R = \frac{1}{\kappa} = \frac{h}{\varepsilon_A} \longrightarrow \boxed{\theta = \varepsilon_A \frac{w}{h}}$$

04 Self-folding of Polymer Layers (C-MEMS)

Modeling-Fold Angle Programming

Fold angle given by **fold width:** $\theta = \varepsilon_A \frac{w}{h}$



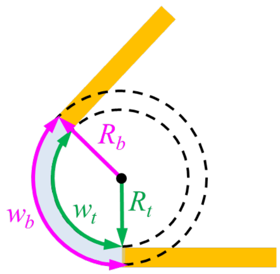


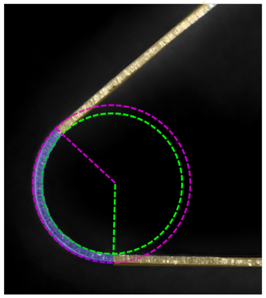
Slope = 6.68 deg/(mm/mm

= 0.117 rad/(mm/mm) = ε_A

Maximum actuation strain, ε_A= 11.7%

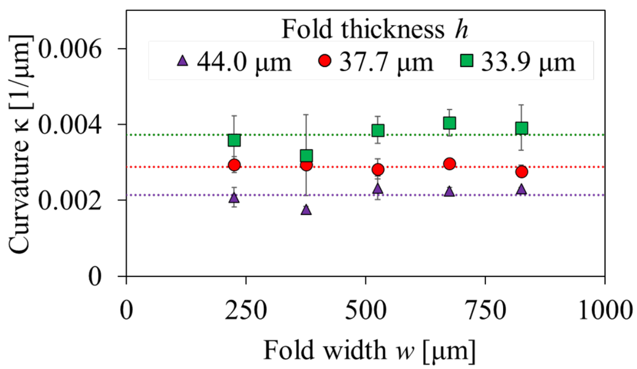
Fold Characterization

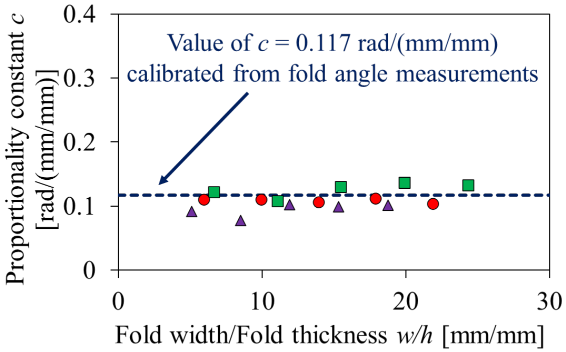




Bottom radius of curvature	R_b
Top radius of curvature	R_t
Bottom fold width	w_b
Top fold width	w_t
Curvature	κ

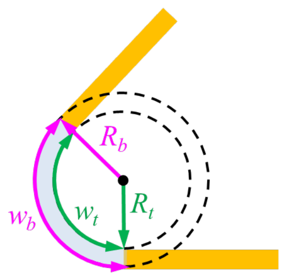
Curvature κ vs. fold width w

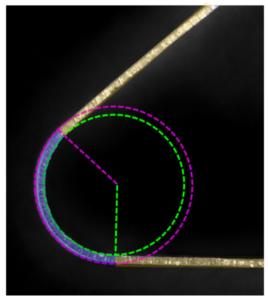




Fold Characterization

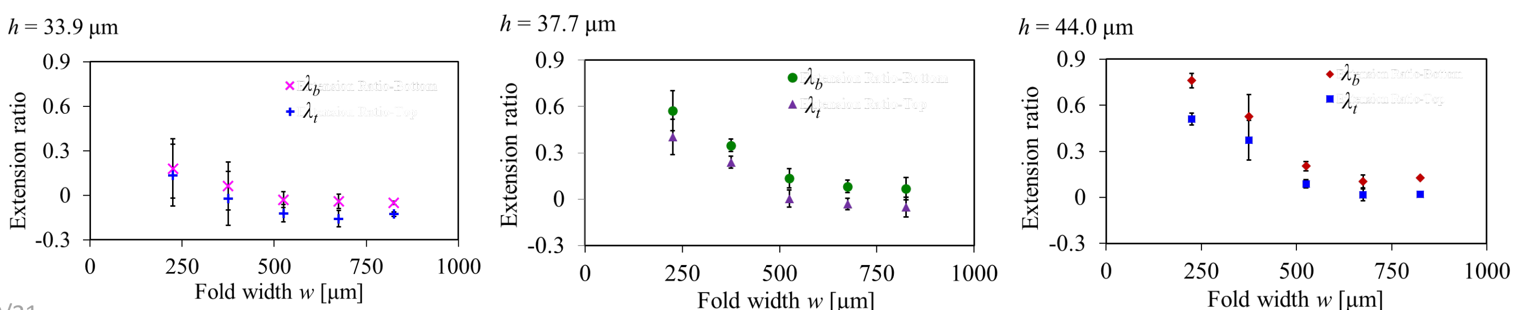
$$\lambda = \frac{l}{L} \; and \; \varepsilon = \frac{\Delta L}{L} = \lambda - 1$$





Bottom radius of curvature	R_b
Top radius of curvature	R_t
Bottom fold width	w_b
Top fold width	w_t
Top extension ratio	$\lambda_t = \frac{w_t - w}{w}$
Bottom extension ratio	$\lambda_b = \frac{w_b - w}{w}$

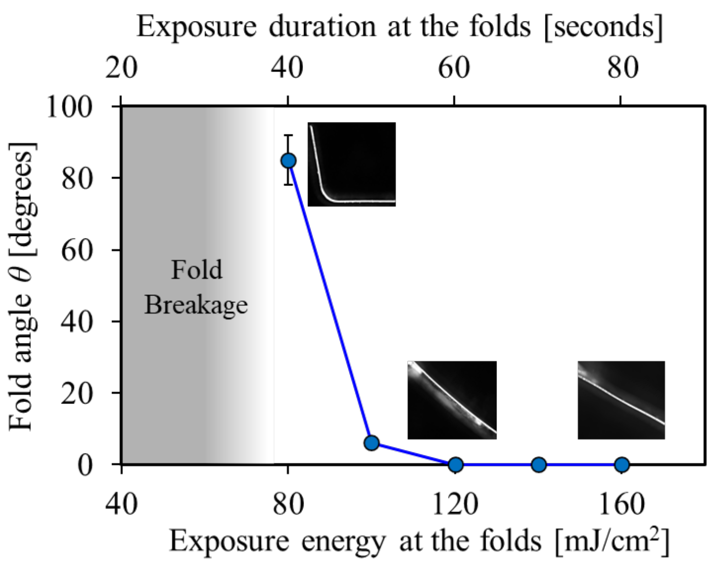
Extension Ratios vs. Fold Width *w*



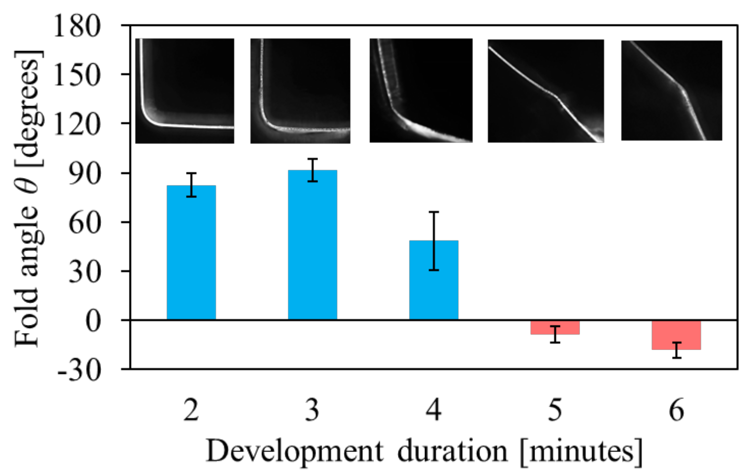
Fold Characterization

Effect of **exposure energy** and **development duration** on the **fold angle**

Exposure energy vs. Fold angle



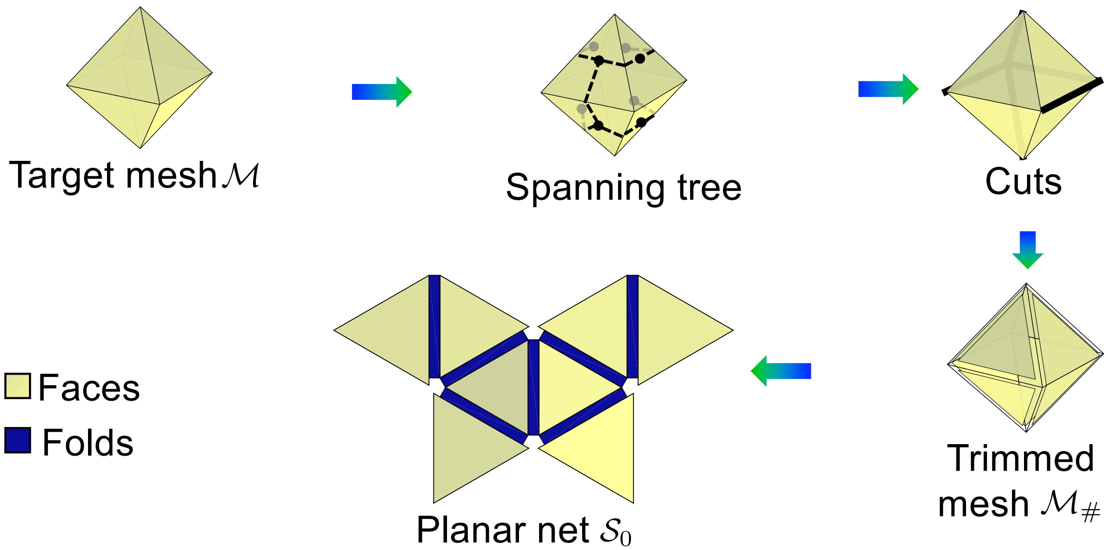
Development duration vs. Fold angle



04 Self-folding of Polymer Layers (C-MEMS)

Unfolding Polyhedra and Net Optimization

- Origami design incorporating calibration data



Optimization problem-optimized net:

Find: $\mathbf{e}$
That minimize: f
Subject to: $e_i \in \{0, 1\}$,
$\mathcal{S}_0$ is single connected shape
$\mathcal{S}_0$ does not contain overlapping faces or folds

e - Vector containing the fold and cut assignments of each interior edge of M
f - Objective function
e_i -Each component of e.
They can take a value of 0 (if interior edge i is a fold) or 1 (if interior edge i is a cut)

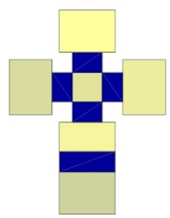
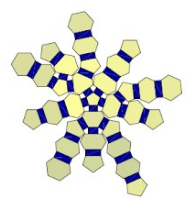
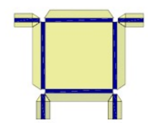
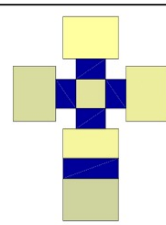
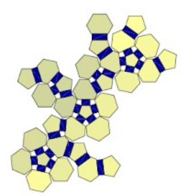
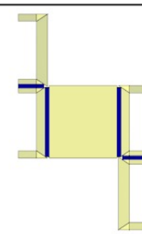
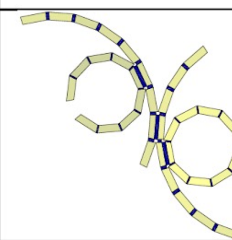
In an optimization problem, there is a (real-valued) function that is to be maximized or minimized. This function is frequently called the *objective function.*

In the mathematical field of graph theory, a **spanning tree** *T* of an undirected graph *G* is a subgraph that is a tree which includes all of the vertices of *G*, with a minimum possible number of edges.

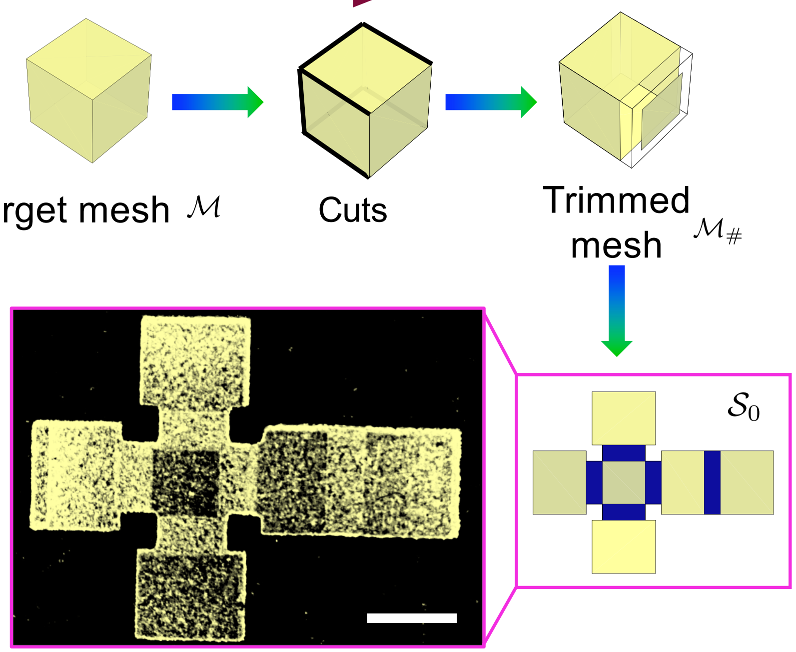
Optimized Net

- Net optimized by minimizing the sum of the distances d between the centroids each pair of faces in the net
  - Net should be compact
  - Error arising from the variability in the fold angle must be reduced
- Net optimized for shape accuracy *a*
  - If the fabrication is perfected, then this make the most accurate shapes (a=1).

$$a = \frac{\text{Area}(\mathcal{M}_{\#})}{\text{Area}(\mathcal{M})}.$$

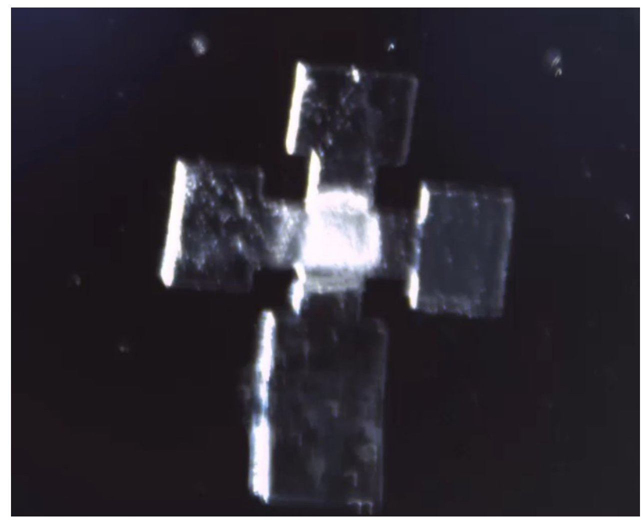
	Cube	Truncated icosahedron	Platform	Trimmed torus
Minimum total distance d				
Maximum accuracy a				

04 Self-folding of Polymer Layers (C-MEMS)



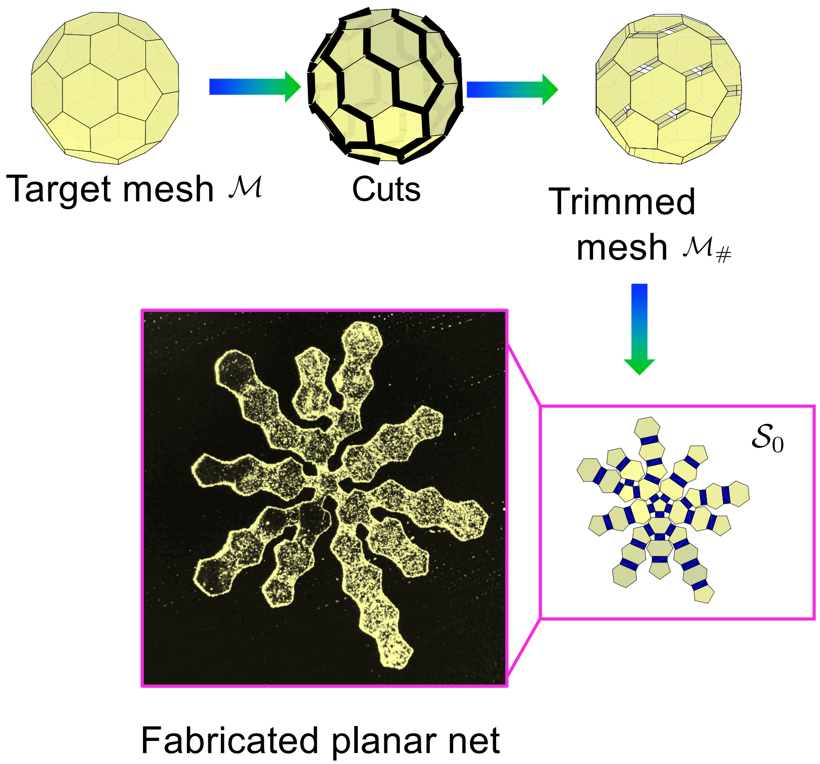
Fabricated planar net

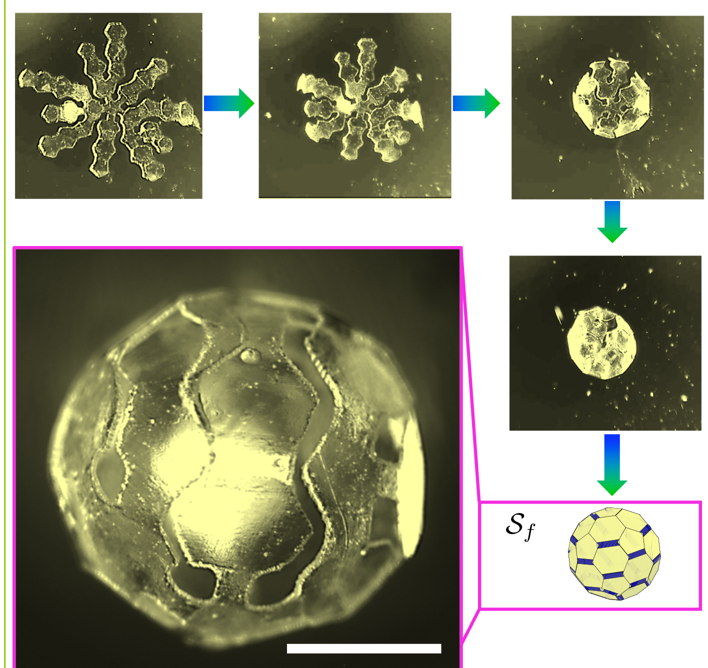
Cube



04 Self-folding of Polymer Layers (C-MEMS)

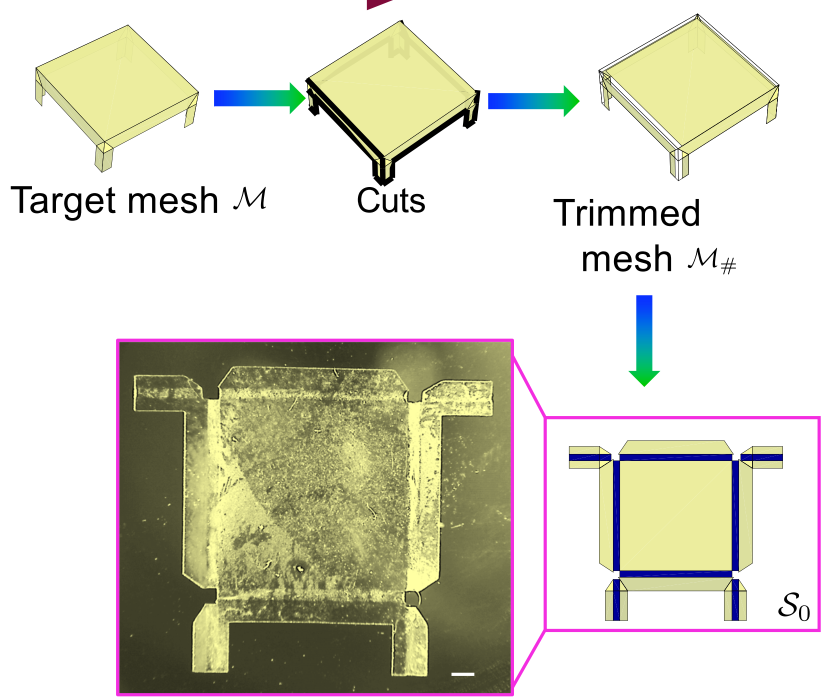
Truncated Icosahedron



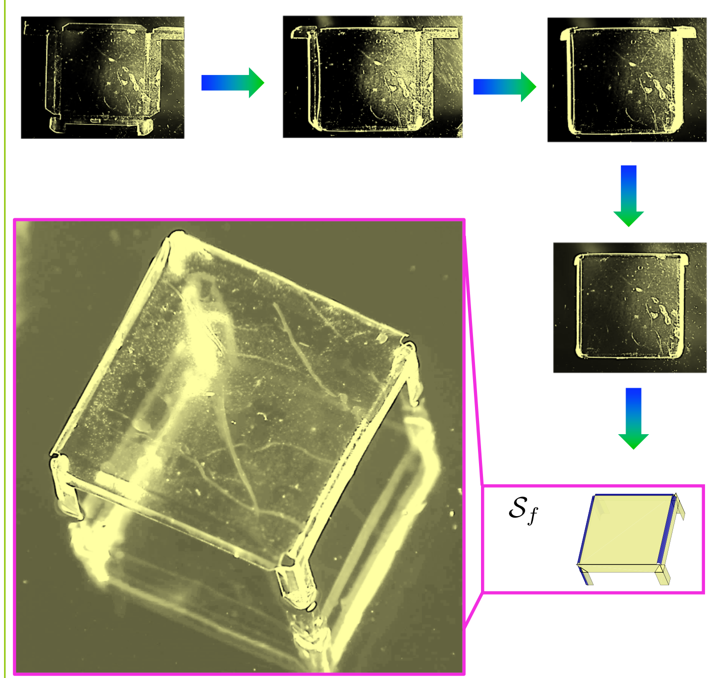


04 Self-folding of Polymer Layers (C-MEMS)

Platform

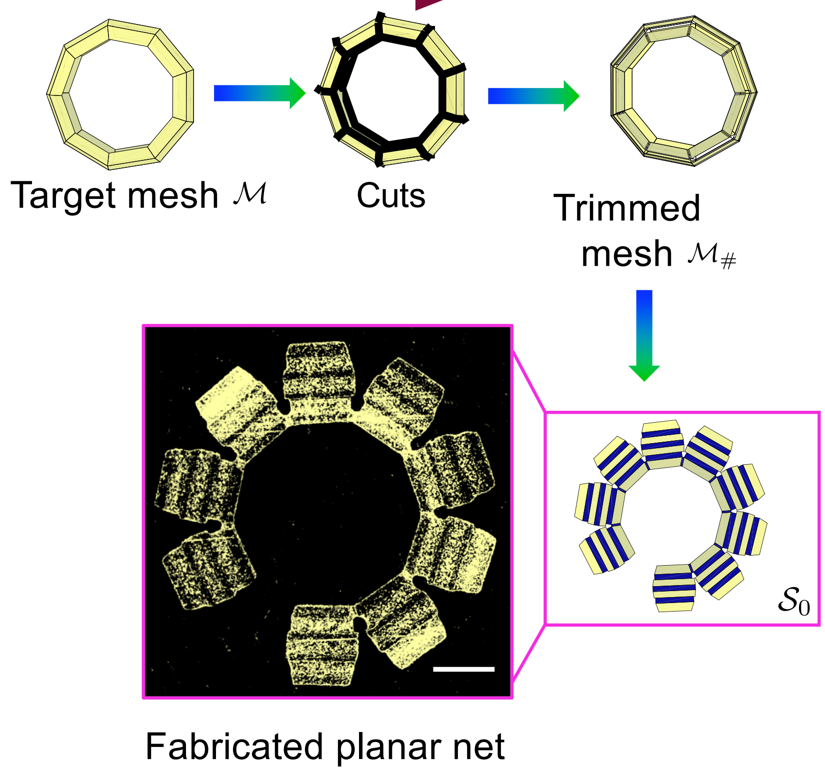


Fabricated planar net



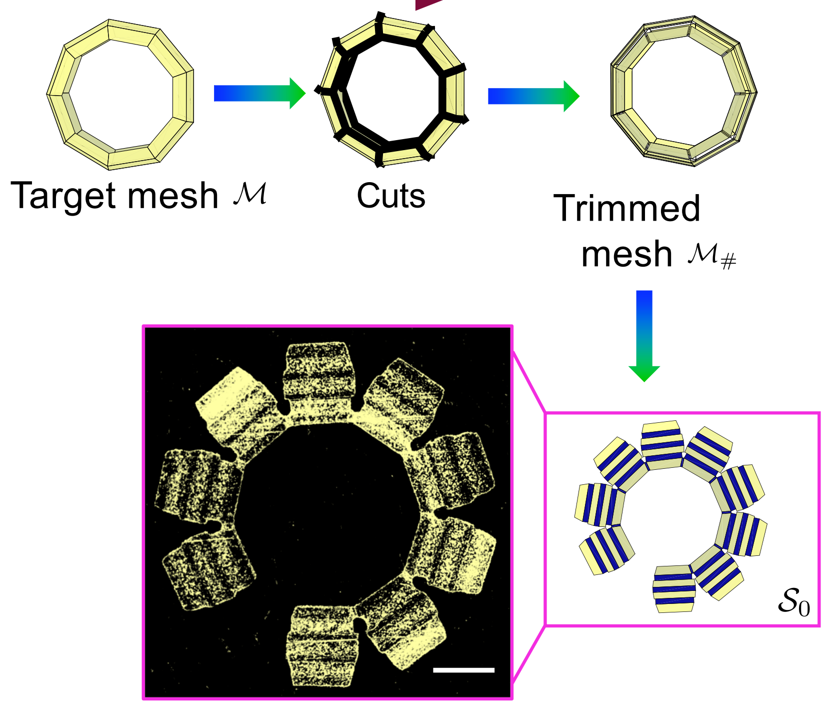
04 **Self-folding of Polymer Layers (C-MEMS)**

Trimmed torus

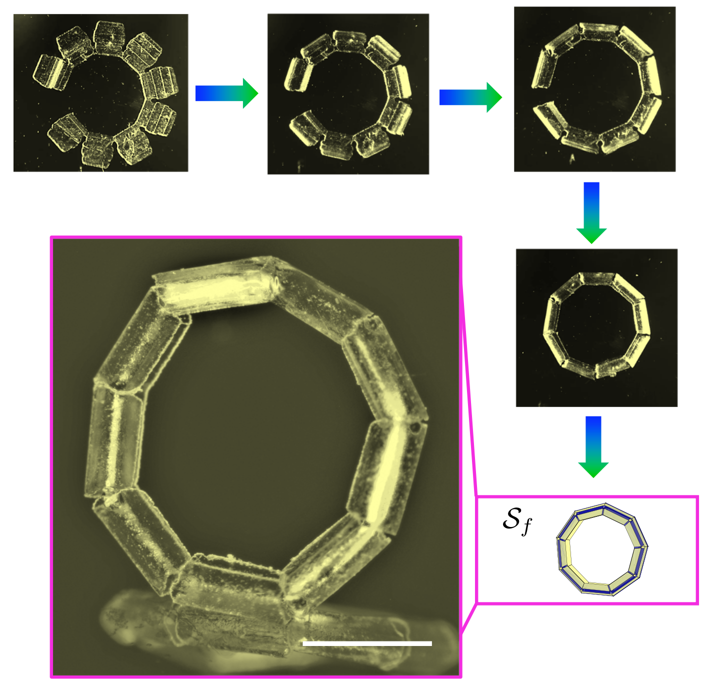


04 Self-folding of Polymer Layers (C-MEMS)

Trimmed torus

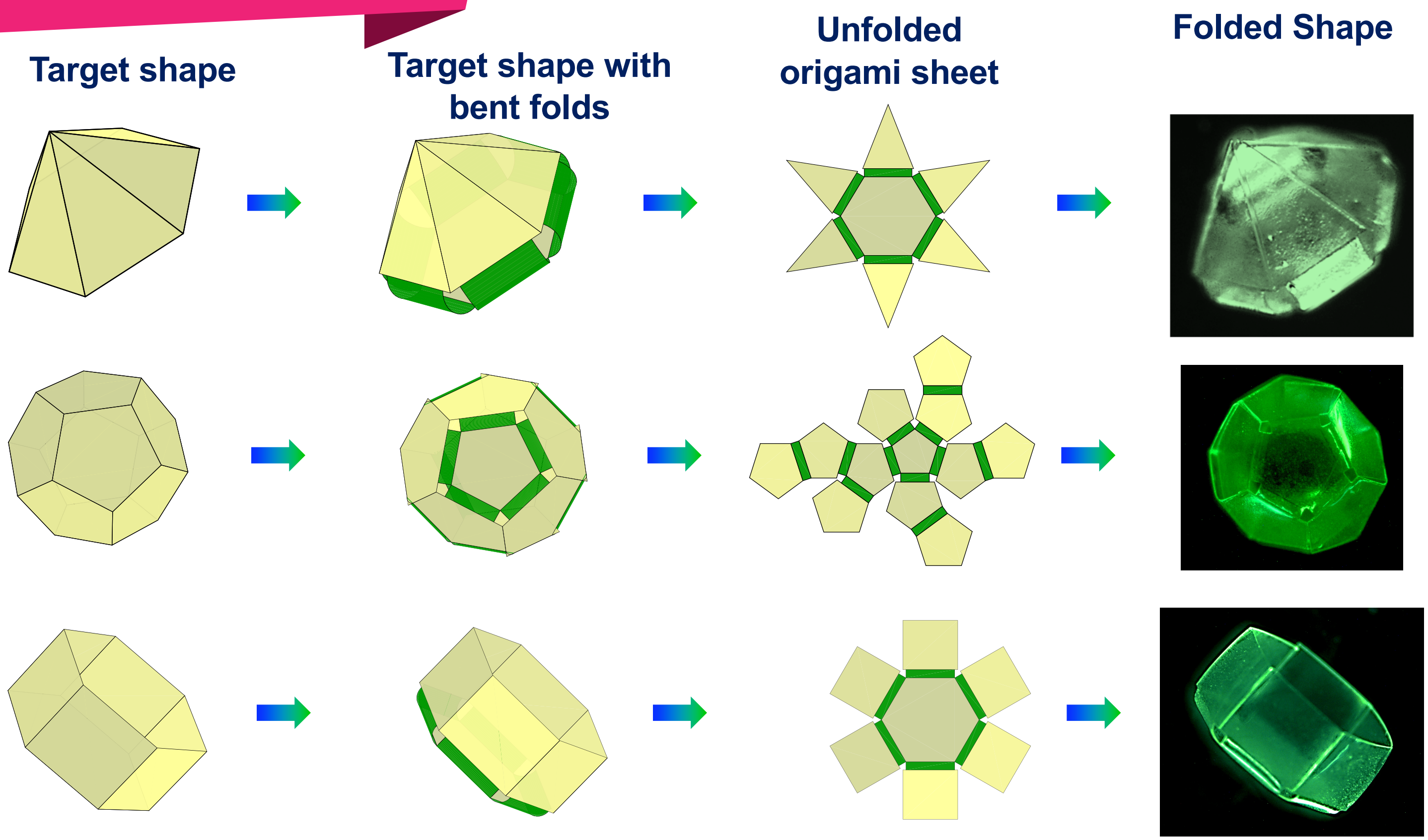


Fabricated planar net



04 Self-folding of Polymer Layers (C-MEMS)

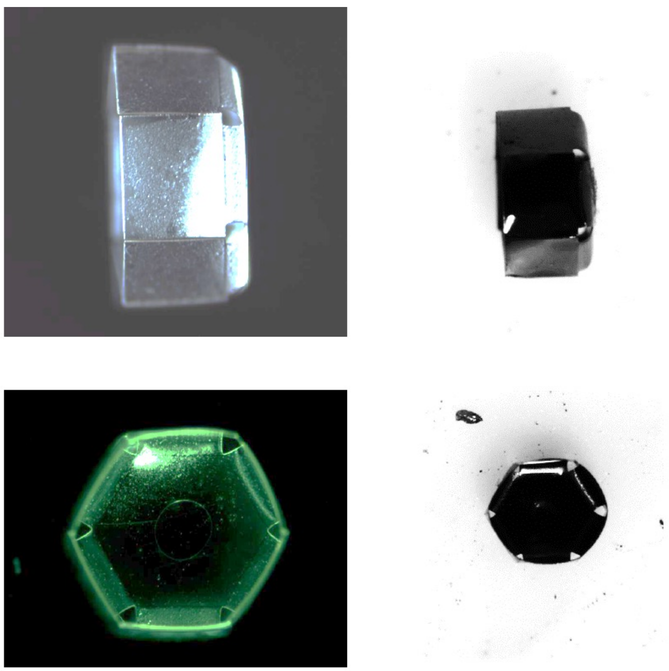
More Shapes



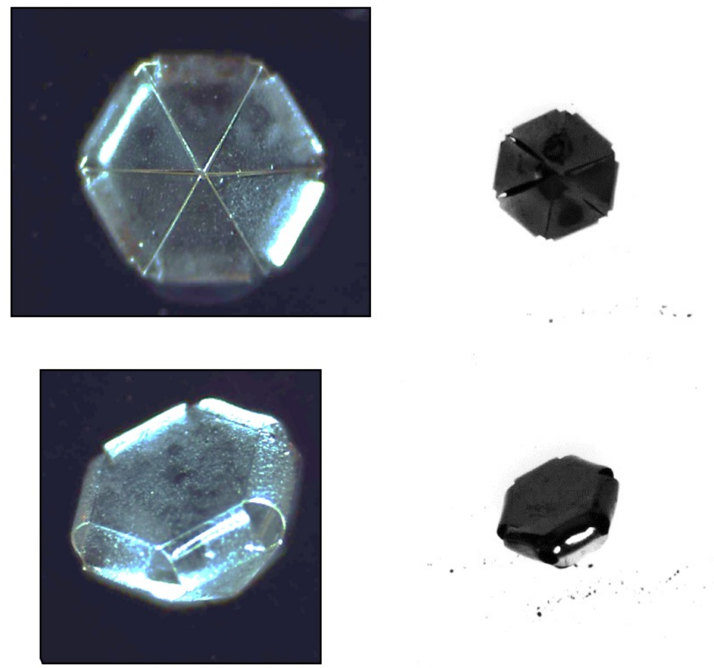
04

Self-folding of Polymer Layers (C-MEMS)

Carbon Origami



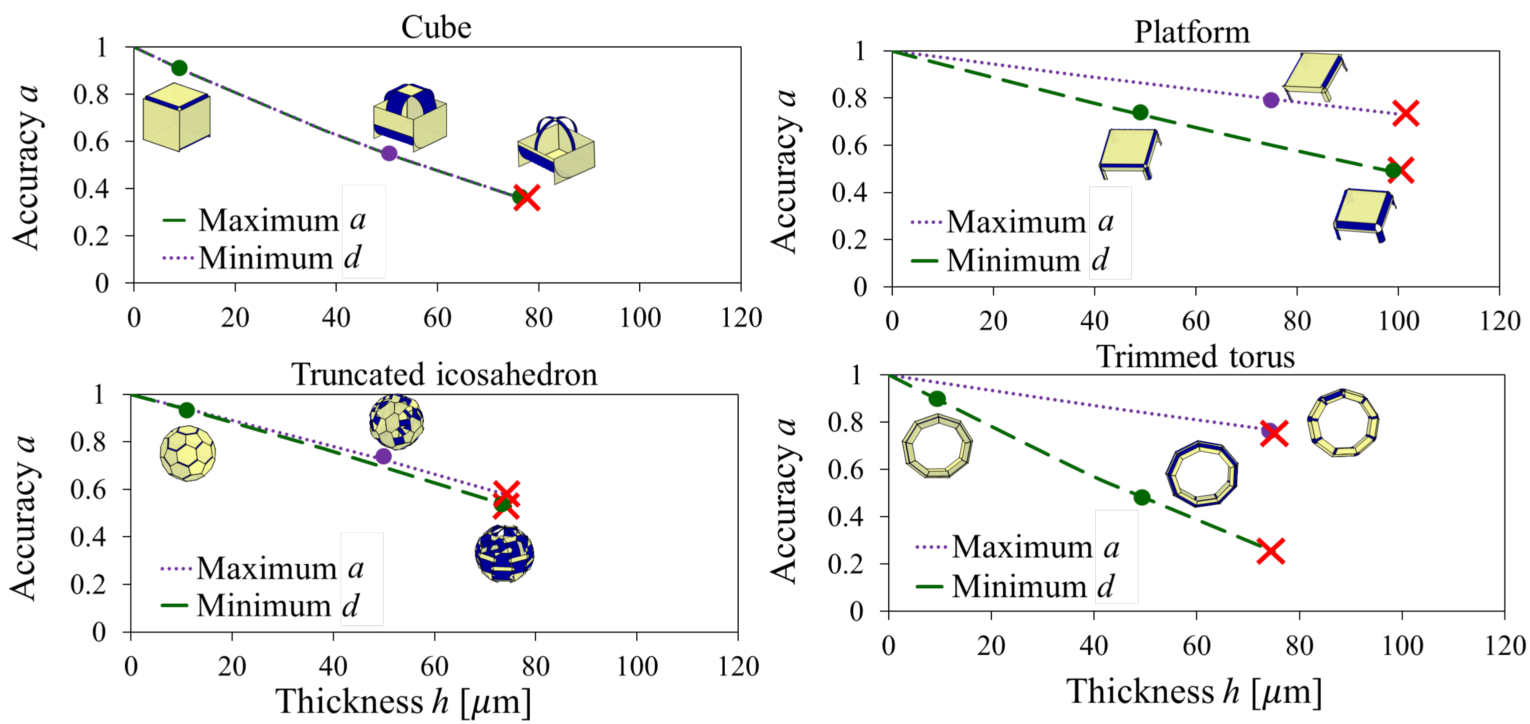
Polymer Origami   Carbon Origami



Polymer Origami   Carbon Origami

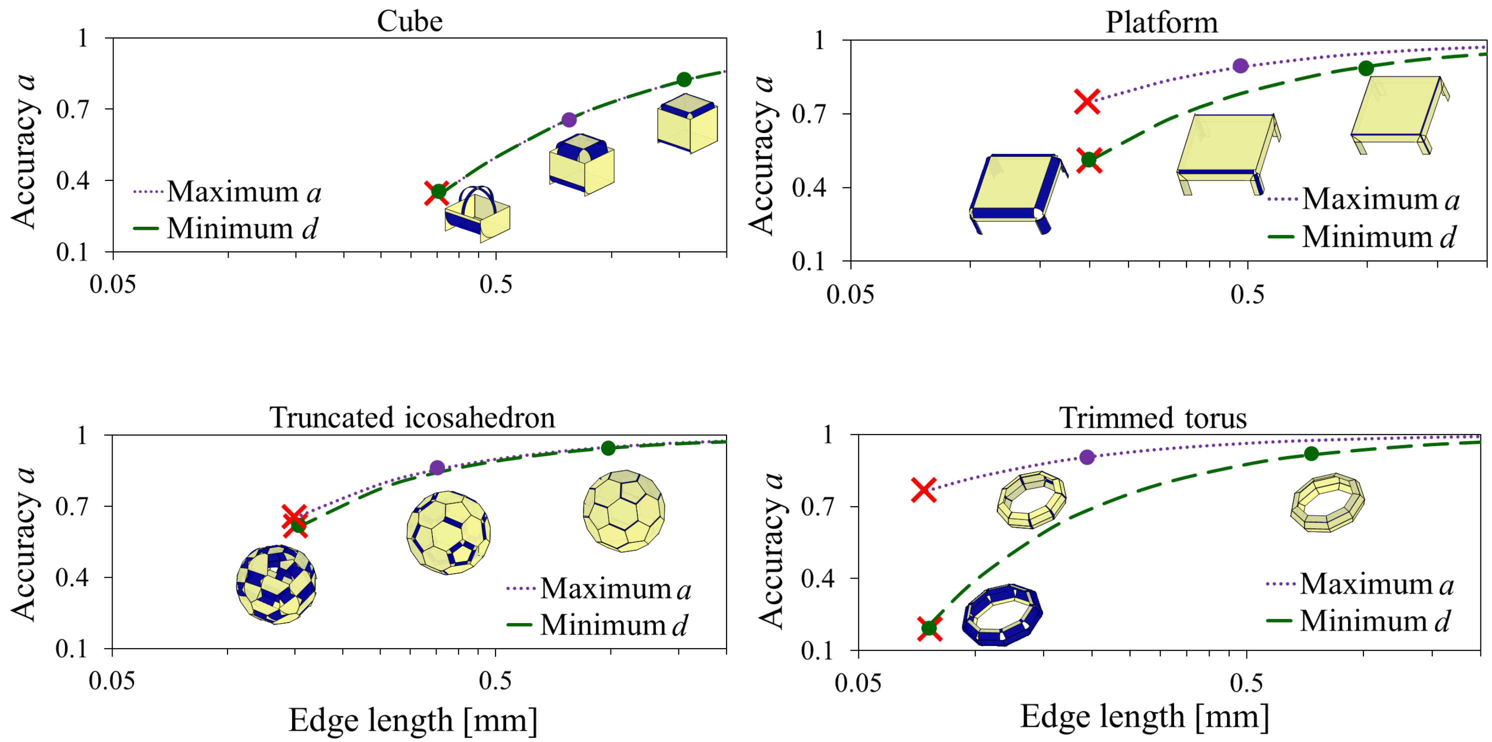
Scaling the Method

$$\text{Accuracy} = \frac{\text{Actual area}}{\text{Target shape area}}$$



04 Self-folding of Polymer Layers (C-MEMS)

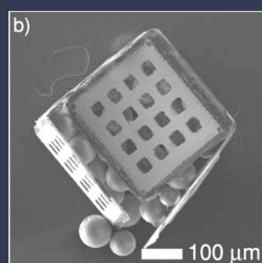
Scaling the Method



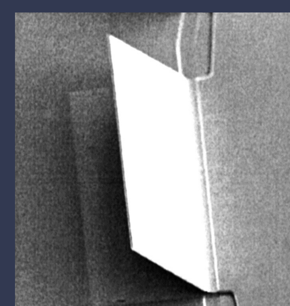
UCI bioMEMS

05 Applications

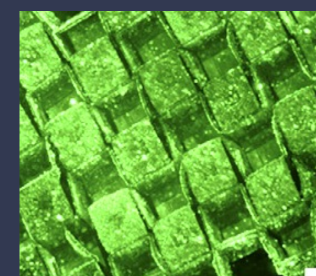
3D electronics
(Randhawa et al. 2010)



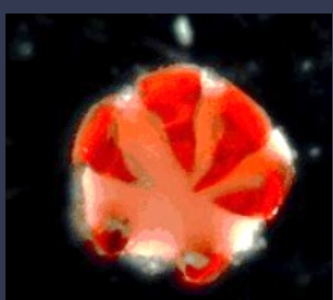
Encapsulation
(Leong et al. 2008)



Micromirror
(Zanardi et al. 2003)

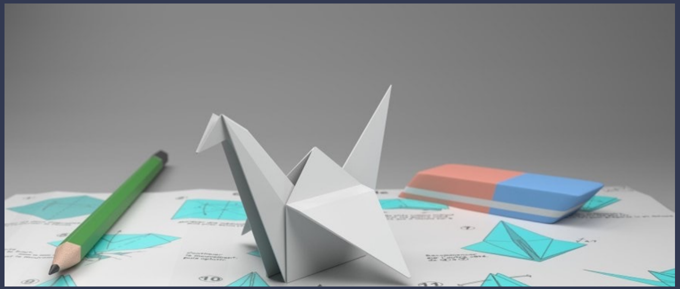


Scaffold
(Jamal et al. 2010)



Microgrippers
(Malachowski et al. 2014)

06 Conclusions/Prospects



Achieved solvent transport-based **self-folding** using **single-layer** photopolymer films

Developed **end-to-end freeform manufacturing** method by leveraging the unfolding polyhedra method

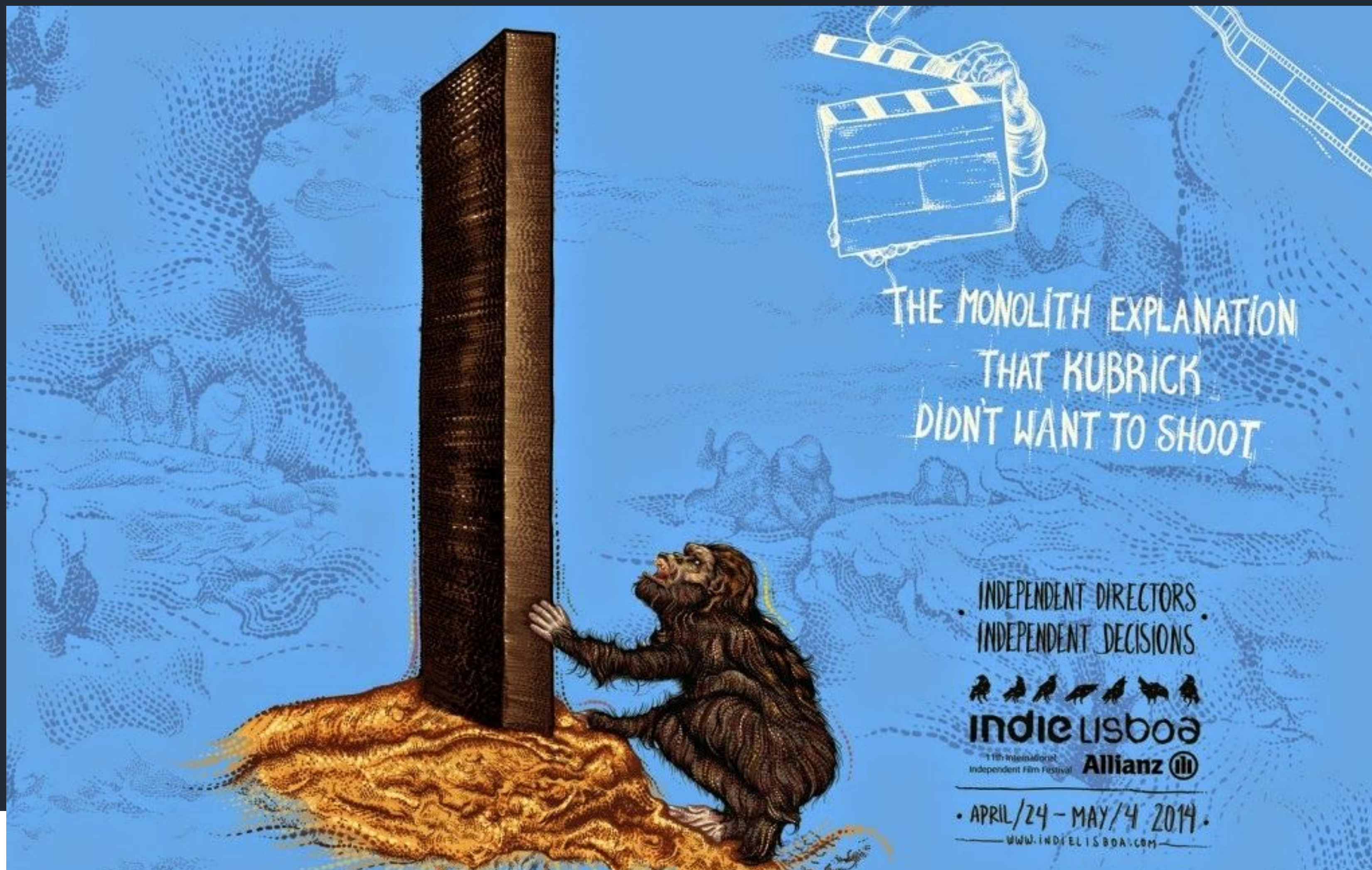
Demonstrated the method with different shapes

Converted polymer shapes to carbon shapes

Development of a new bi-directional folding strategy

Testing different photopolymers to enable folding at relatively lower temperature

Scaling in size and numbers.



http://www.archipelagofiles.com/2014/04/poster-campaign-by-international-film.html