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
• 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”
• 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).

https://documentaryheaven.com/between-folds-art-of-origami/
• 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
• 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: 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
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: Spontaneous Wrapping of a Droplet with an Elastic Sheet
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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 deformations
George, EAP Hernandez, RC Lo, M Madou
Soft Matter 15 (45), 9171-9177
3/30/21

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

Fabrication of polymer and carbon polyhedra through controlled cross-linking and capillary deformations

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Folded free-standing carbon shapes

Before pyrolysis

After pyrolysis

Free-standing patterned precursor polymer and carbon shapes

Raman spectrum of the carbon
Fabrication of polymer and carbon polyhedra through controlled cross-linking and capillary deformations

George, EAP Hernandez, RC Lo, M Madou

Soft Matter 15 (45), 9171-9177
We need origami manufacturing that is:
- Scalable in numbers and sizes
- Complex shapes
- Self-folding
- Simple construction
- Freeform
- Minimal materials consumption

Programmable Self-Foldable Films for Origami-based Manufacturing
D. George, MJ Madou, EAP Hernandez
Smart Materials and Structures
Self-folding of polymer layers (C-MEMS)

1. Single layer photopolymer films as precursors
2. Controlled folding using programmable films and origami design
3. An end-to-end freeform manufacturing method

Programmable Self-Foldable Films for Origami-based Manufacturing
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Self-folding of Polymer Layers (C-MEMS)

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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
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
Self-folding of Polymer Layers (C-MEMS)

Programmable Self-Foldable Films for Origami-based Manufacturing
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Film Folding

Folding by heating
Exposure and PEB

Heating of patterned film
Folded film
Completely cross-linked free-standing structures
Self-folding of Polymer Layers (C-MEMS)

Fabrication - Summary

- **Film preparation**
  - Silicon wafer
  - PDMS spin coating and curing
  - Silicone wafer with PDMS coating
  - SU8 spin coating
  - Silicone wafer with PDMS and SU8 coatings

- **Photolithography**
  - PEB, developing and removing
  - Free-standing patterned thin film
  - Second exposure
  - UV-exposed SU8 (Extra exposure on faces)
  - First exposure
  - UV-exposed SU8 (Folds and faces)

- **Self-folding**
  - Heating of patterned film
  - Folding by heating
  - Folded film
  - Exposure and PEB
  - Completely cross-linked free-standing polyhedra
• **Fold angle** given by **fold width**

\[
\theta = c \frac{w}{h}
\]

Increasing fold width

- **Width** $w = 0.225 \text{ mm}$
- **Width** $w = 0.375 \text{ mm}$
- **Width** $w = 0.825 \text{ mm}$
Self-folding of Polymer Layers (C-MEMS)

Modeling

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

Concentration field
\[ c(z) = C_{c0} + C_{c1}z \]

Actuation strain field
\[ \varepsilon_a(z) = C_{\varepsilon0} + C_{\varepsilon1}z \]
\[ \varepsilon_a\left(-\frac{h}{2}\right) = 0 \quad \varepsilon_a\left(\frac{h}{2}\right) = -\varepsilon_A \]
\[ \varepsilon_a(z) = -\varepsilon_A \left(\frac{1}{2} + \frac{z}{h}\right) \]

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

Now using
\[ -b \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma(z) z \, dz = m = 0 \]
where
\[ \sigma(z) = E\varepsilon_e(z) \]

\[ R = \frac{1}{\kappa} = \frac{h}{\varepsilon_A} \quad \theta = \frac{\varepsilon_A w}{h} \]
Self-folding of Polymer Layers (C-MEMS)

Fold angle given by fold width: \[ \theta = \epsilon_A \frac{w}{h} \]

Maximum actuation strain, \( \epsilon_A = 11.7\% \)
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 $\kappa$

Curvature $\kappa$ vs. fold width $w$

Value of $c = 0.117$ rad/(mm/mm)
calibrated from fold angle measurements

Fold thickness $h$
- 44.0 $\mu$m
- 37.7 $\mu$m
- 33.9 $\mu$m

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Fold Characterization

\[ \lambda = \frac{l}{L} \text{ and } \varepsilon = \frac{\Delta L}{L} = \lambda - 1 \]

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 \( \lambda_t \)
Bottom extension ratio \( \lambda_b \)

\[ \lambda_t = \frac{w_t - w}{w} \]
\[ \lambda_b = \frac{w_b - w}{w} \]

Extension Ratios vs. Fold Width \( w \)

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Fold Characterization

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

**Exposure energy vs. Fold angle**

**Development duration vs. Fold angle**

- Fold angle $\theta$ [degrees]
  - Exposure duration at the folds [seconds]
  - Development duration [minutes]

- Fold Breakage

- Exposure energy at the folds [mJ/cm$^2$]
- Development duration [minutes]
Unfolding Polyhedra and Net Optimization

- Origami design incorporating calibration data

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

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 ($a=1$).

$$a = \frac{\text{Area}(\mathcal{M}_\#)}{\text{Area}(\mathcal{M})}.$$
04 Self-folding of Polymer Layers (C-MEMS)

Target mesh $\mathcal{M}$  →  Cuts  →  Trimmed mesh $\mathcal{M}_\#$

Fabricated planar net $S_0$

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

Truncated Icosahedron

Target mesh $\mathcal{M}$ → Cuts → Trimmed mesh $\mathcal{M}_\#$

Fabricated planar net

$S_0$ → $S_f$
Self-folding of Polymer Layers (C-MEMS)

Target mesh $\mathcal{M}$

Cuts

Trimmed mesh $\mathcal{M}_\#$

Fabricated planar net

Platform

$S_0$

$S_f$
Self-folding of Polymer Layers (C-MEMS)

Trimmed torus

Target mesh $\mathcal{M}$ → Cuts → Trimmed mesh $\mathcal{M}_\#$

Fabricated planar net $\mathcal{S}_0$
Self-folding of Polymer Layers (C-MEMS)

- Target mesh $\mathcal{M}$
- Cuts
- Trimmed mesh $\mathcal{M}_\#$
- Fabricated planar net

Trimmed torus

Fabricated planar net

UCI bioMEMS
More Shapes

Target shape

Target shape with bent folds

Unfolded origami sheet

Folded Shape

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

Carbon Origami

Polymer Origami

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Scaling the Method

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

Self-folding of Polymer Layers (C-MEMS)

[Diagrams showing accuracy vs. thickness for different shapes (Cube, Platform, Truncated icosahedron, Trimmed torus)]
04 Self-folding of Polymer Layers (C-MEMS)

Scaling the Method

Cube

Platform

Truncated icosahedron

Trimmed torus

Accuracy $a$

Edge length [mm]

Accuracy $a$

Edge length [mm]
Applications

- 3D electronics (Randhawa et al. 2010)
- Encapsulation (Leong et al. 2008)
- Microgrippers (Malachowski et al. 2014)
- Micromirror (Zanardi et al. 2003)
- Scaffold (Jamal et al. 2010)
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
THE MONOLITH EXPLANATION
THAT KUBRICK
DIDN'T WANT TO SHOOT

INDEPENDENT DIRECTORS.
INDEPENDENT DECISIONS.

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APRIL 24 - MAY 4, 2014