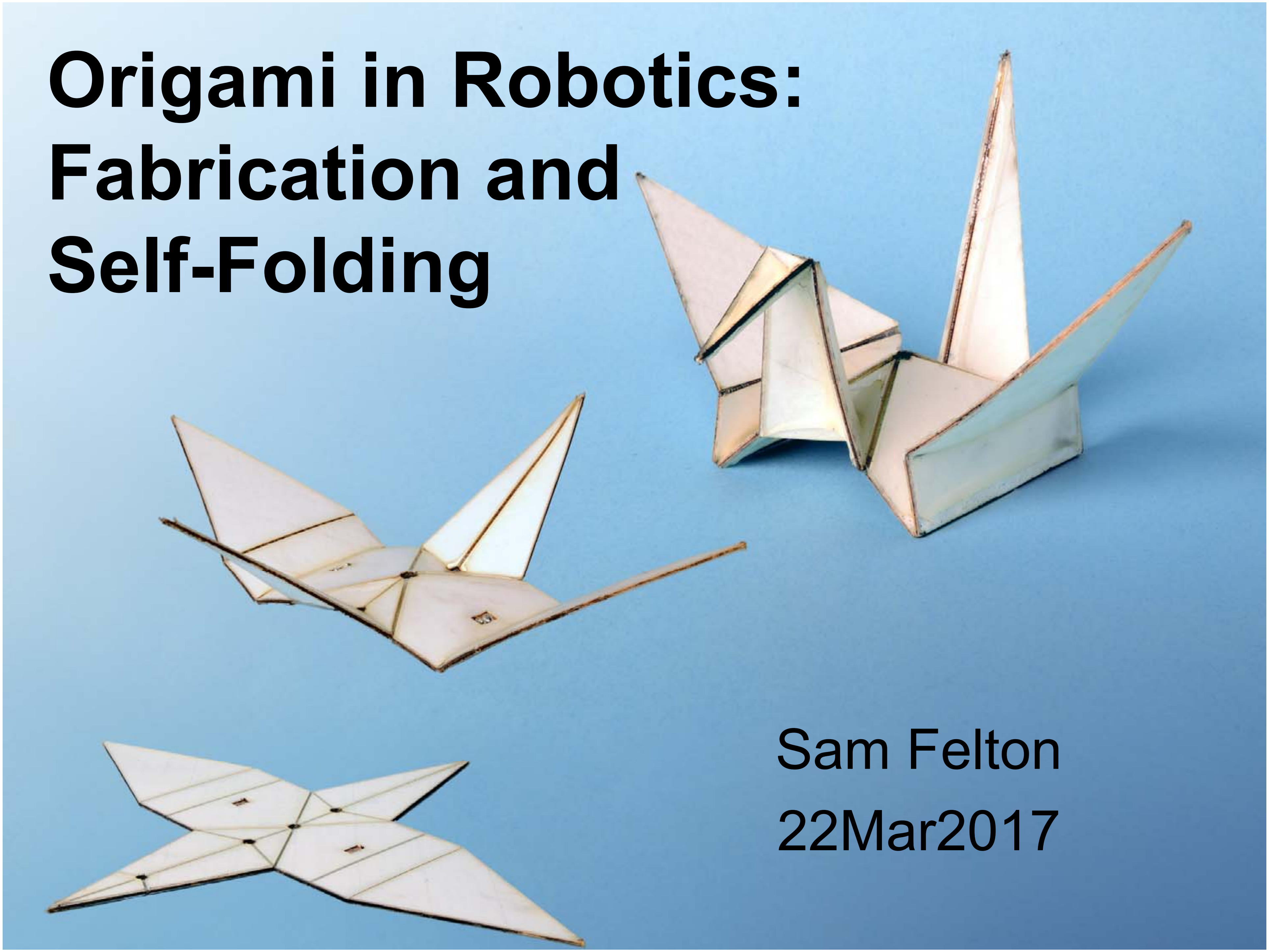
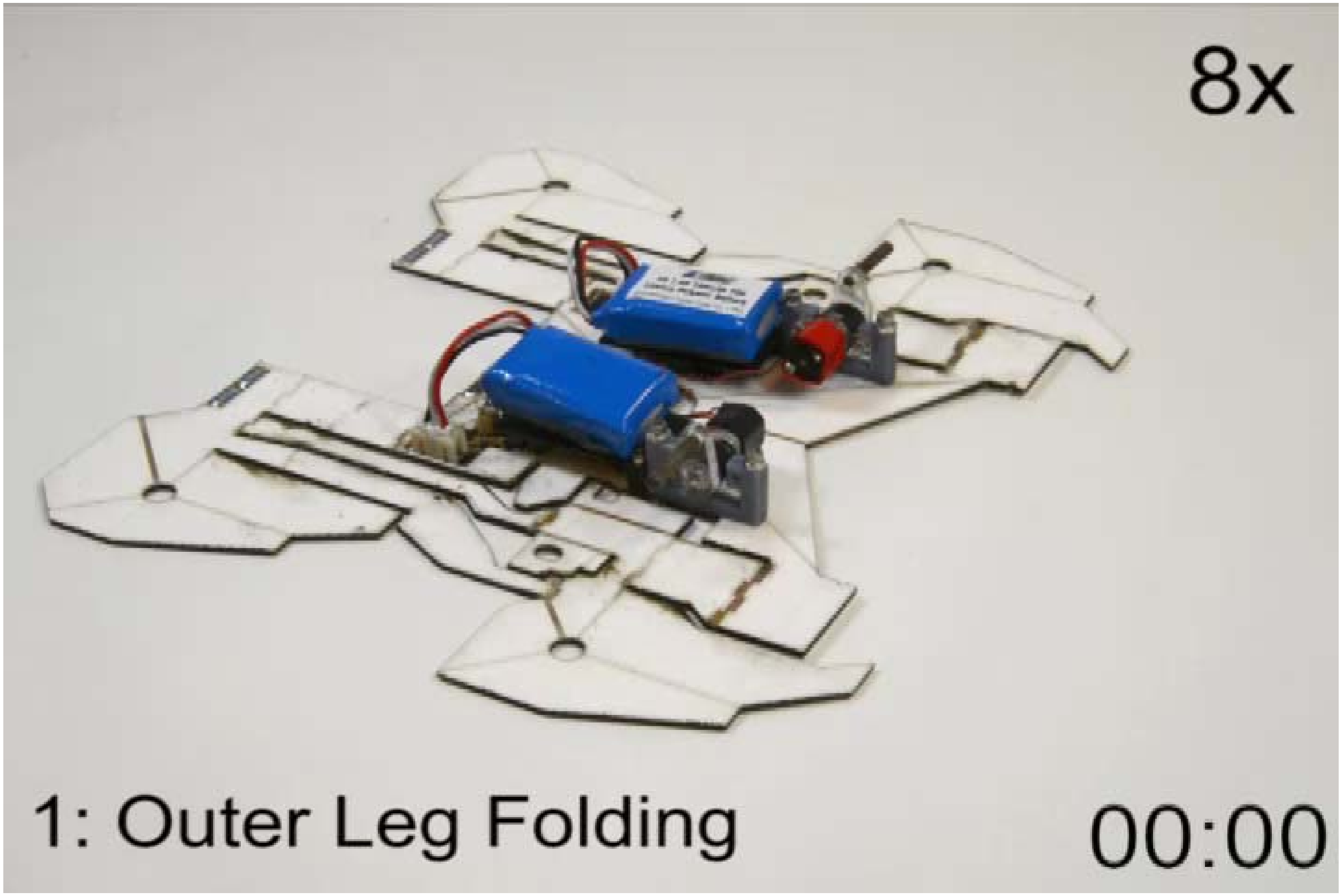
Origami in Robotics: Fabrication and Self-Folding



Sam Felton

22Mar2017

Autonomous Folding

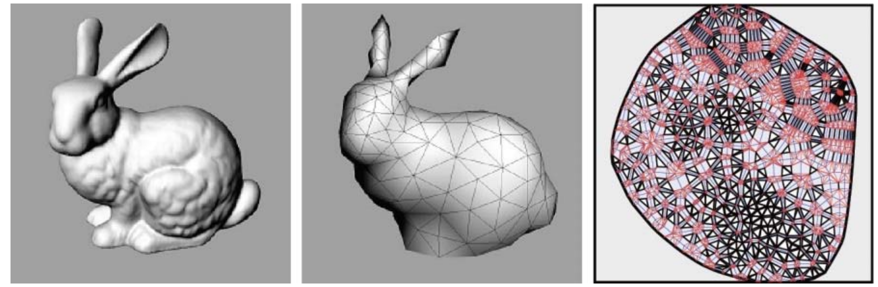


Felton *et al.*, *Science* 2014

Origami Engineering

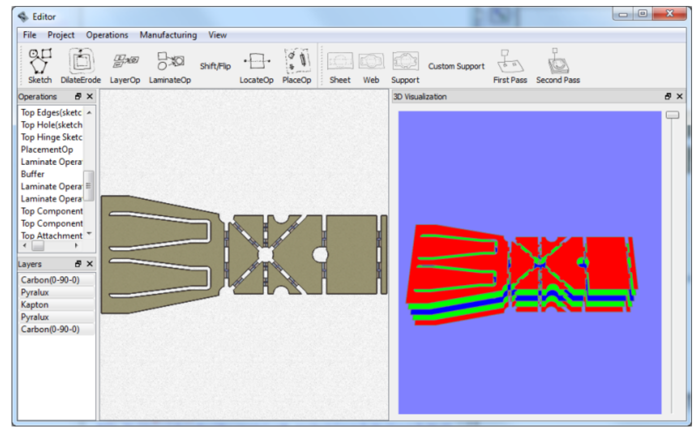
Mathematically…

We can fold anything



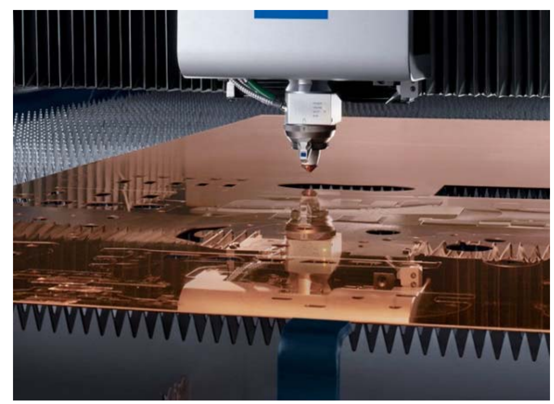
Computationally…

We can generate fold patterns automatically



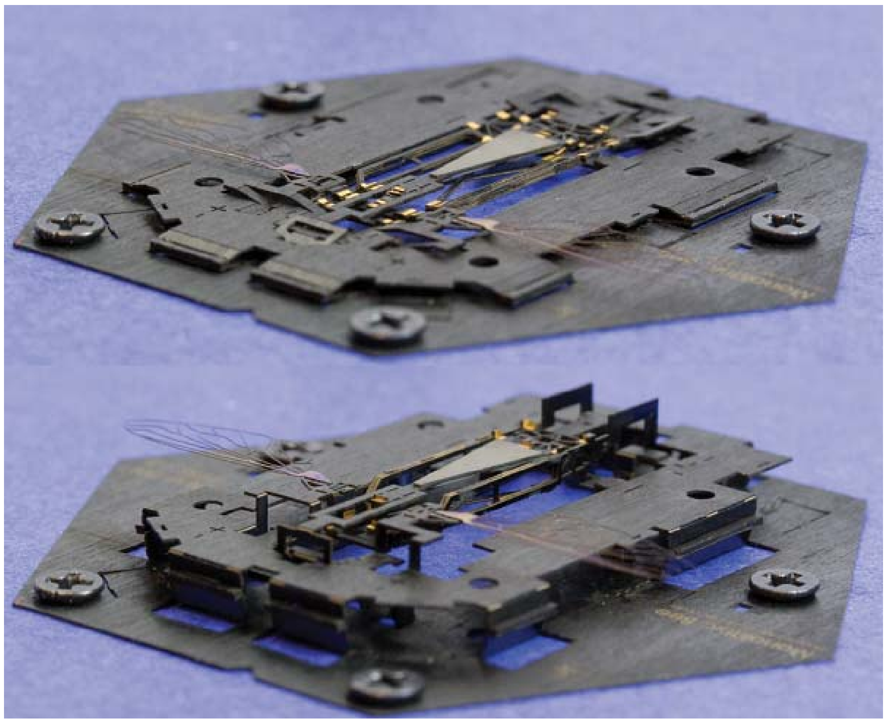
Physically…

It’s fast and inexpensive



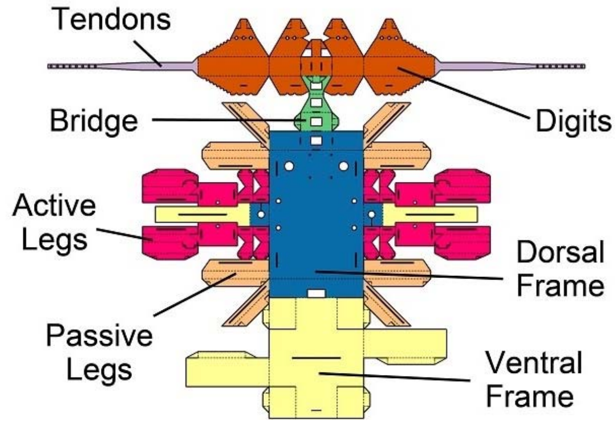
Folded Fabrication

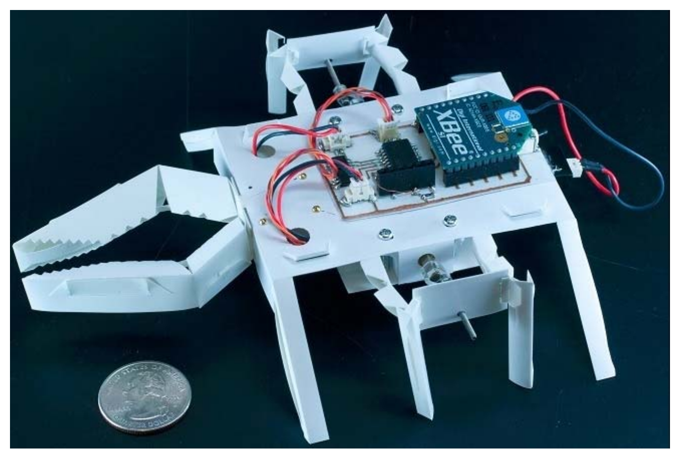
Pop-up Book MEMS



Sreetharan *et al. JMM* 2012

Printable Machines



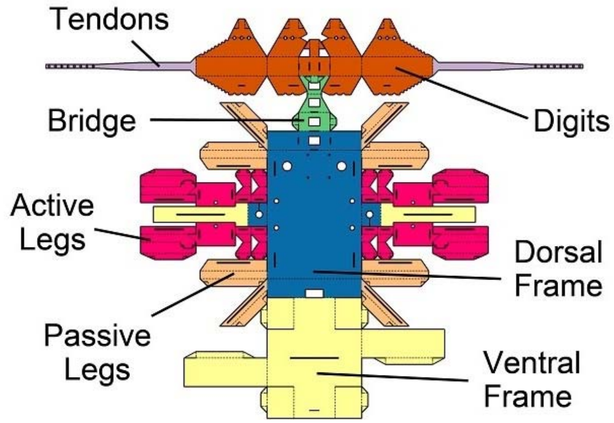


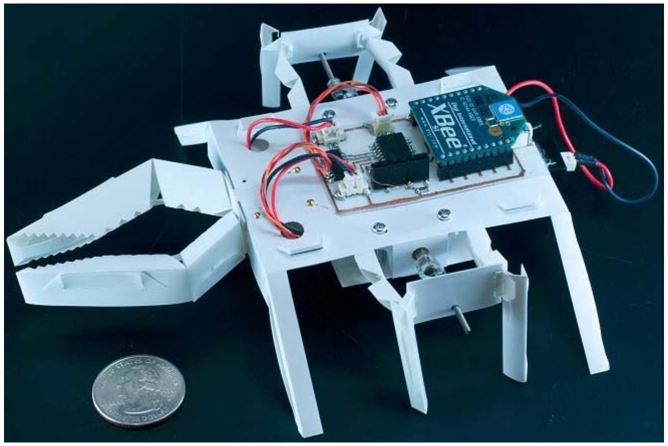
Onal *et al. IEEE Trans Mech* 2015

Folded Fabrication

Printable Machines

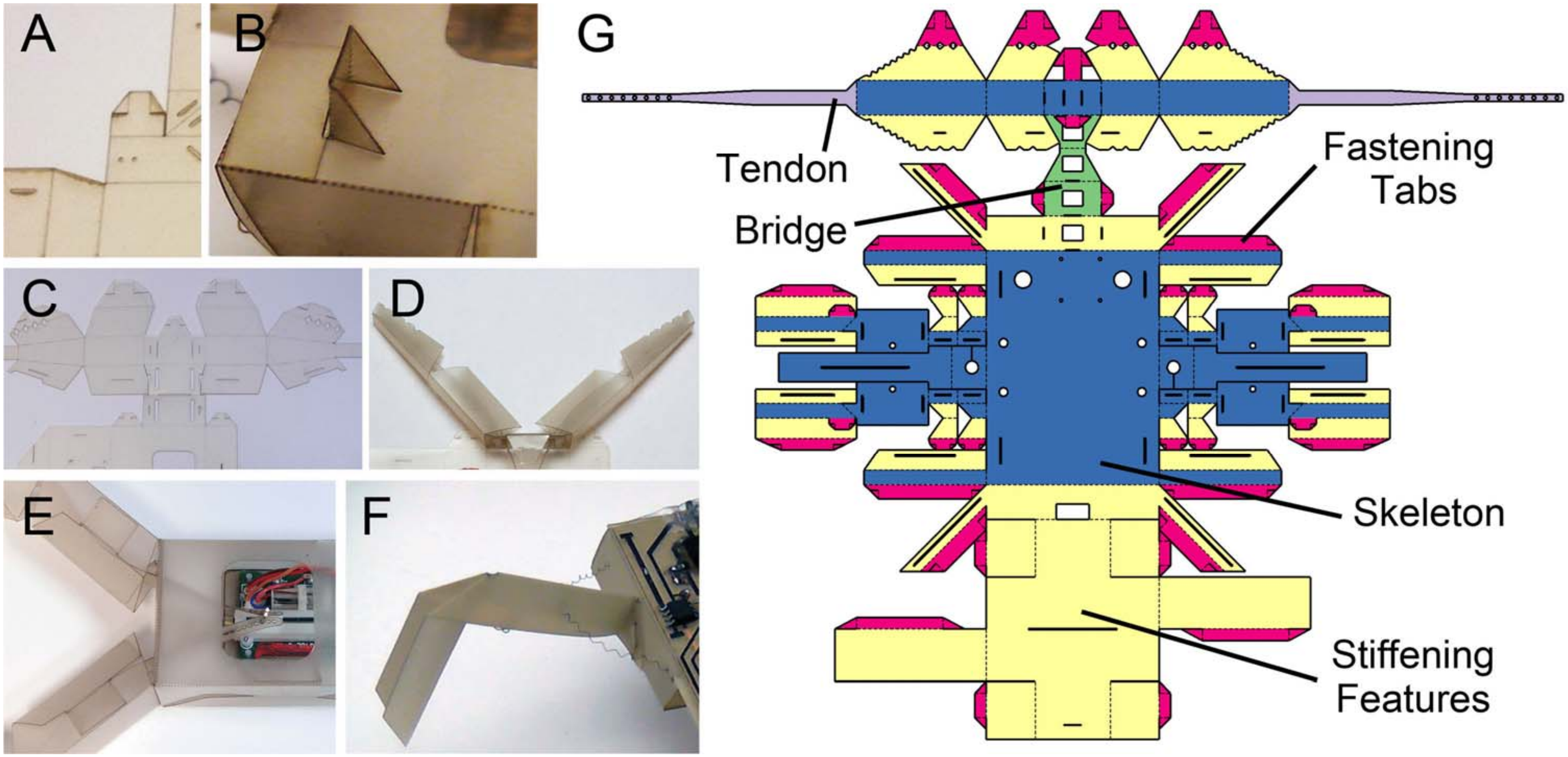
Rapidly built from **digital** blueprints with **minimal cost** and equipment





Onal *et al. IEEE Trans Mech* 2015

Origami-Style Robot Features



Onal *et al. IEEE Trans Mech* 2015

Folded Fabrication

Origami-inspired printed robots

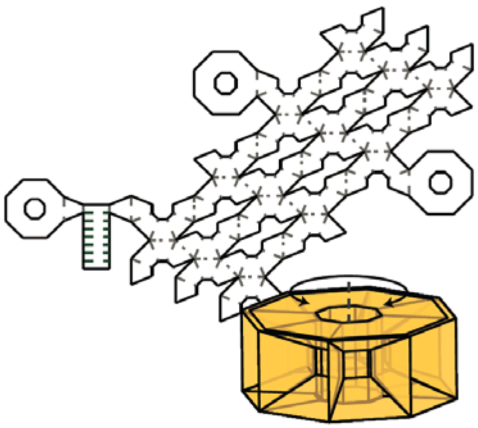
Cagdas D. Onal, Michael T. Tolley, Robert J. Wood,
Daniela Rus

Supplemental Video S2

Onal *et al. IEEE Trans Mech* 2015

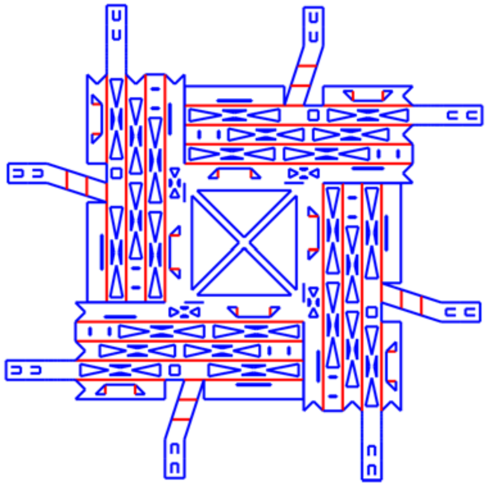
Folded Design

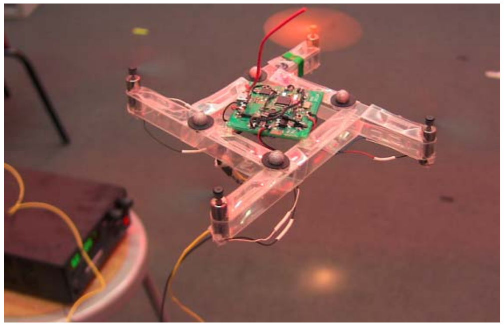
Mechanisms



Sung *et al.*, *JMR* 2015

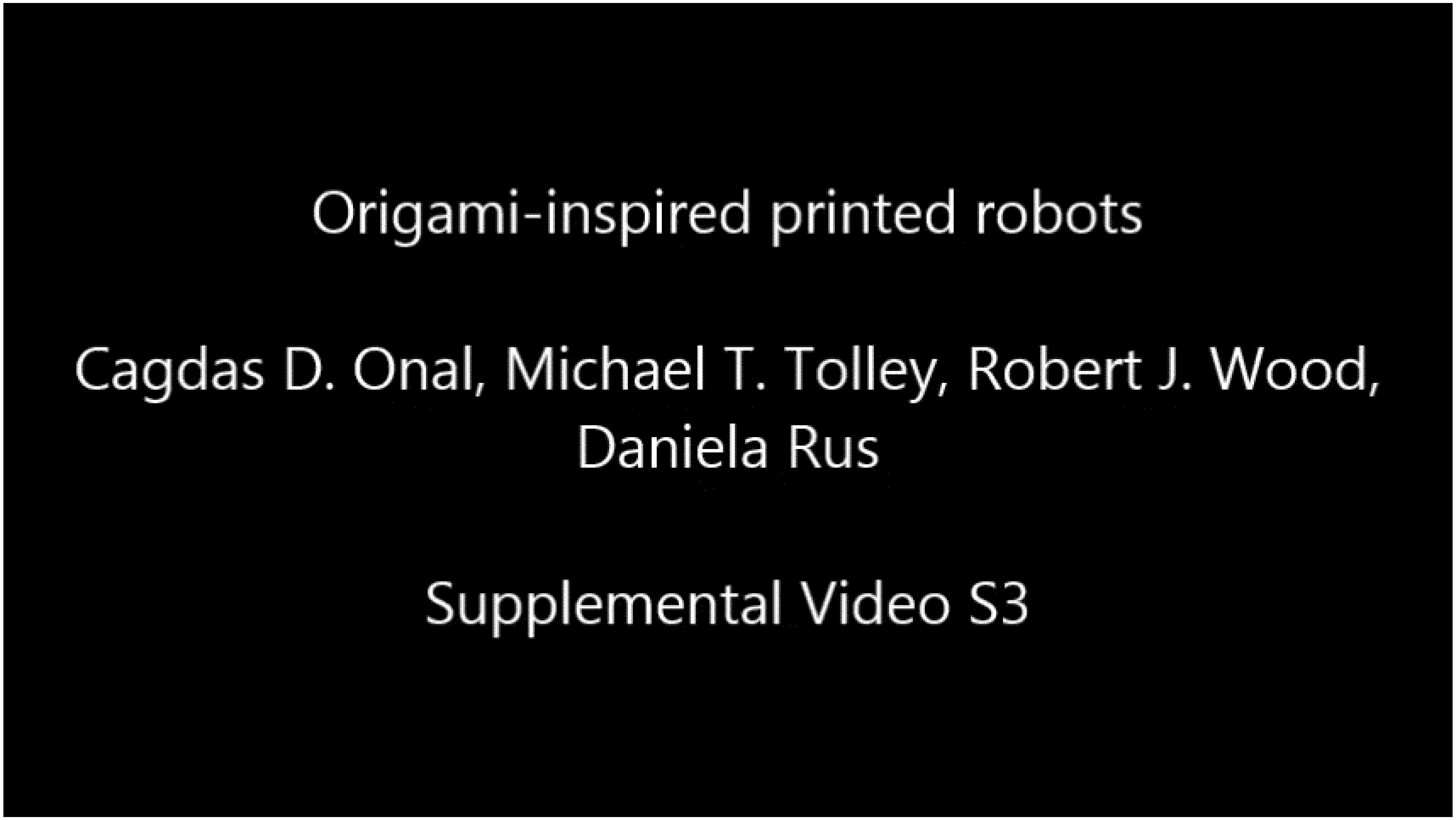
Machines





Mehta *et al.*, *ISRR* 2013

Folded Fabrication

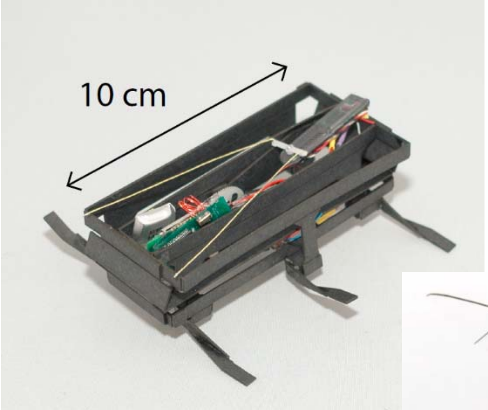


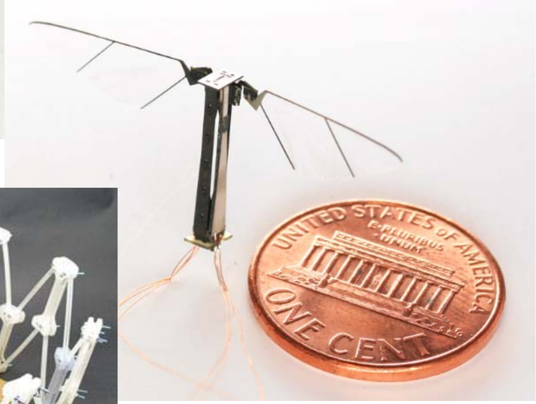
Onal *et al. IEEE Trans Mech* 2015

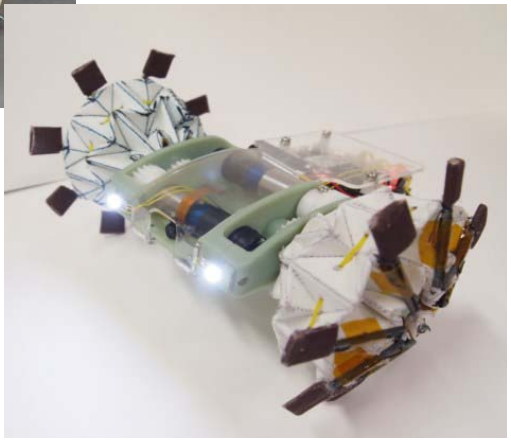
Multi-Layered Folded Machines

Advantages

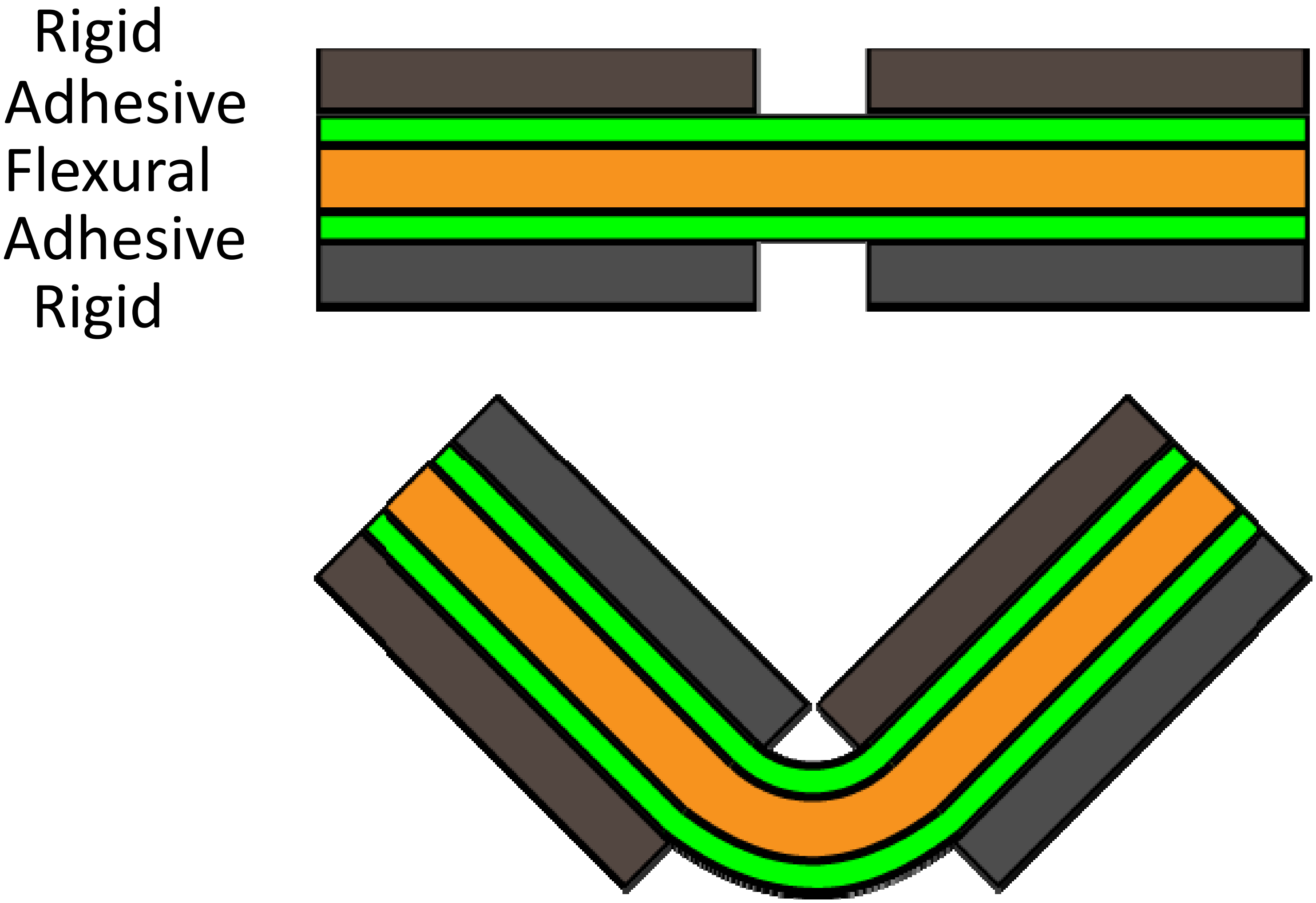
- Tailored mechanical properties
- Better hinge behavior
- Asymmetric behavior
- Additional functional properties
- Multi-layer fold patterns





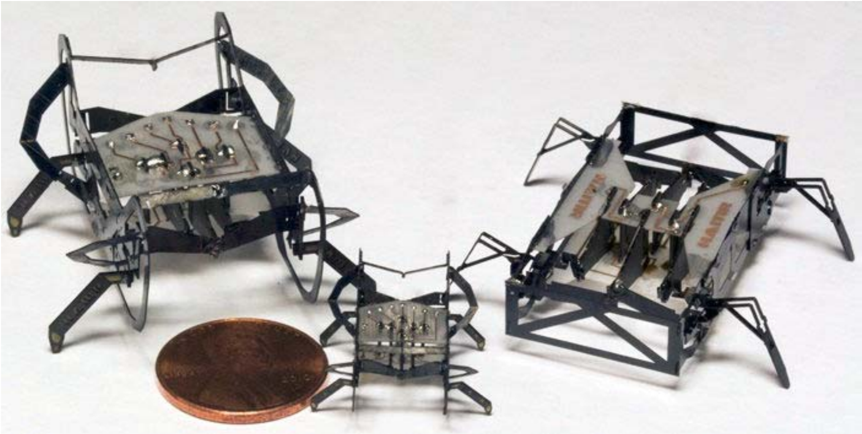


Common Design

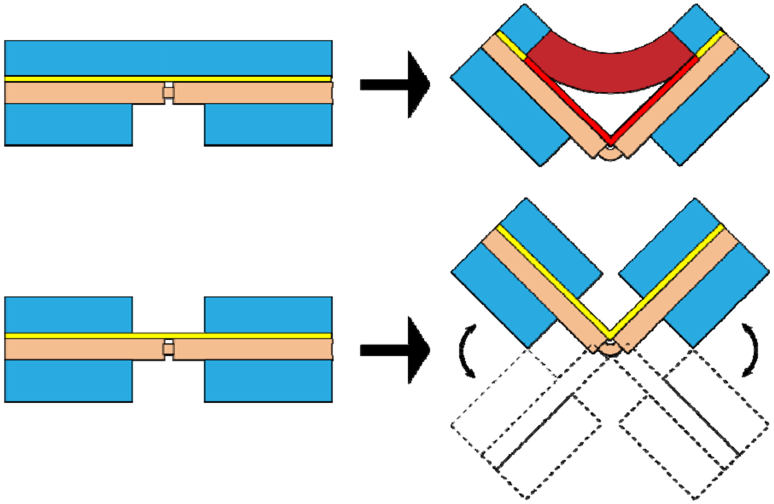


Alternative Layers

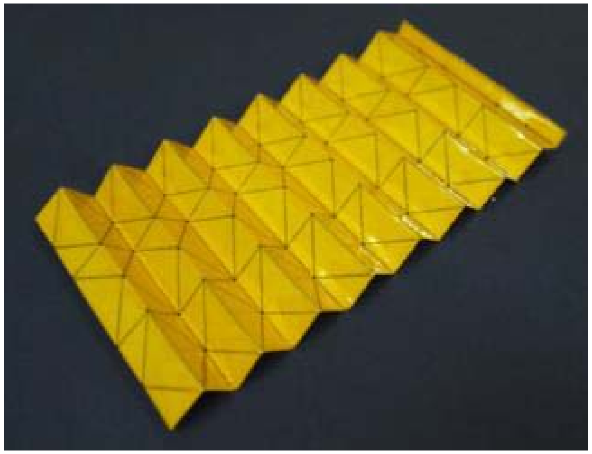
Flexible Circuit Boards

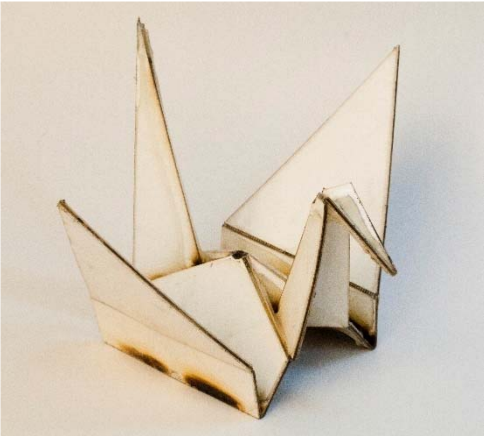


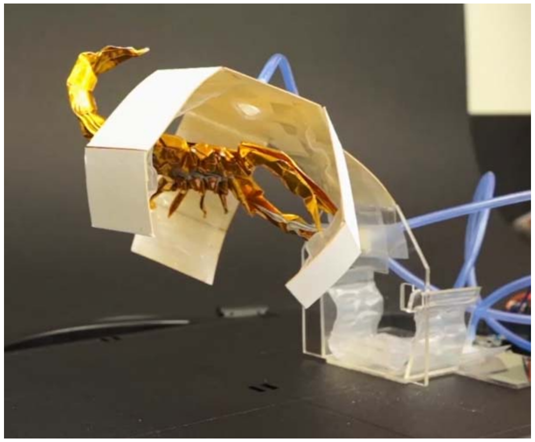
Active Materials



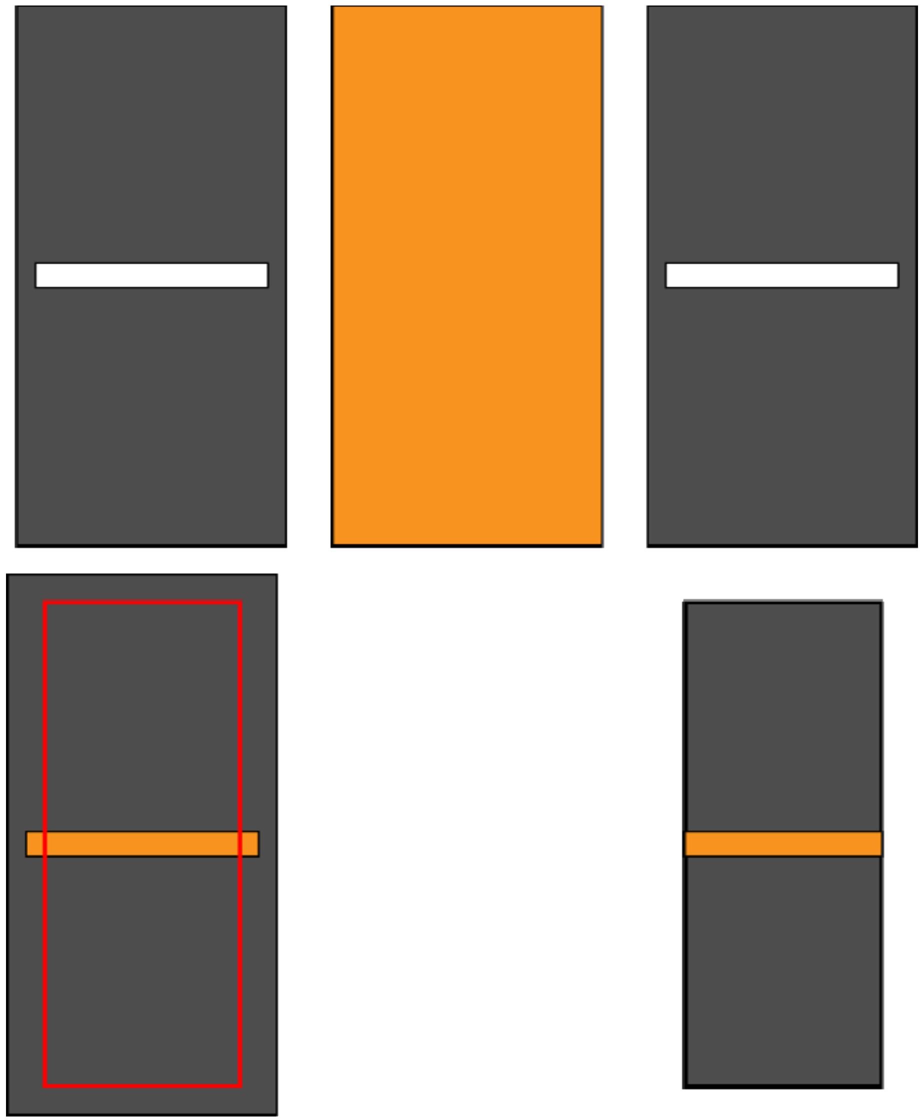
Inelastic Materials







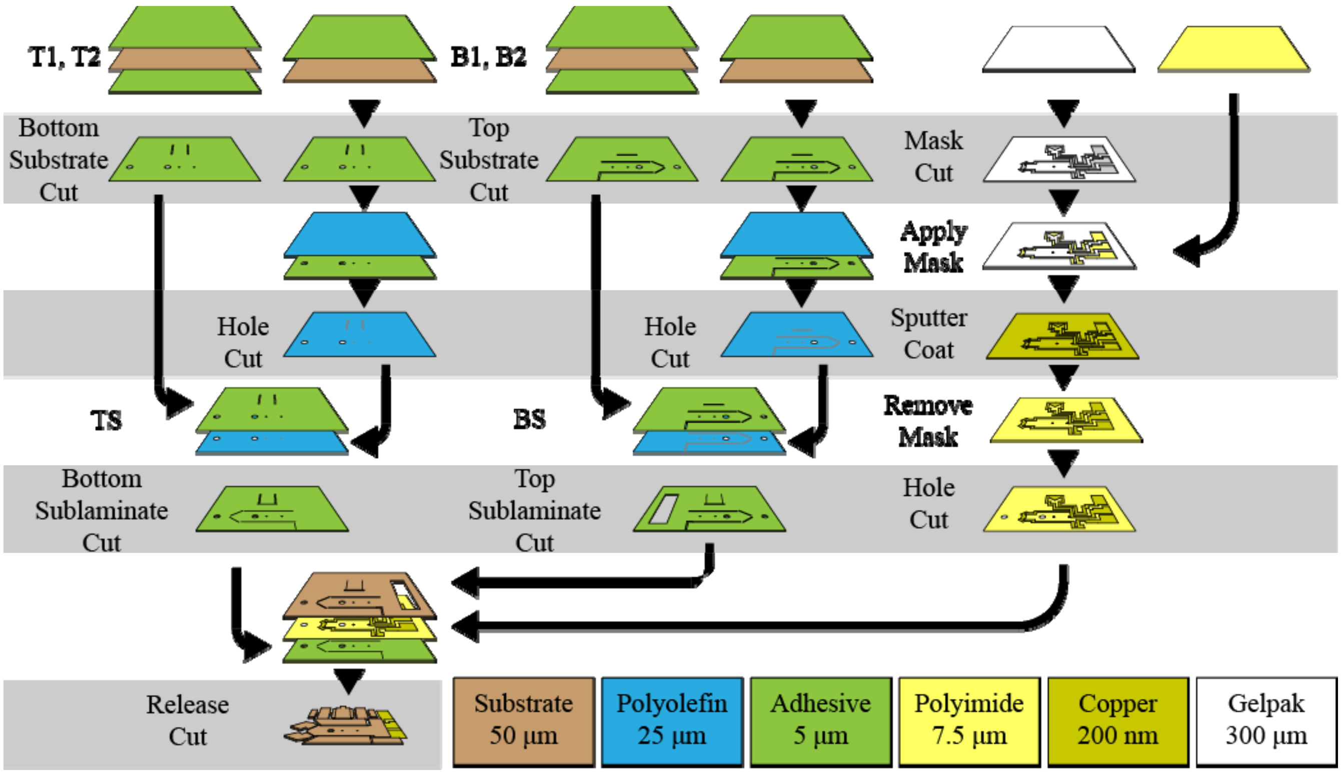
Discontinuous Layers



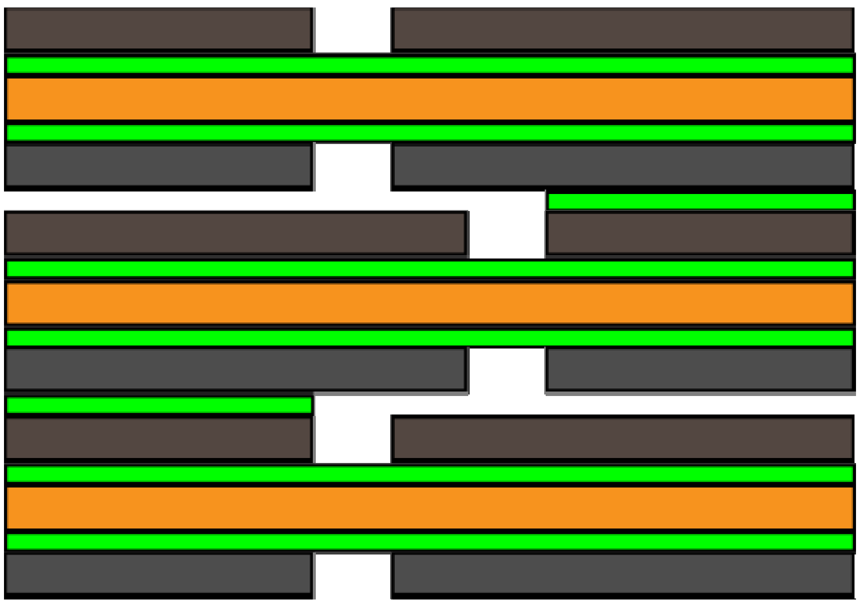
Fabrication Process

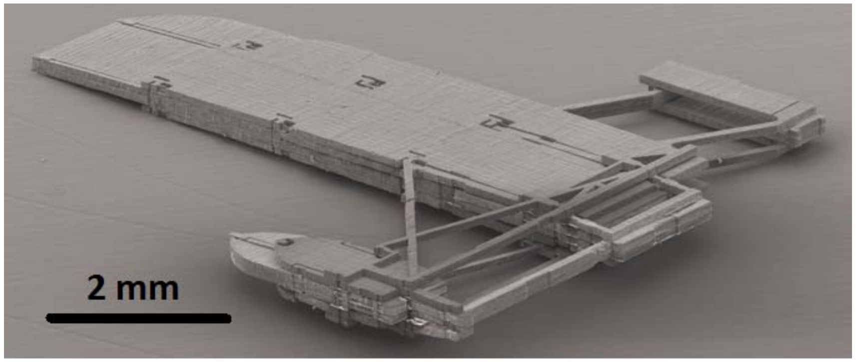
Layer Machining

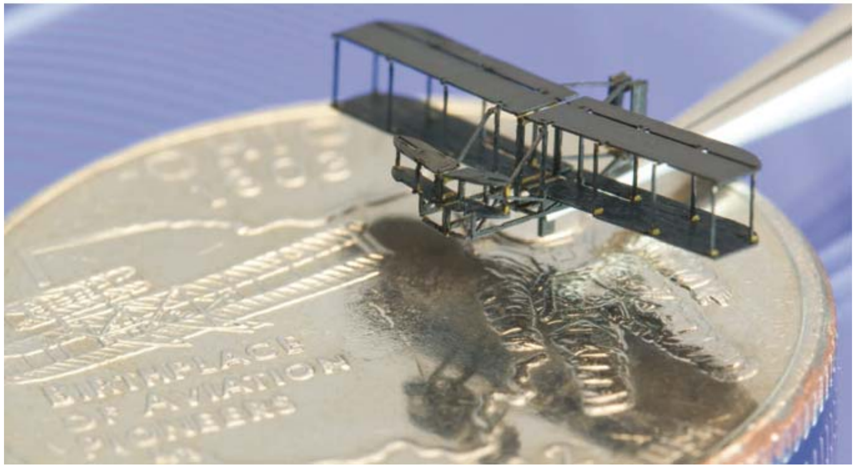
Layer Bonding



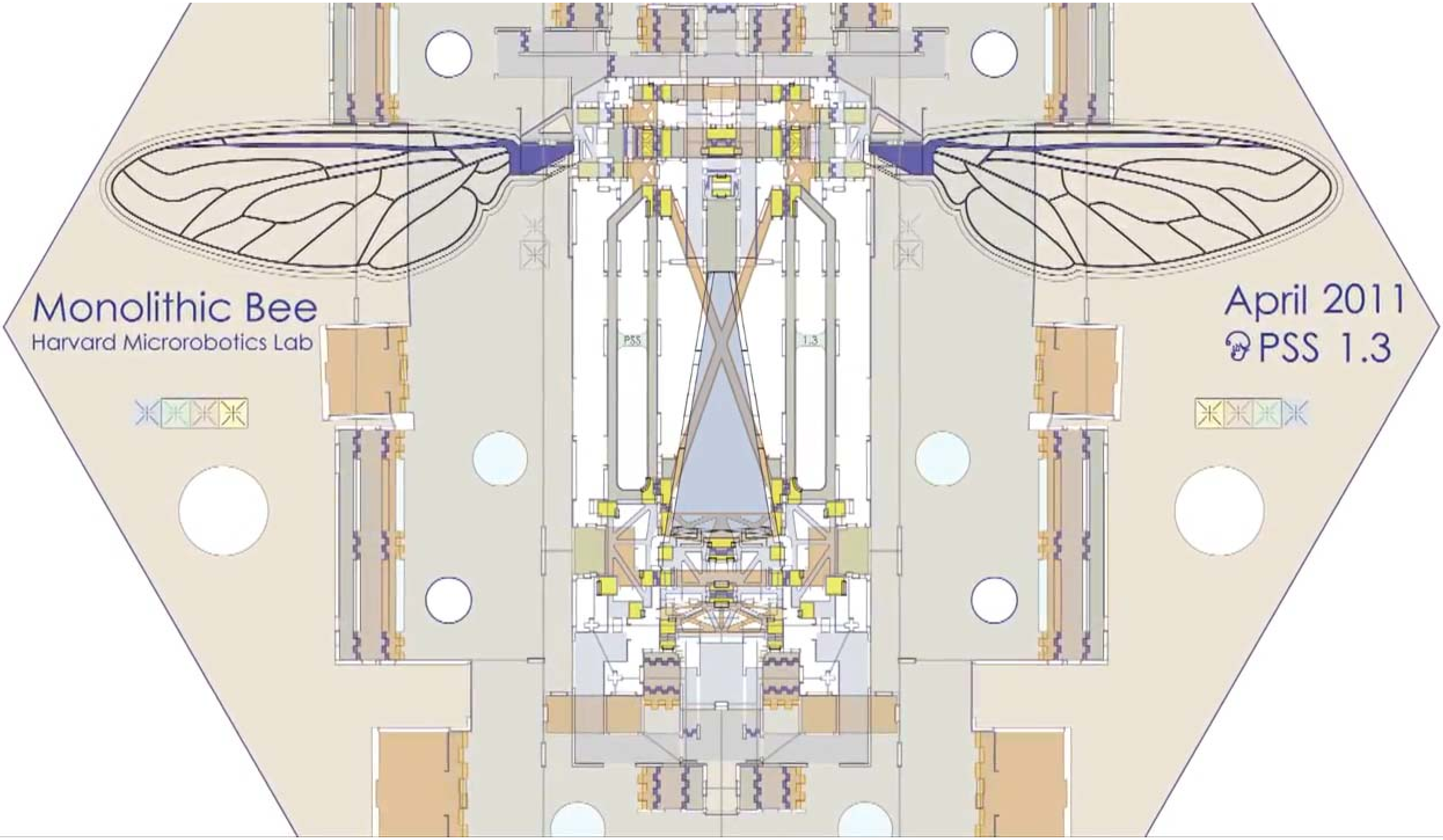
Pop-Up Folding







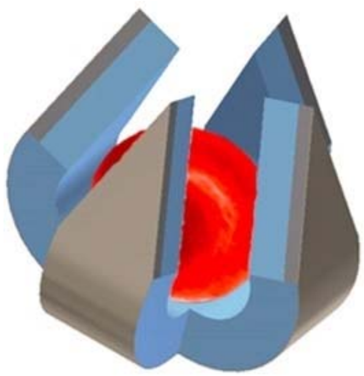
Pop-Up Book MEMS

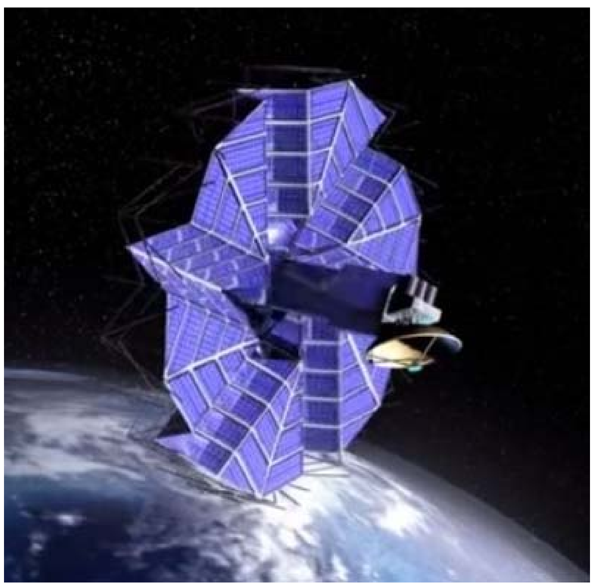


Self-Assembly through Folding

Autonomous Assembly

Malachowski *et al.*, *Nano* 2014



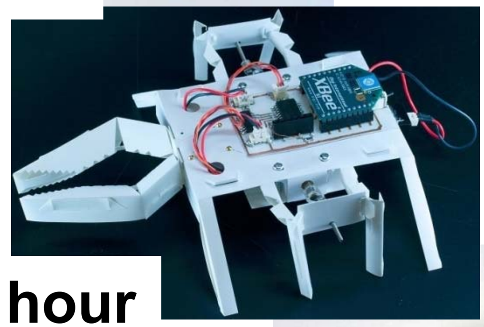


Zirbel *et al.*, *J Mech Des* 2013

Fast, Parallel Assembly

3D printing

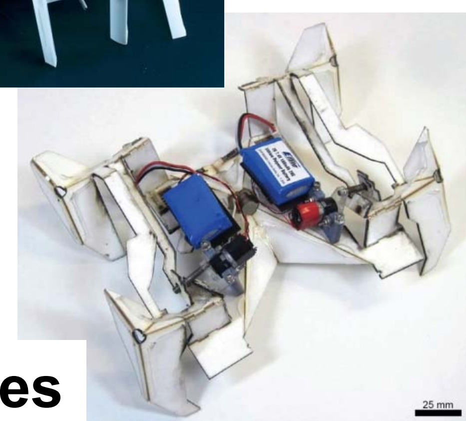
5 hours



Hand folded

1 hour

Onal *et al.* *IEEE Trans Mech* 2015



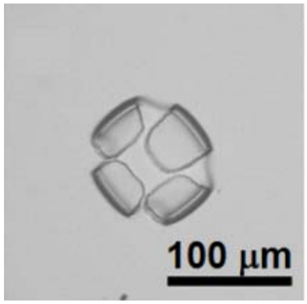
Self-folded

5 minutes

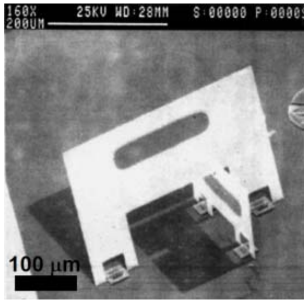
Felton et al., *Science* 2014

Prior Self-Folding

Hydrogel Swelling
Guan et al. 2005

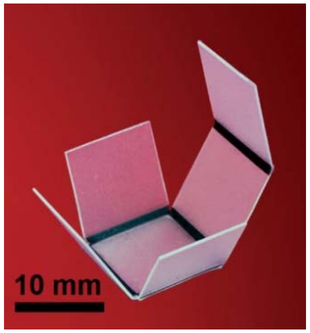


Magnetic Field
Yi et al. 1999



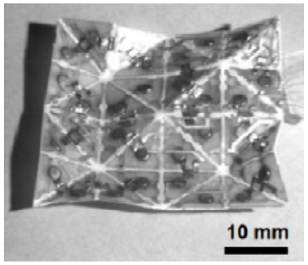
Prestressed Layers
Laflin et al. 2012

Shape Memory Polymers
Liu et al. 2012



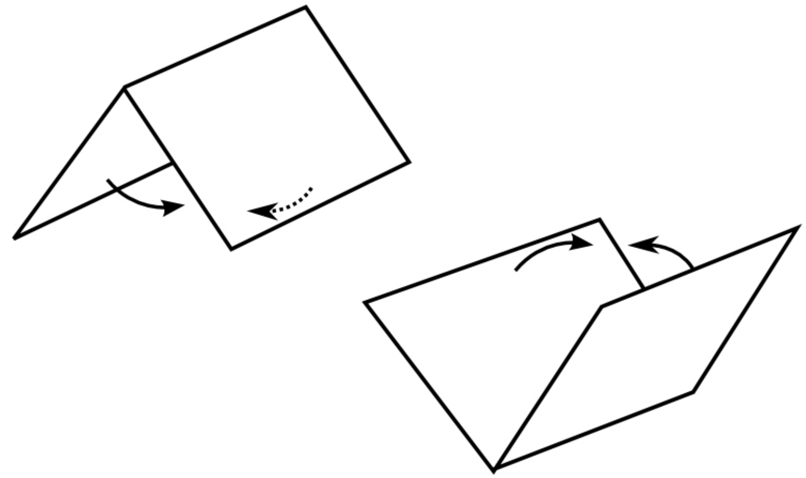
Capillary Forces
Antkowiak et al. 2012

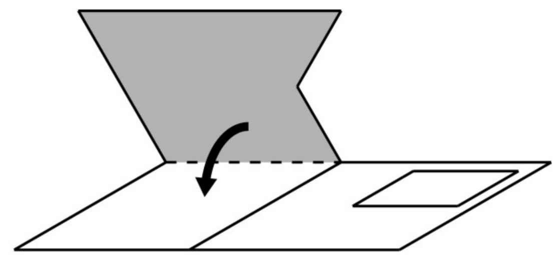
Shape Memory Alloys
Hawkes et al. 2010

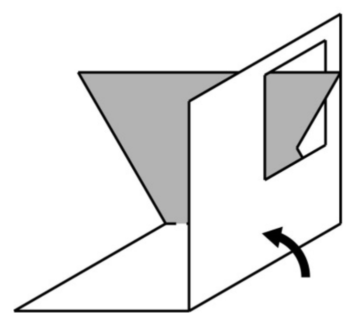


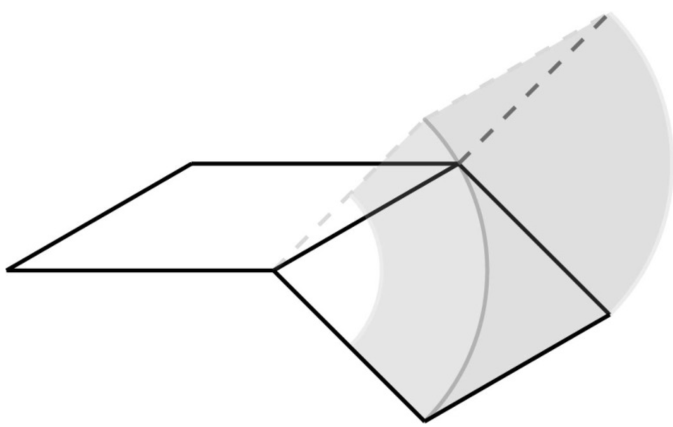
Robotic Self-Folding

1. Bidirectional Folds
2. Sequential Folding
3. Angular Control
4. Flexural Hinges
5. Centimeter Scale



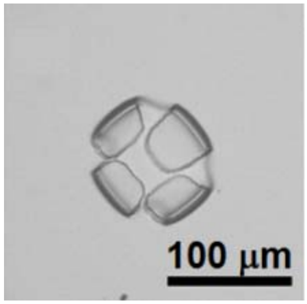




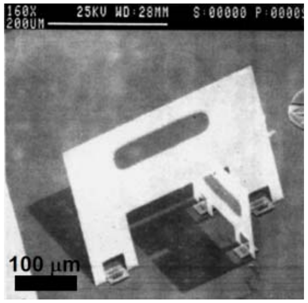


Prior Self-Folding

Hydrogel Swelling
Guan et al. 2005

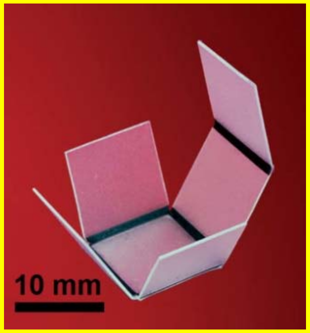


Magnetic Field
Yi et al. 1999



Prestressed Layers
Laflin et al. 2012

Shape Memory Polymers
Liu et al. 2012



Capillary Forces
Antkowiak et al. 2012

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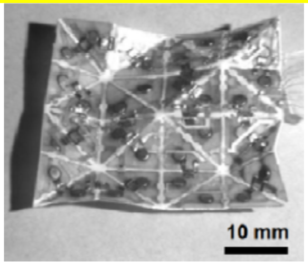
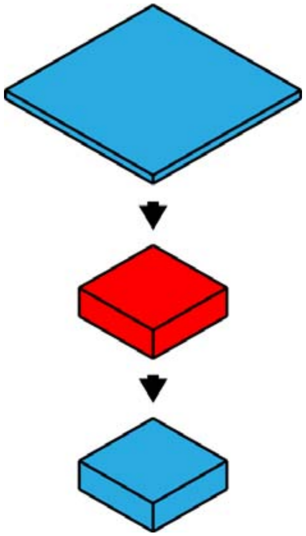
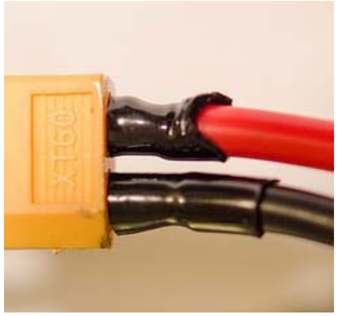
Hawkes et al. 2010



Shape Memory Polymers

Mechanically programmed **shape change triggered** by environmental stimulus like **heat.**

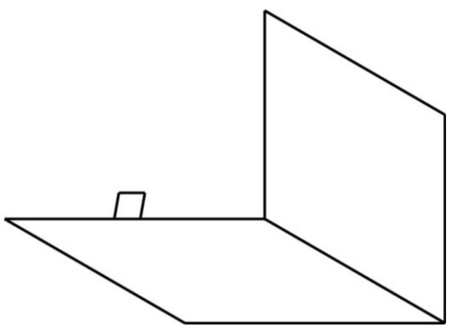




Self-Folding Parameters

Size

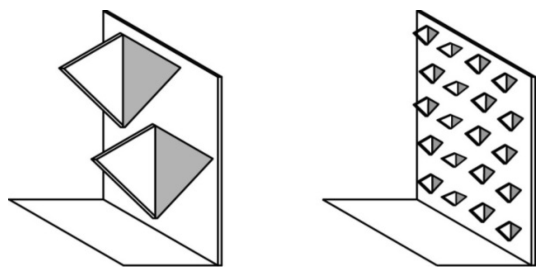
Maximum length governed by **torque**



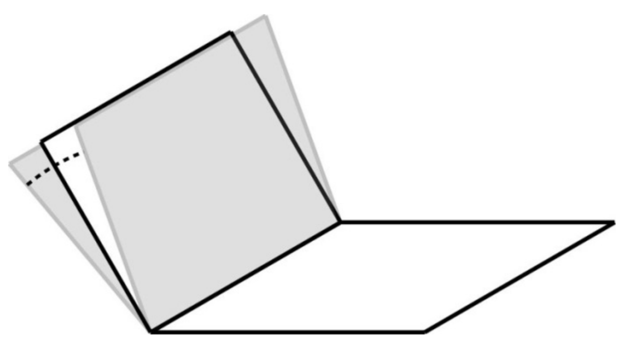
Minimum length governed by **materials**

Complexity

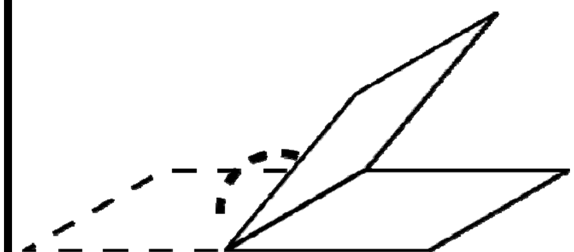
$$Complexity \propto \frac{Max\ Size}{Min\ Size}$$



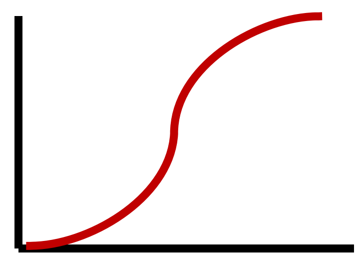
Precision



Max Angle



Speed

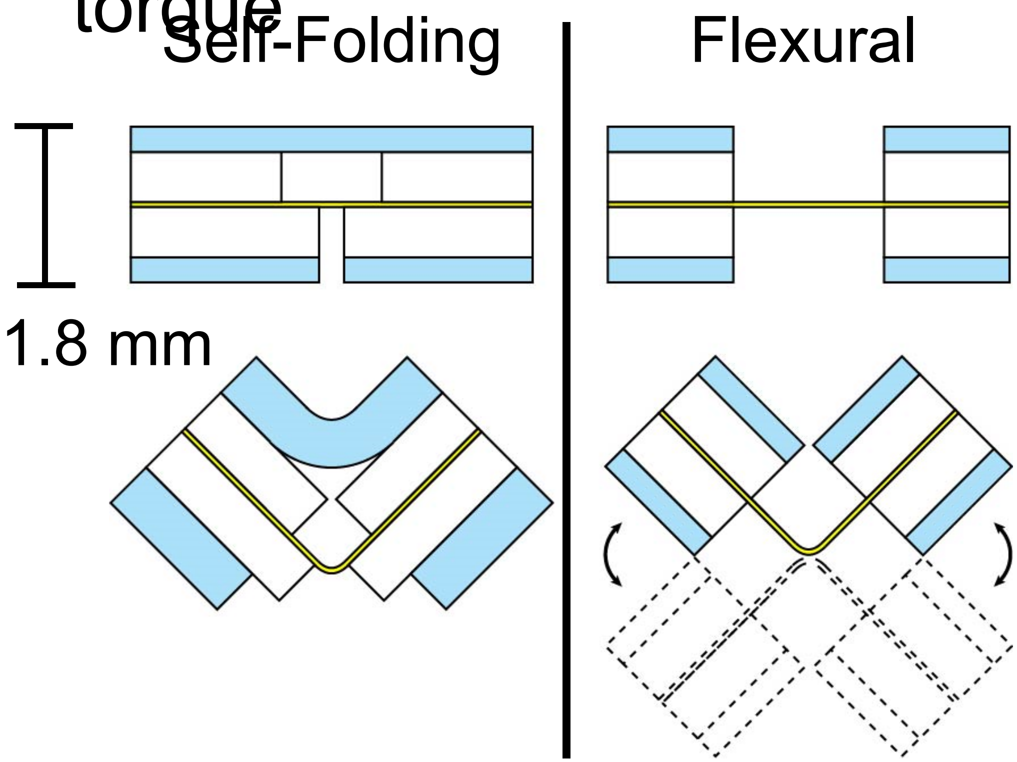


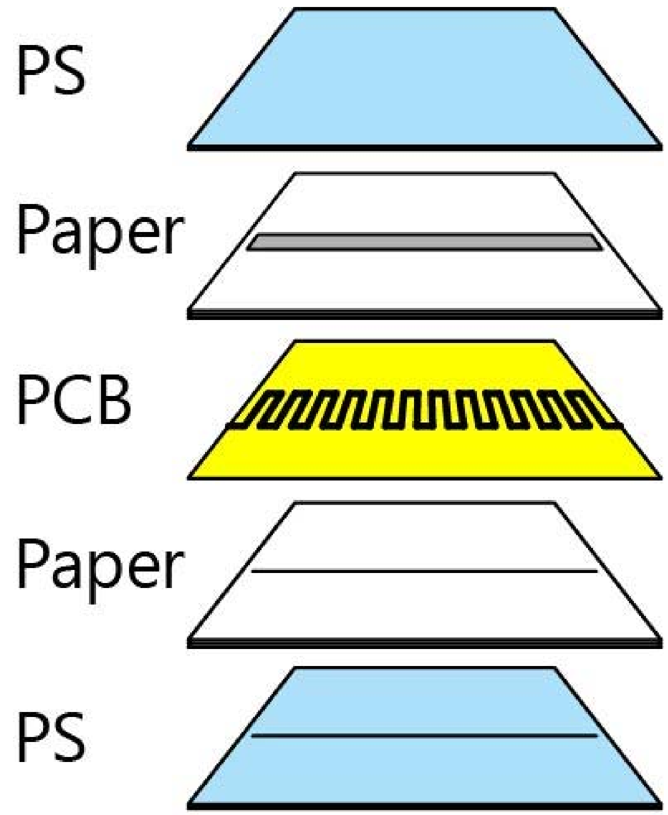
Improved Composite

Stiffer

Symmetric

Raised SMP increases torque

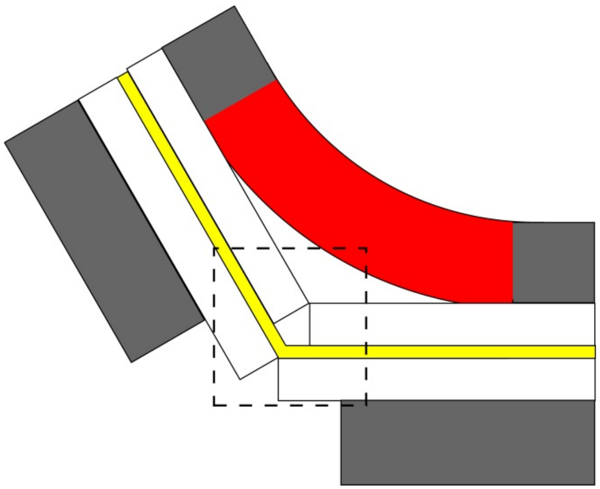




Felton *et al.*, *Soft Matter* 2013

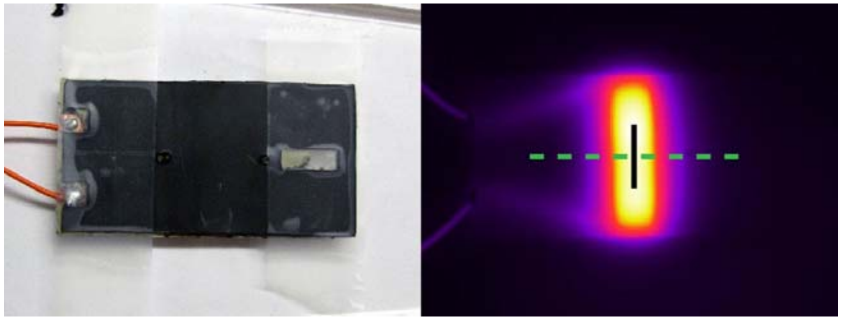
Design Rules through Models

fold angle



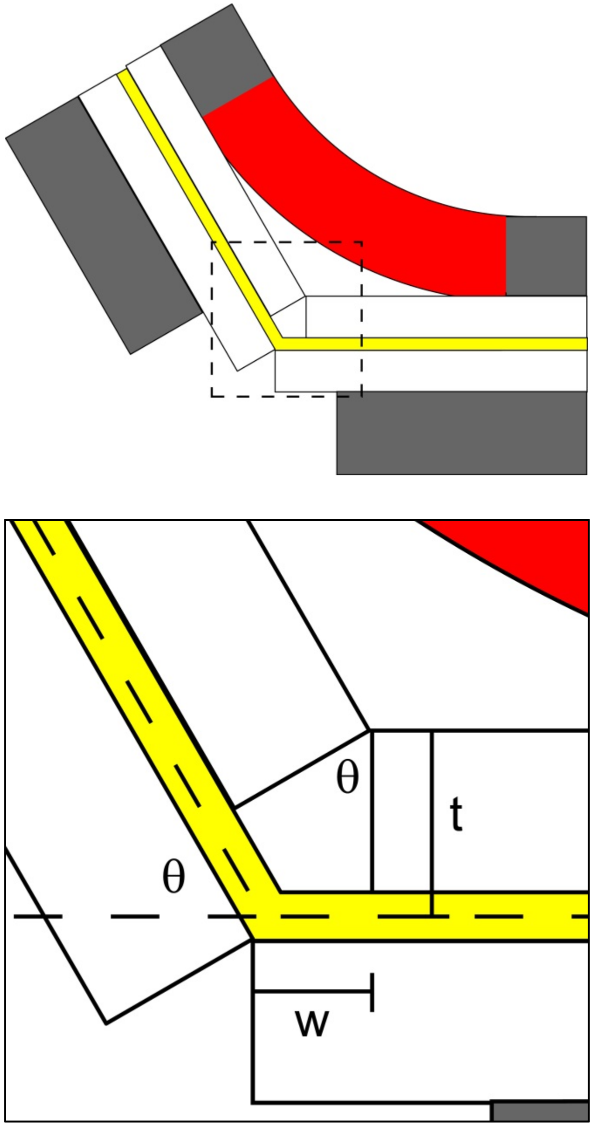
- Accuracy
- Precision
- Max angle

thermo-mechanical model

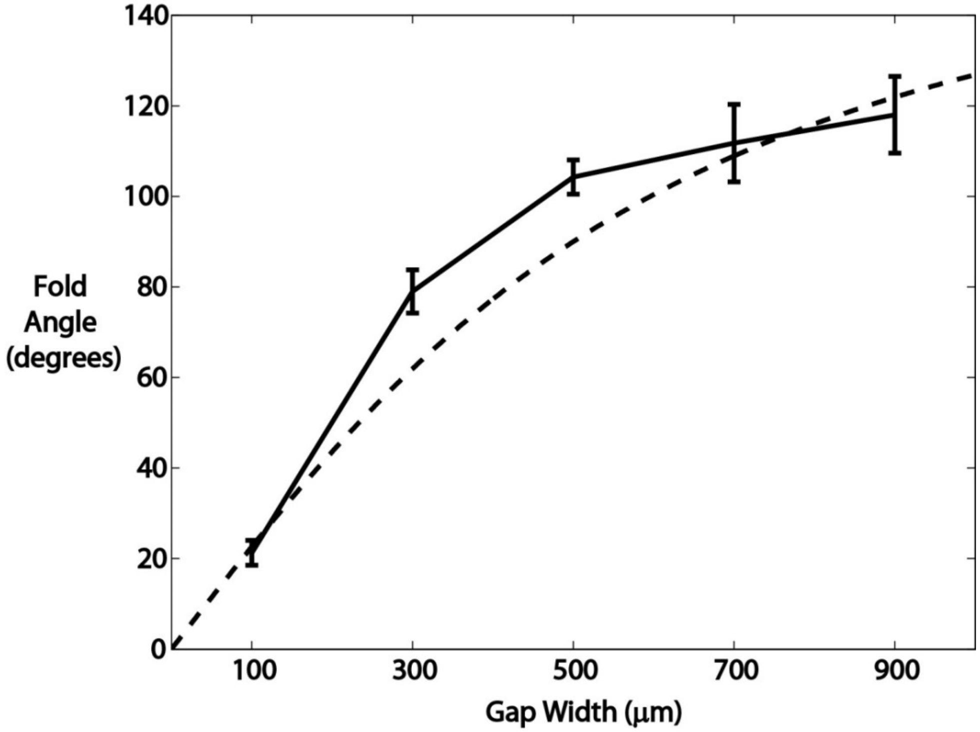


- Hinge torque
- Fold time

Model: Fold Angle



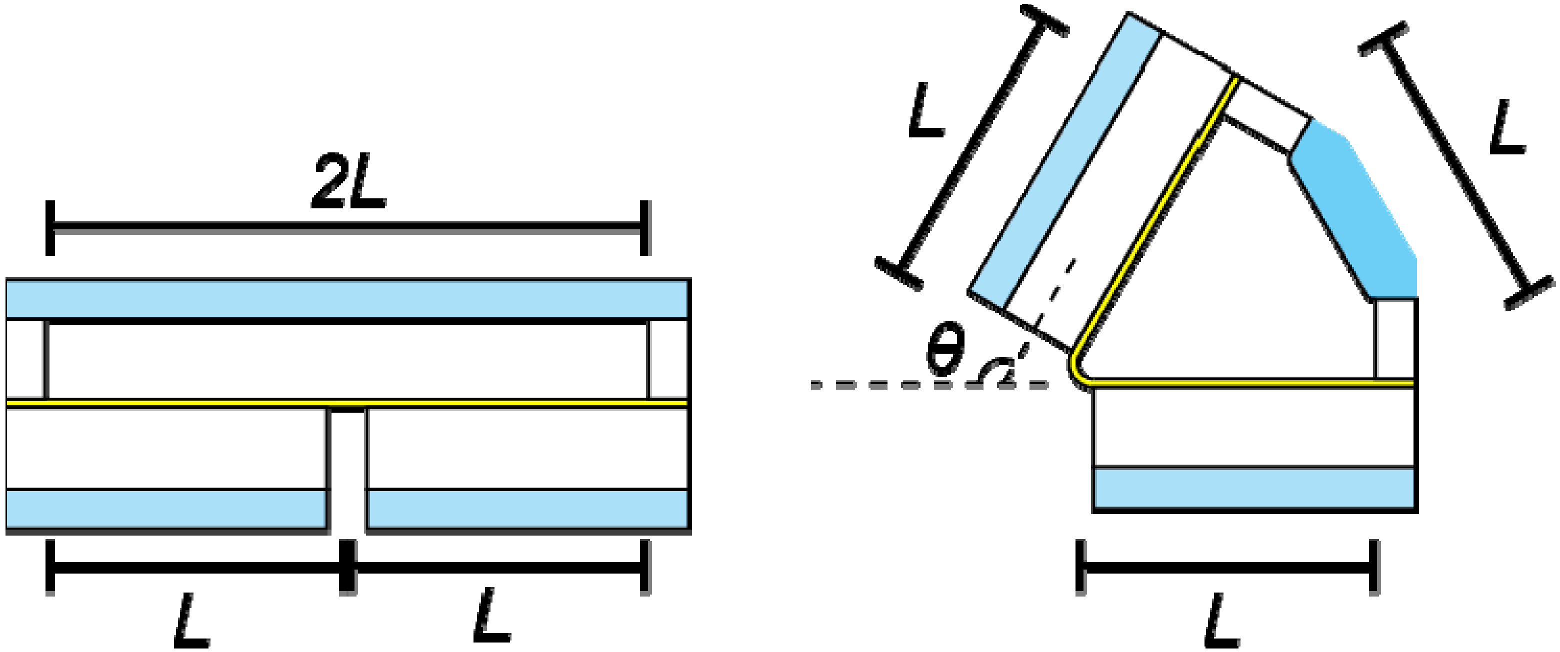
$$\theta = 2arctan\left(\frac{w}{t}\right)$$



Precision ≈ 5°-8°

Felton *et al.*, *Science* 2014

Model: Max Angle



$$\theta = 2\cos^{-1}(C)$$

Felton *et al.*, *Soft Matter* 2013

Model: A Quasistatic Approach

Hinge Characteristics:
SMP thickness
Trace width
Current

Thermal Model

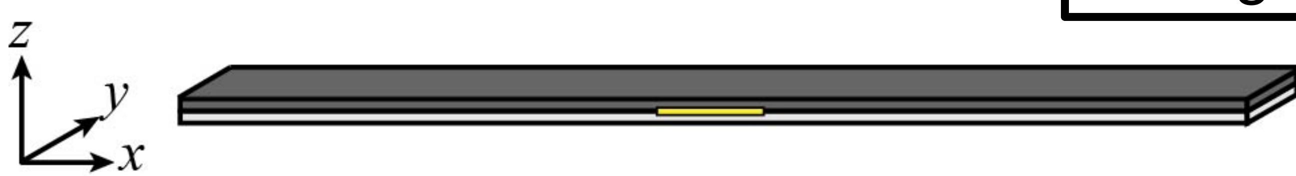
Temperature Profile

SMP Model

SMP Behavior:
Strain
Stress

**Mechanica
l Model**

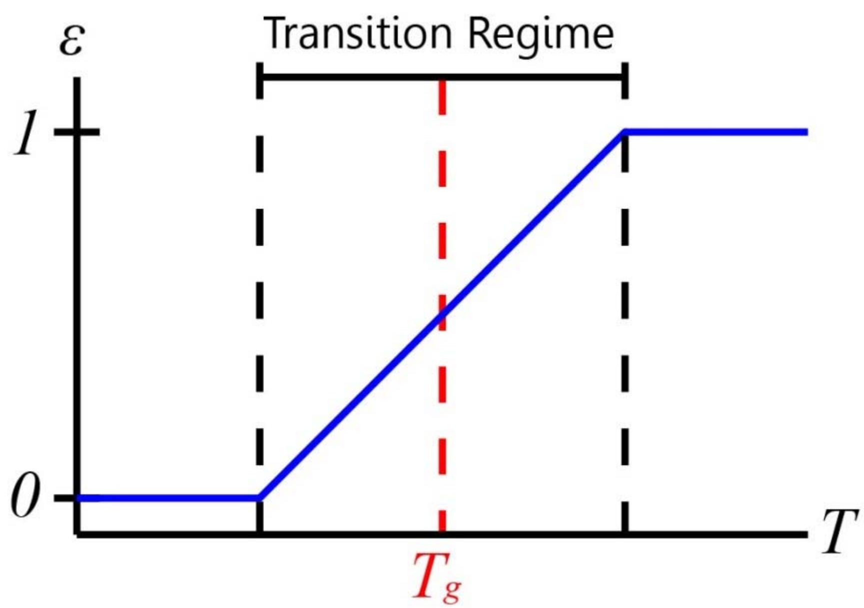
Hinge Torque



Felton *et al.*, *Soft Matter* 2013

Model: Material Properties

Strain



Based on:

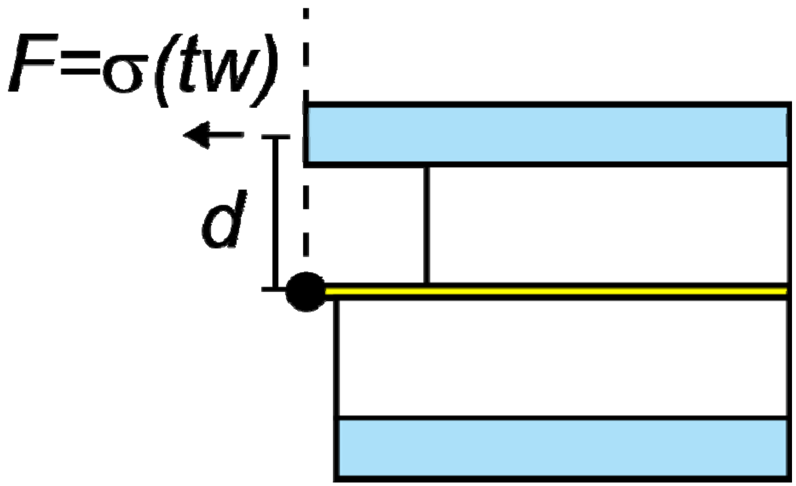
Thermomechanical Constitutive Model of Shape Memory Polymer, Tobushi et al. 2001

Stress

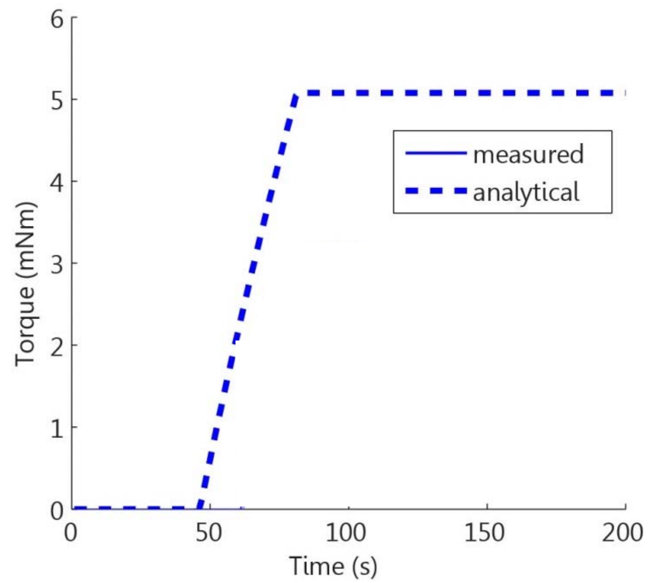
$$\sigma = \begin{cases} 0 & T \le T_g - T_r \\ \sigma_c \left(\dfrac{T - T_g + T_r}{2T_r} \right) & T_g - T_r \le T \le T_g + T_r \\ \sigma_c & T \ge T_g + T_r \end{cases}$$

Felton *et al.*, *Soft Matter* 2013

Model: Hinge Torque



$$\tau_s \propto \sigma w t d$$

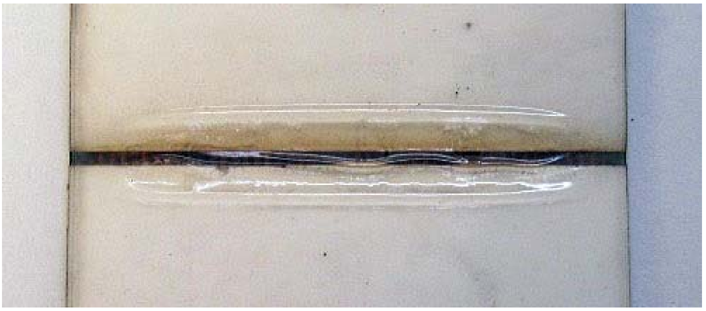


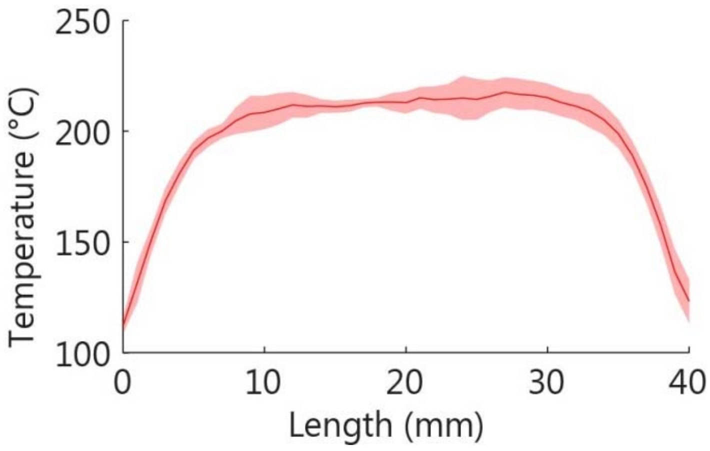
$$\tau_{mod} = 5\ mNm$$

Hinge Torque

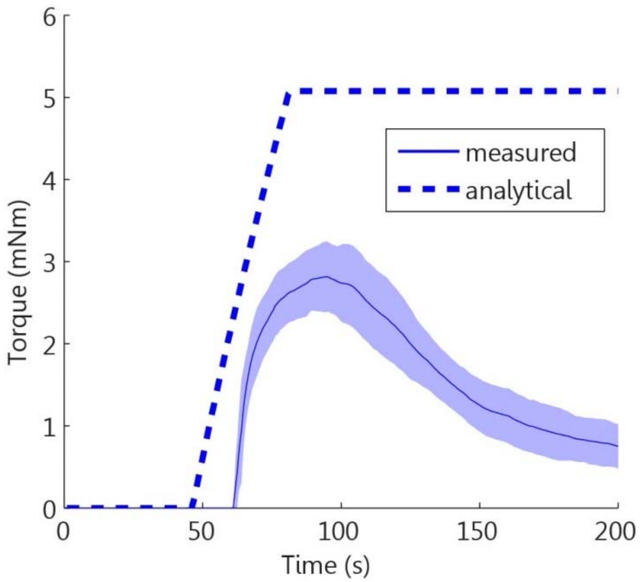
Model: Hinge Torque

Polystyrene: viscoelastic





Temperature Profile



$$\tau_{mod} = 2.8\ mNm$$

Hinge Torque

Felton *et al.*, *Soft Matter* 2013

Feature Size

Max Face Length:

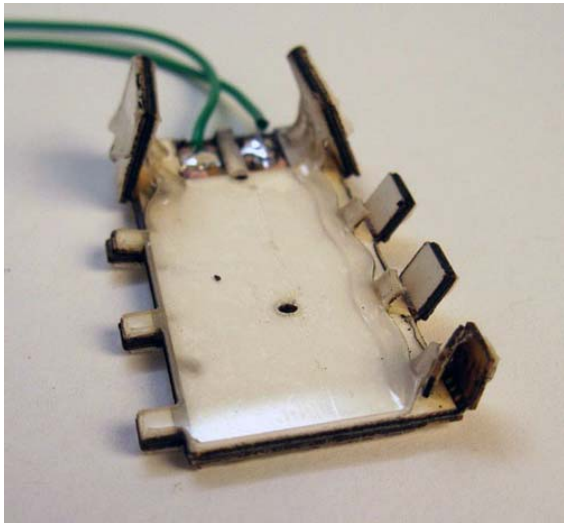
$$\tau_s = \tau_g = g\rho_A W \frac{L^2}{2}$$

$$L_{max} = 97 \text{ mm}$$

Effective range of feature sizes:

10 mm – 100 mm

Min Face Length:

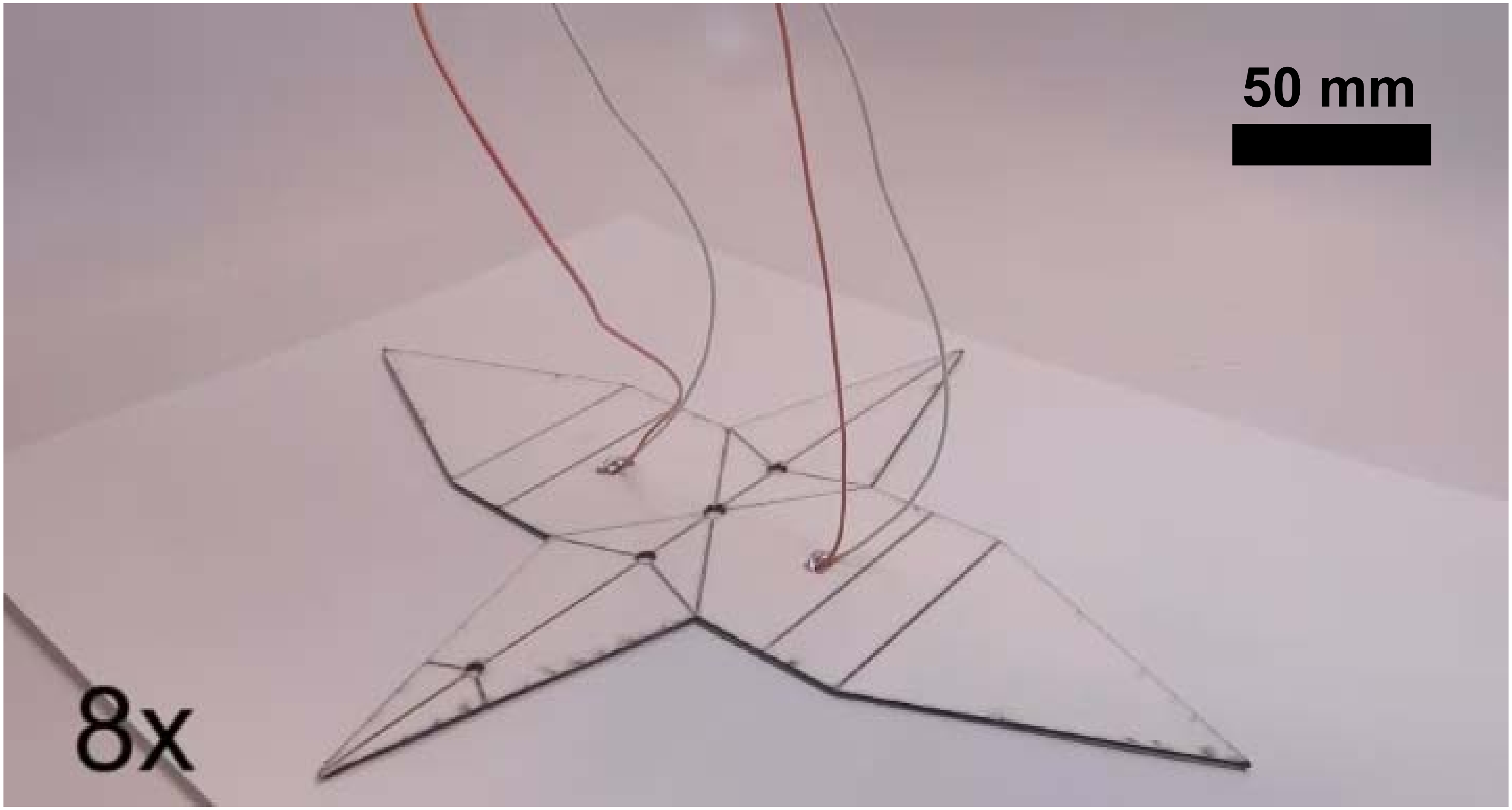


10 mm: Minimum size

5 mm: folded, then delaminated

3 mm: failed to activate

Example – Crane



Felton *et al.*, *Soft Matter* 2013

Design Rules

Factors	Design rule	
Contractile stress Contractile thickness Contractile offset	**Maximum Size**	**Complexity**
Adhesion strength	**Minimum Size**	**Complexity**
Current Material properties Composite geometry	**Fold Time**	
Hinge geometry	**Fold Angle**	
Hinge geometry Contractile shrink ratio	**Max Angle**	

Self-Folding Machines

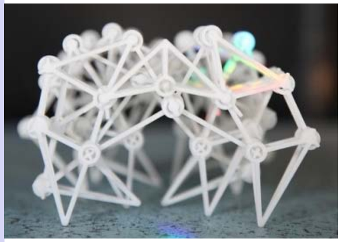
Hinge-level capabilities:

1. Controlled ✓
2. Bidirectional ✓
3. Sequential ✓
4. Dynamic ✓

Machine-level capabilities:

1. Complex geometries ☐
2. Complex mechanisms ☐
3. Autonomous folding ☐

Origamizing Polyhedral Surfaces, Tachi 2010



“Strandbeest” by Jared Tarbell

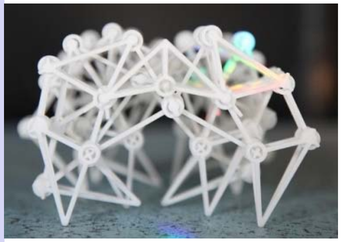
“M-TRAN” by Distributed System Design Group, Intelligent Systems Institute, AIST

Self-Folding Machines

Machine-level capabilities:

1. Complex geometries ☐
2. Complex mechanisms ☐
3. Autonomous folding ☐

Origamizing Polyhedral Surfaces, Tachi 2010



“Strandbeest” by Jared Tarbell

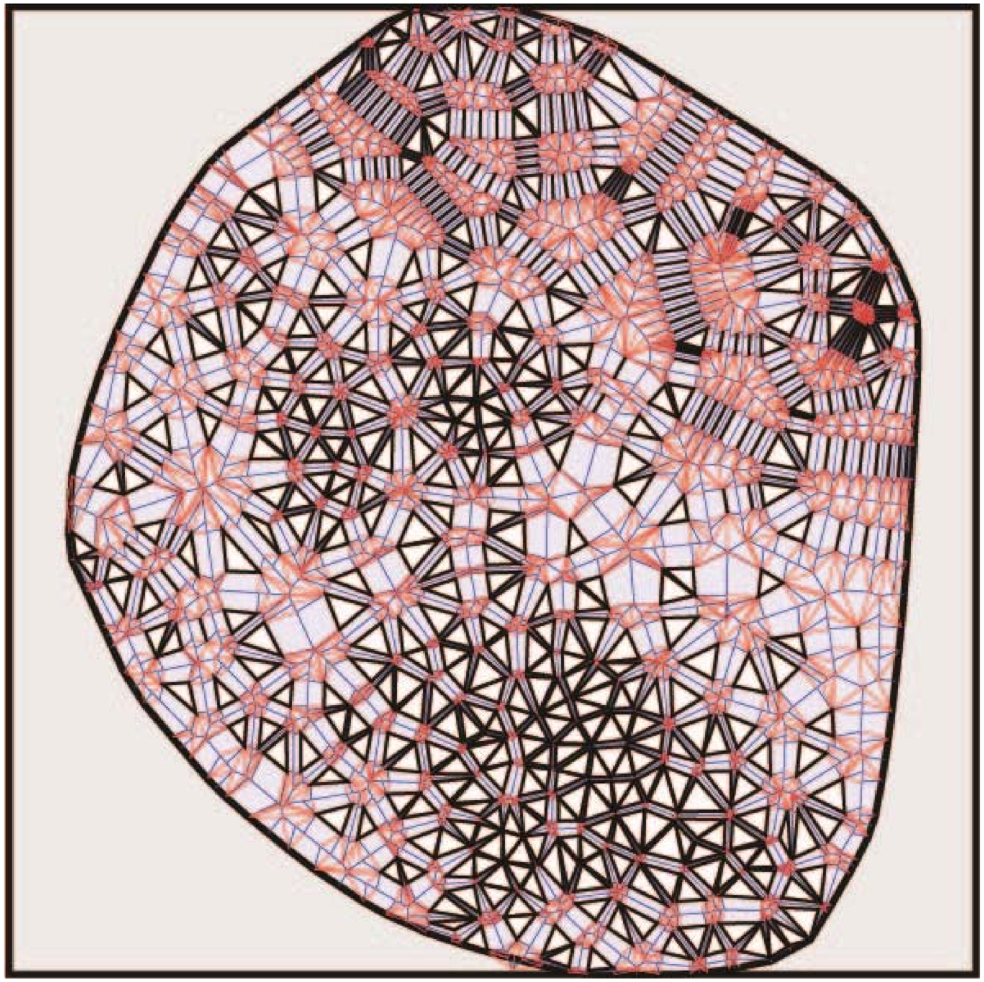
“M-TRAN” by Distributed System Design Group, Intelligent Systems Institute, AIST

Arbitrary Geometries

Requirements:

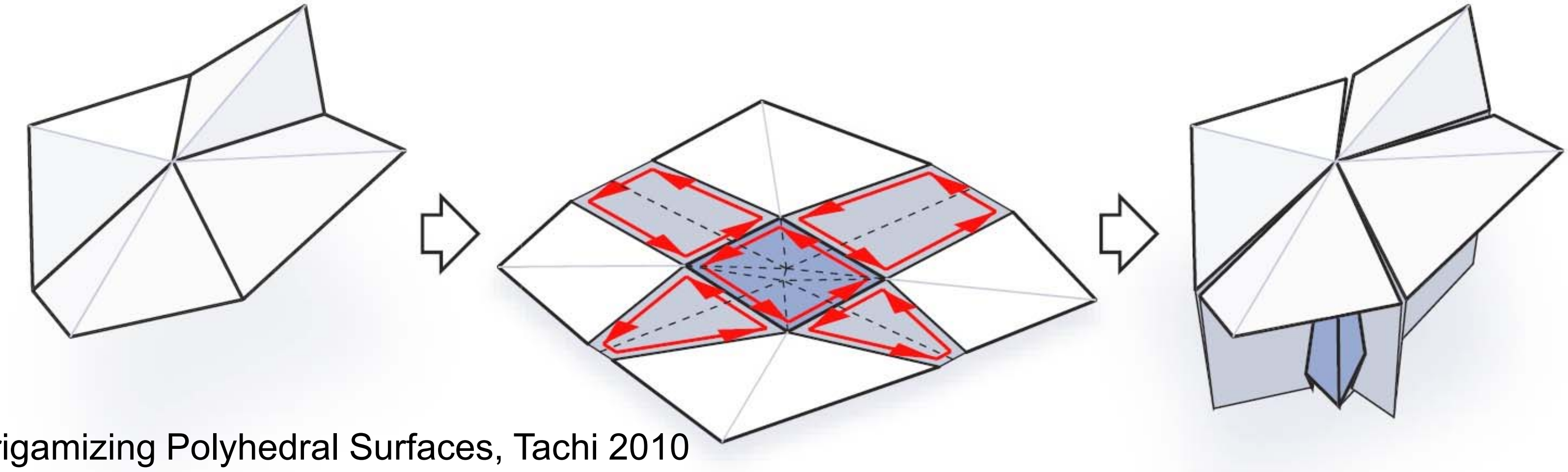
1. Controlled ☑
2. Bidirectional ☑
3. Cyclic Folds ☐

“Metal Bunny” by Tomohiro Tachi

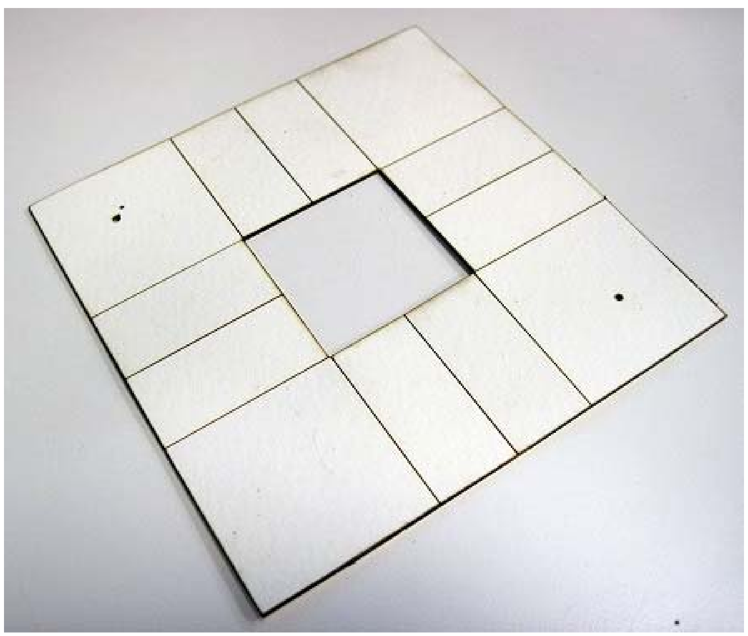


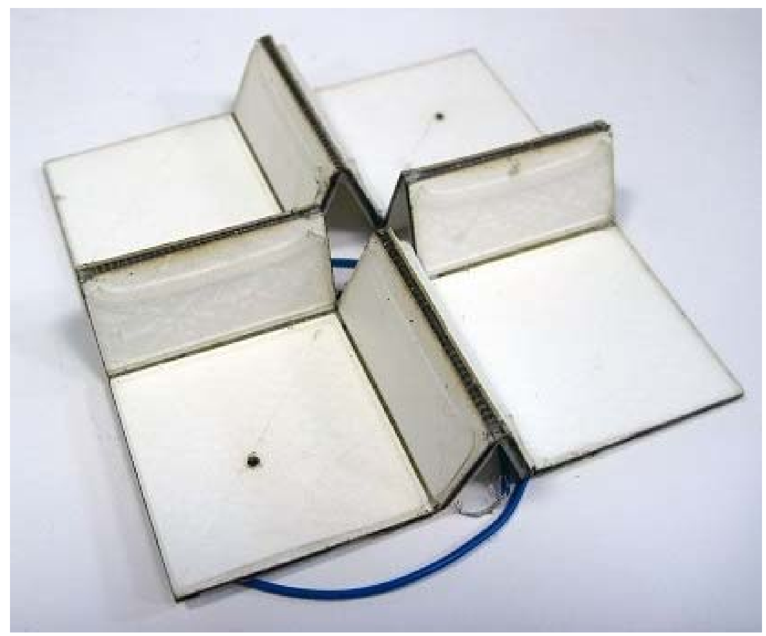
Origamizing Polyhedral Surfaces, Tachi 2010

Cyclic Folds



Origamizing Polyhedral Surfaces, Tachi 2010

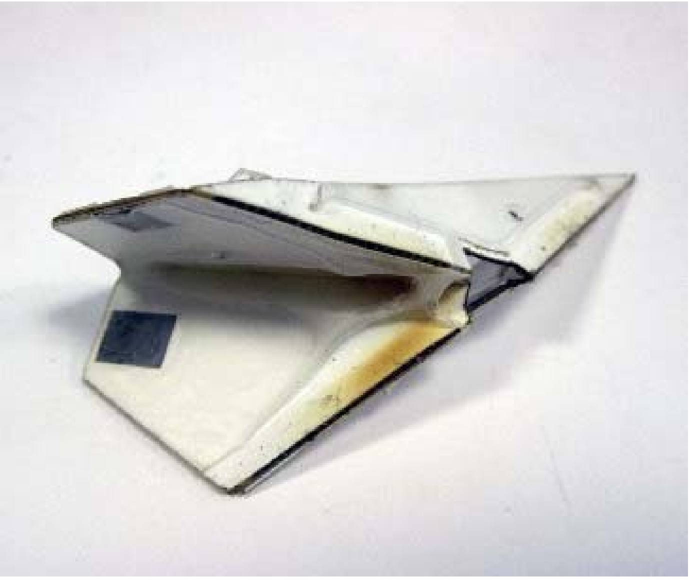


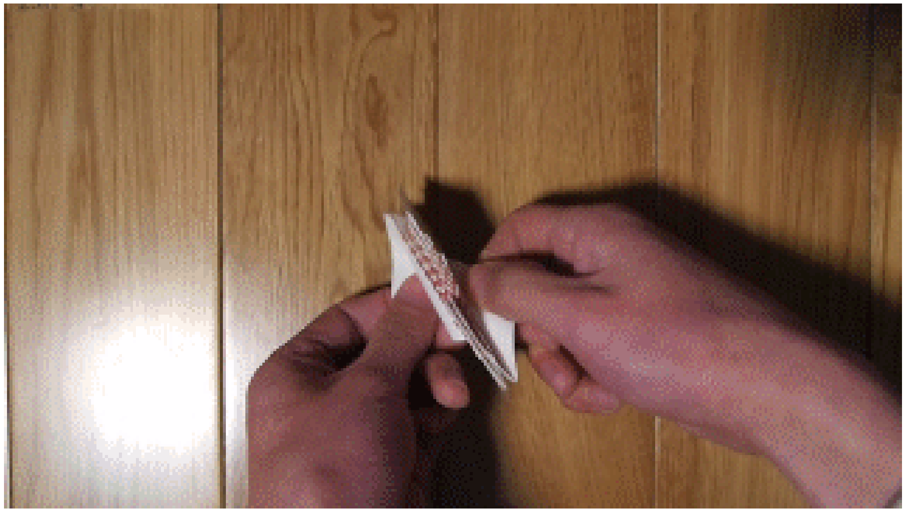


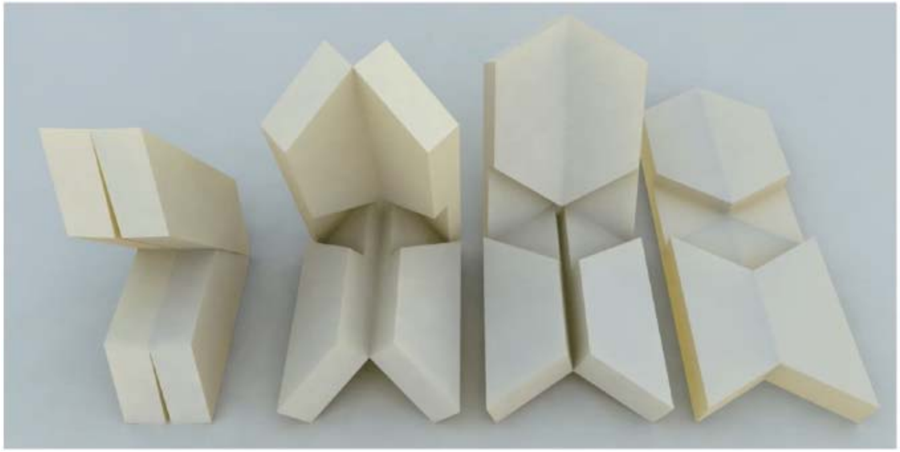
Miura Pattern

Four edge – single vertex

One degree of freedom

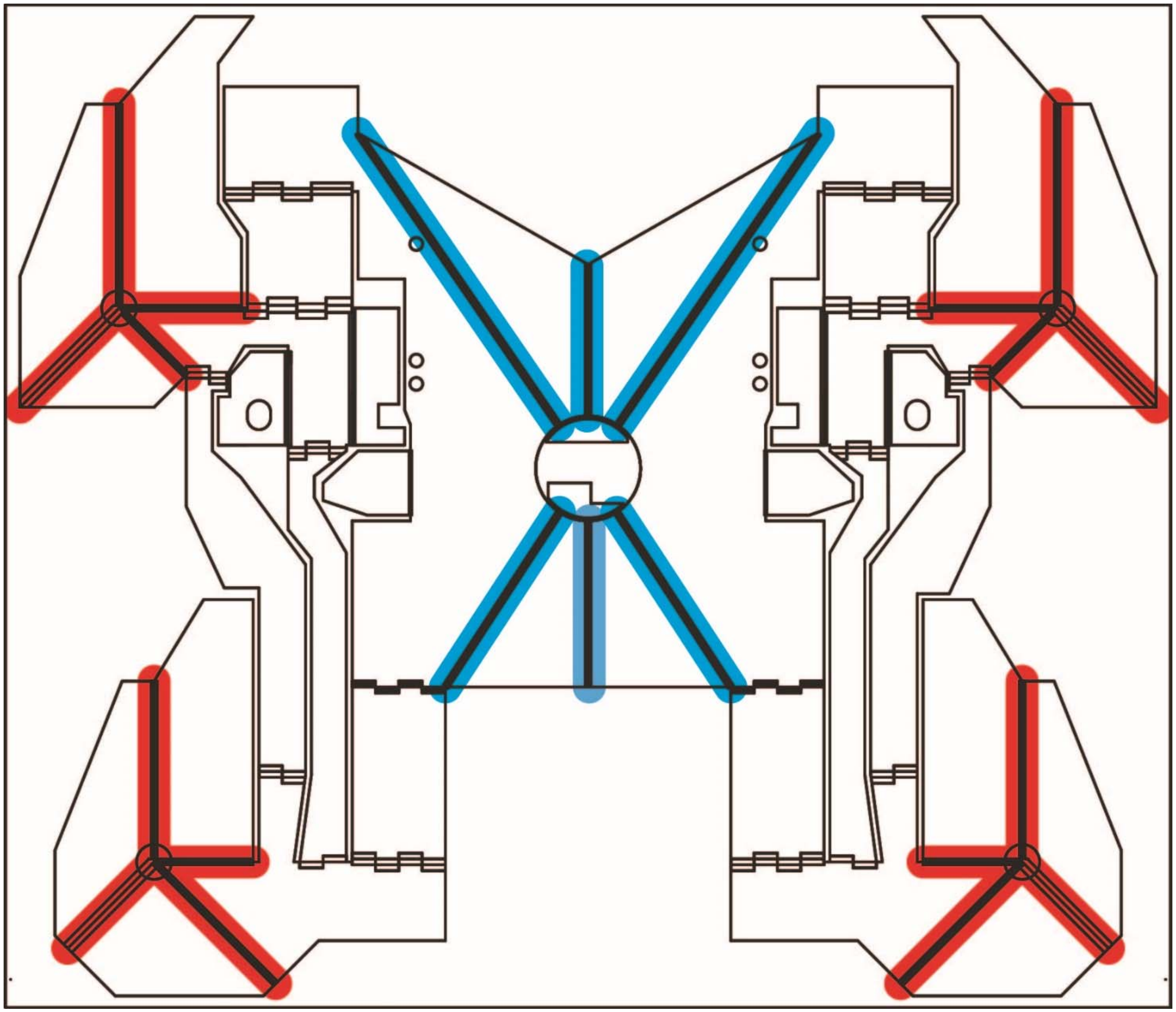






Rigid-foldable thick origami, Tachi 2010

Cyclic Folds



A Method for Building Self-Folding Machines, Felton et al. 2014

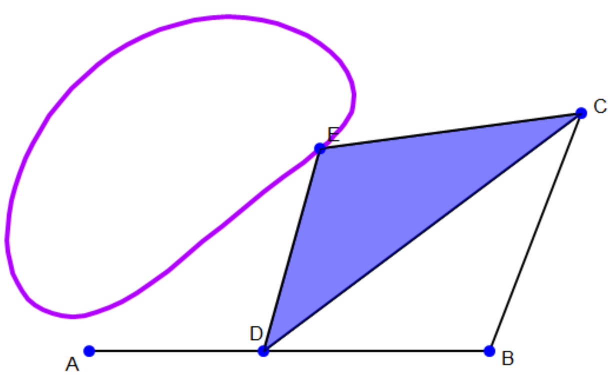
Arbitrary Mechanisms

Requirements:

1. Complex Linkages ☐
2. Actuator Coupling ☐

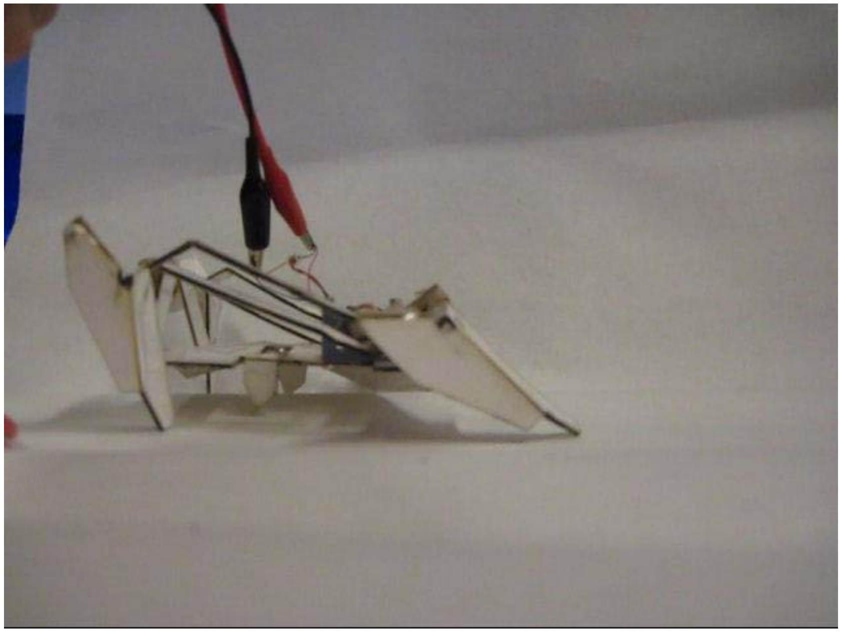
Generalizations of Kempe's Universality Theorum, Abbott 2008: Proof that $O(n^d)$ linkage bars needed to trace a **polynomial curve** of power *n* in *d* dimensions.

Computational Design of Mechanical Characters, Coros et al. 2013: Algorithm that **approximates a sketched curve** in two dimensions.

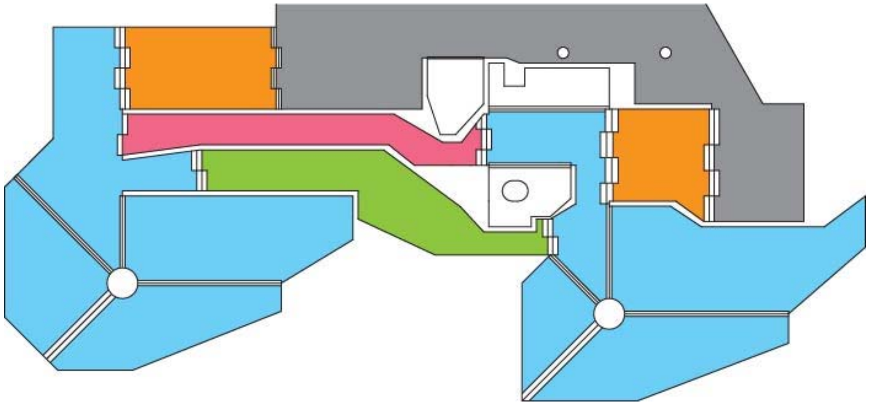


Alberthyang, Wikimedia Commons

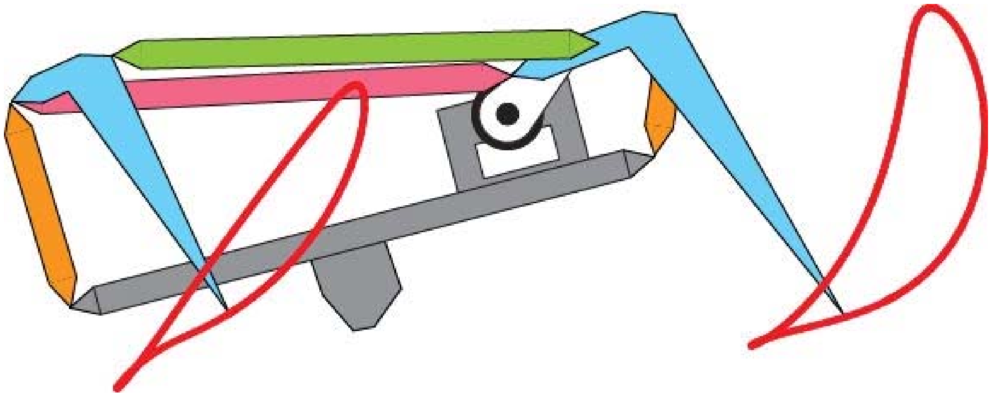
Self-Folding Linkages



Flat

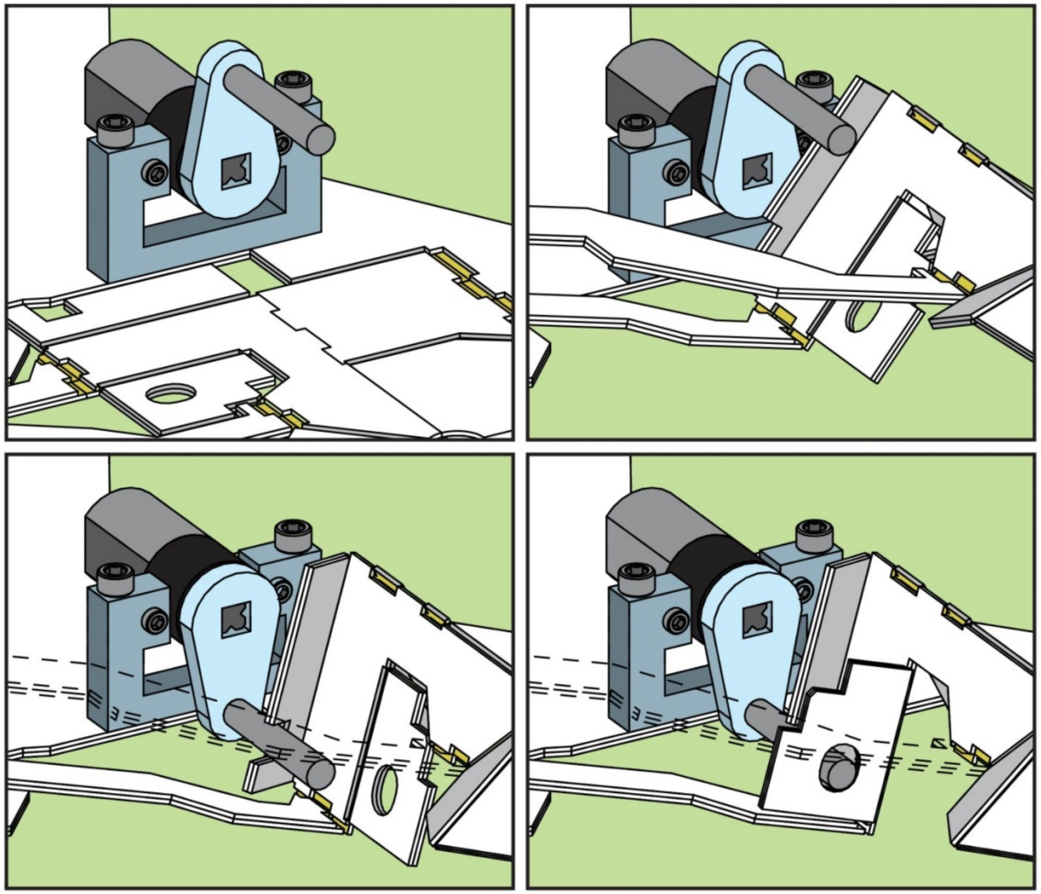


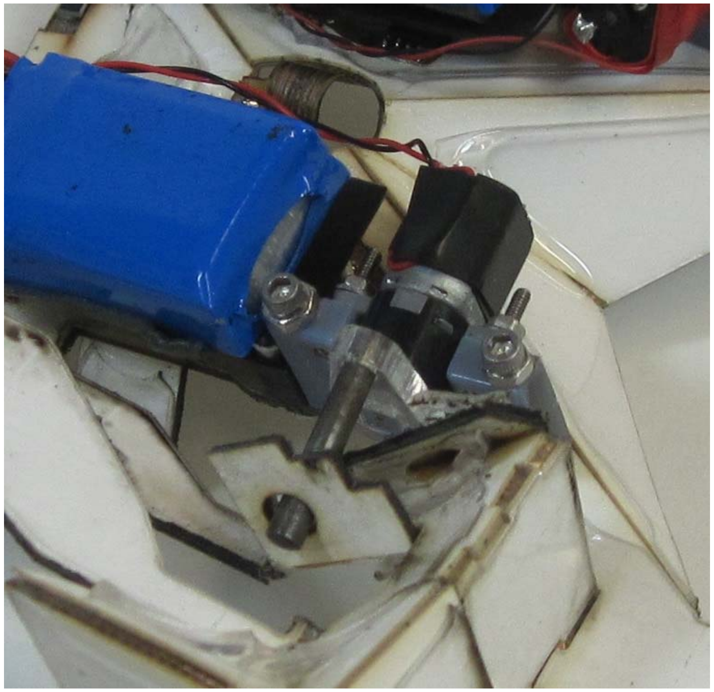
Folded



Felton *et al.*, *Science* 2014

Actuator Coupling

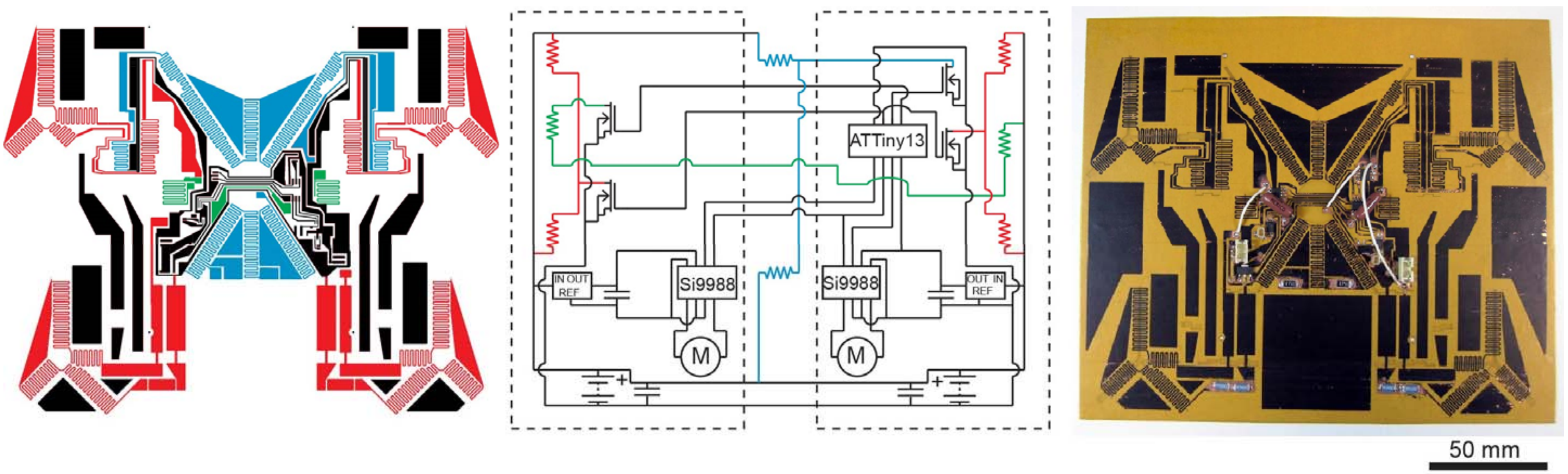




Felton *et al.*, *Science* 2014

Autonomous Folding

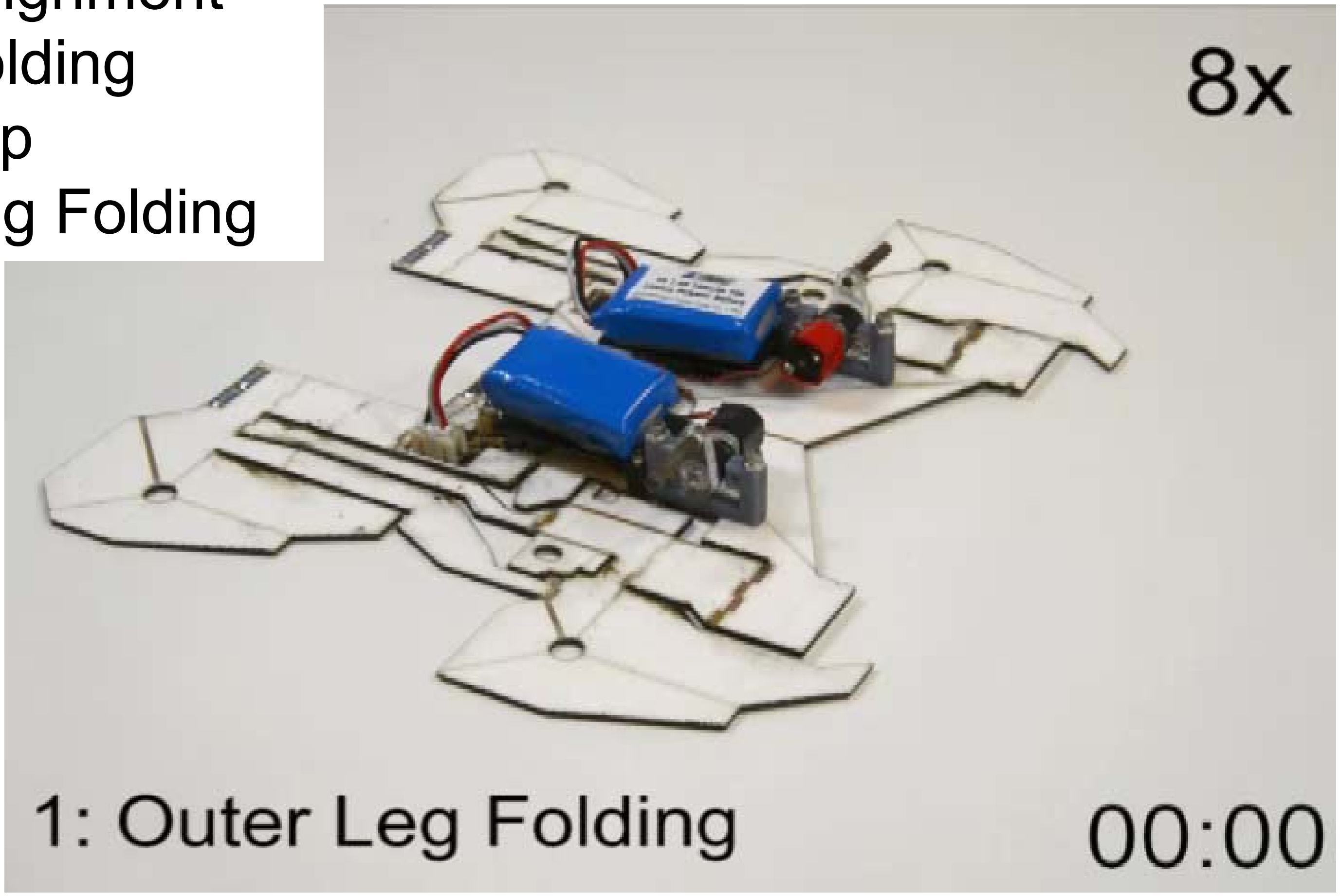
Requirements:
1. Onboard Power ☐
2. Onboard Controls ☐



Felton *et al.*, *Science* 2014

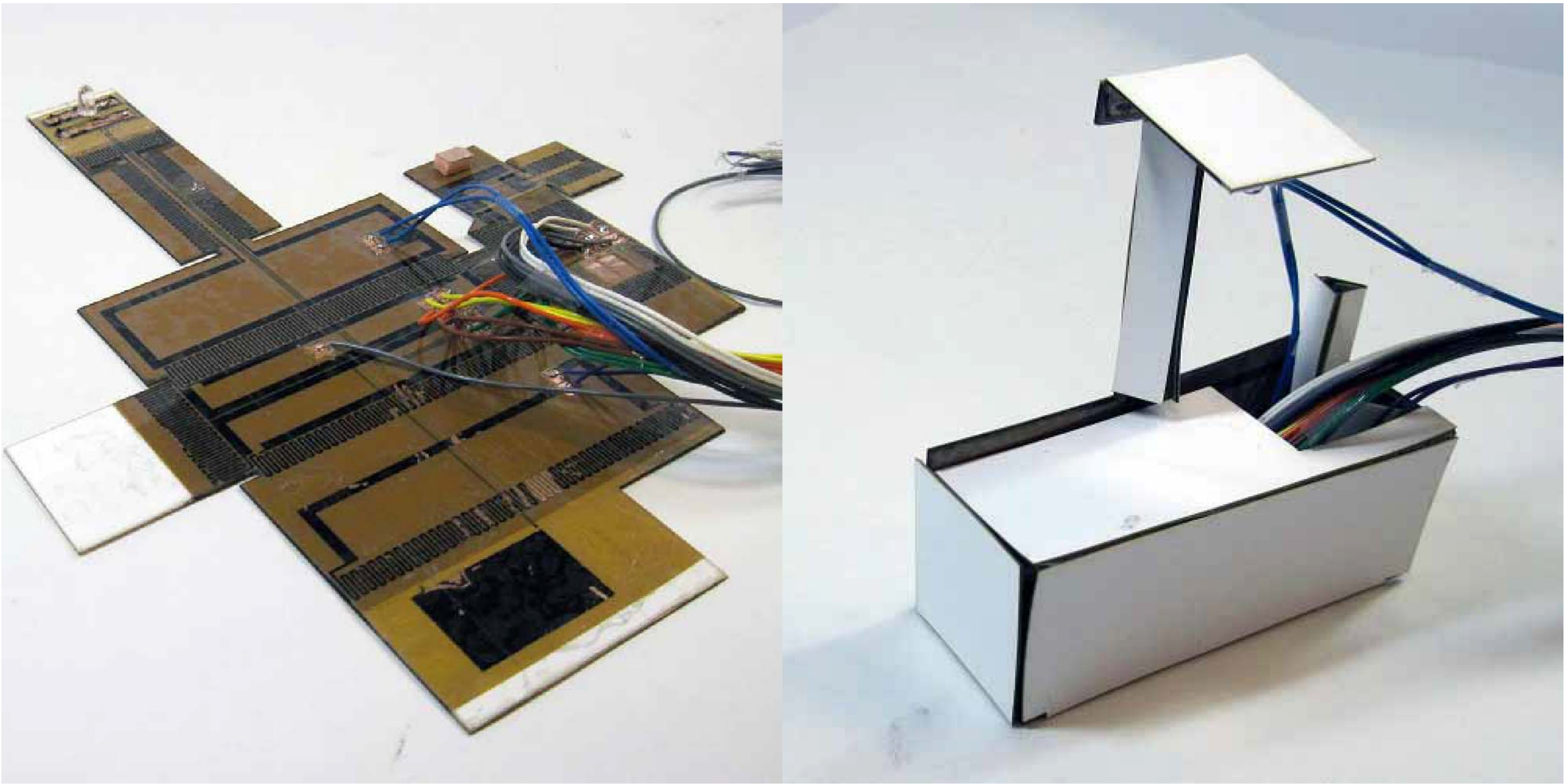
Autonomous Folding

1. Outer Leg Folding
2. Motor Alignment
3. Body Folding
4. Stand Up
5. Inner Leg Folding



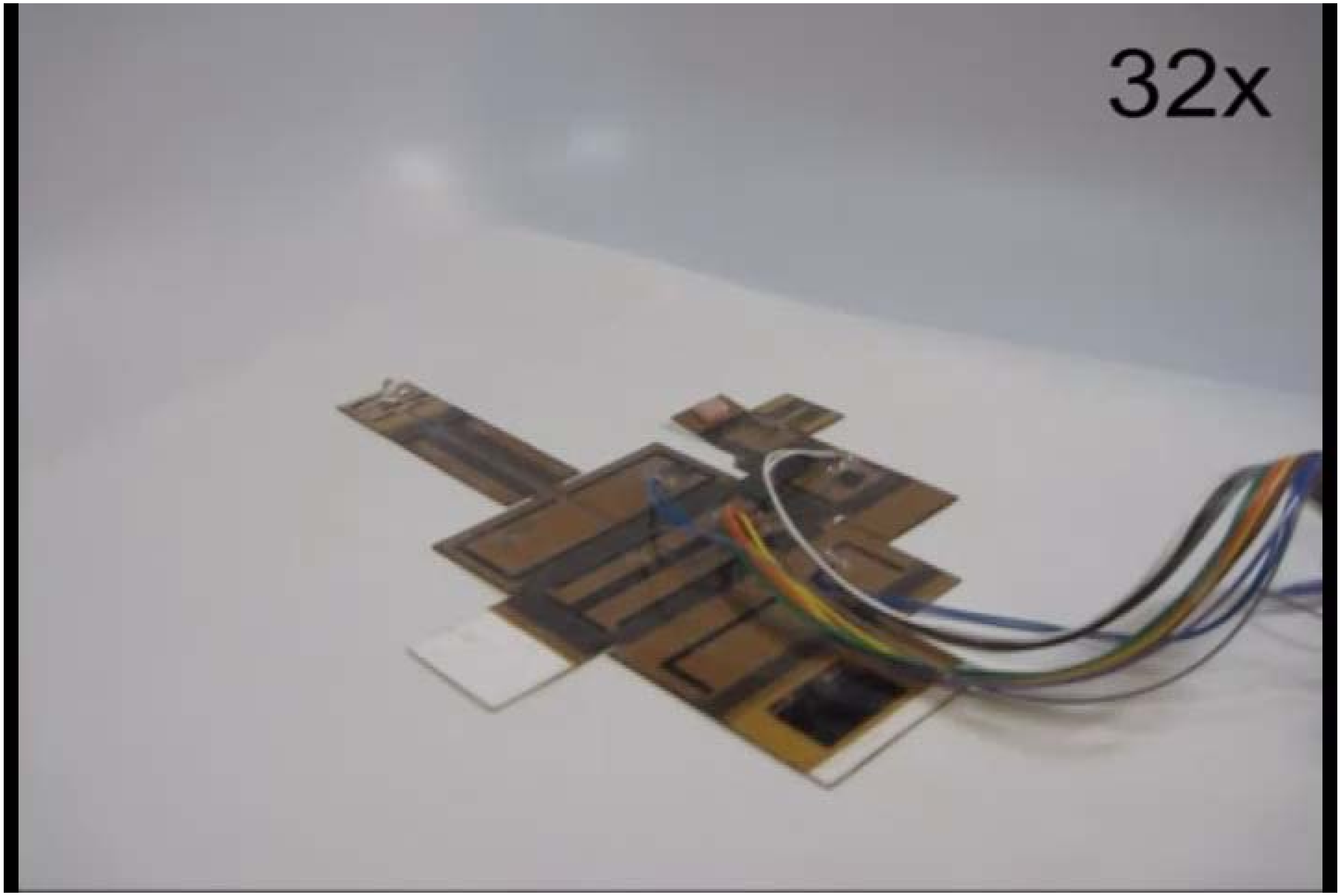
Felton *et al.*, *Science* 2014

Self-Folding Sensors



Shin *et al.*, *ICRA* 2014

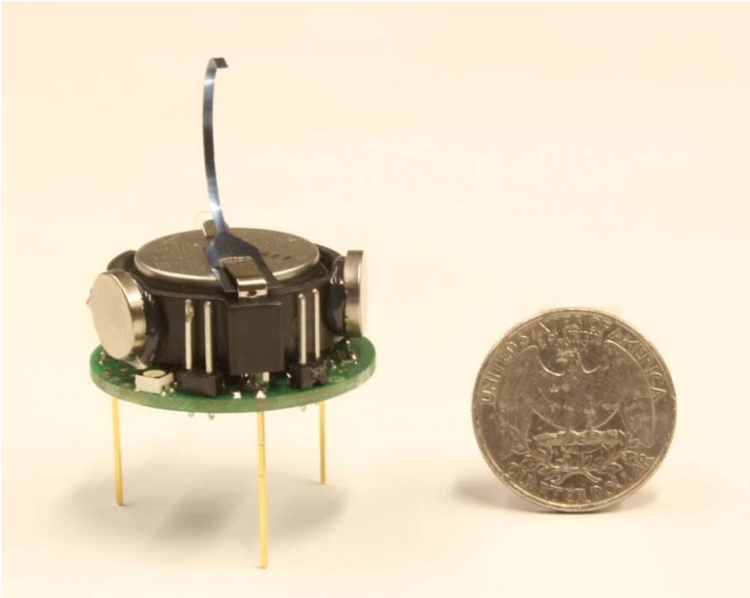
Self-Folding Lamp



Shin *et al.*, *ICRA* 2014

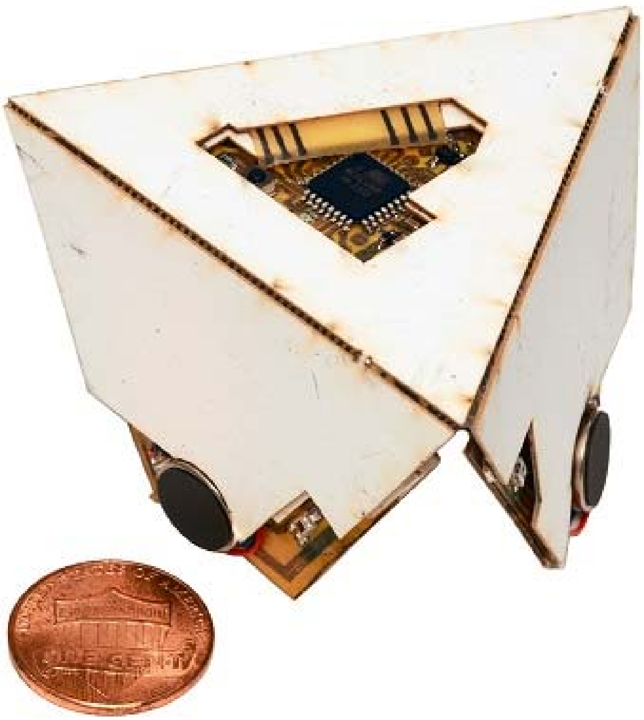
Swarm Self-Folding

Kilobot



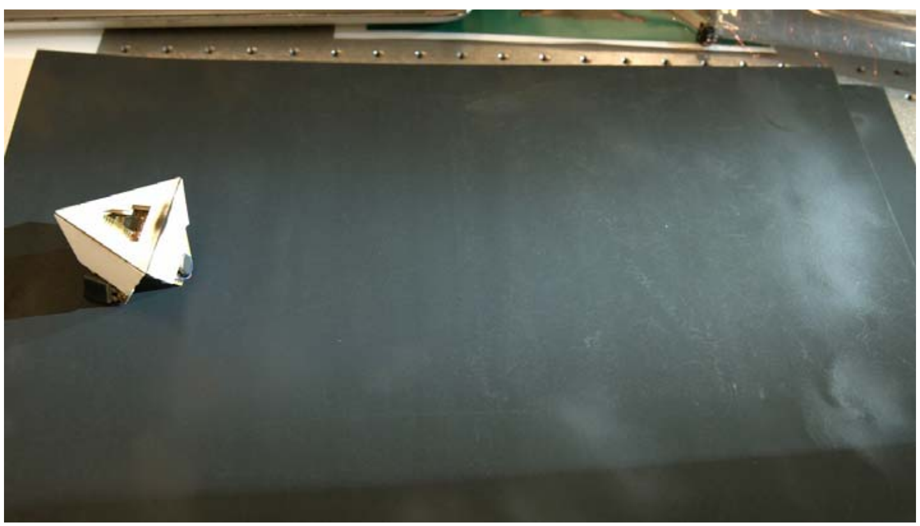
Rubenstein *et al.*, *ICRA* 2012

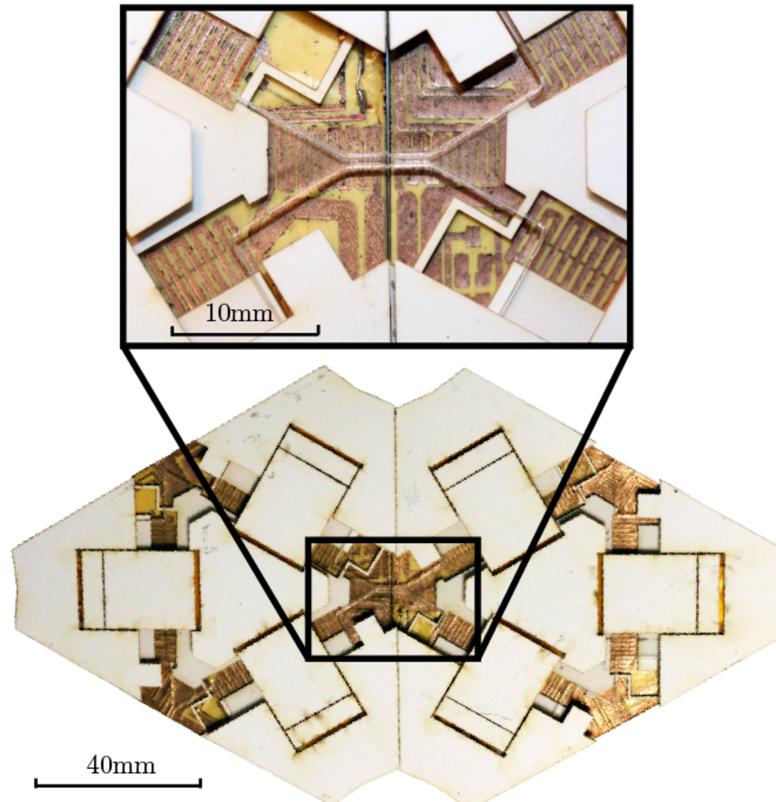
Self-Folding
Swarm Bot



Nisser *et al.* in prep

Swarm Self-Folding





Nisser *et al.* in prep

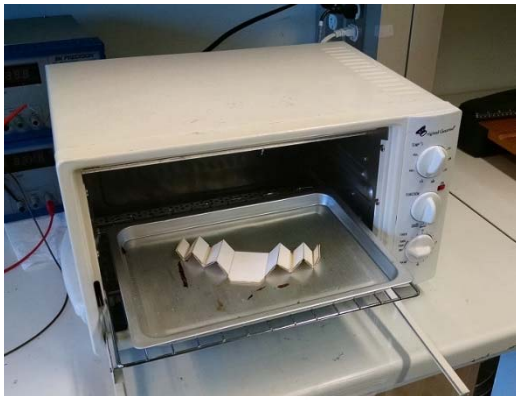
Other self-folding methods

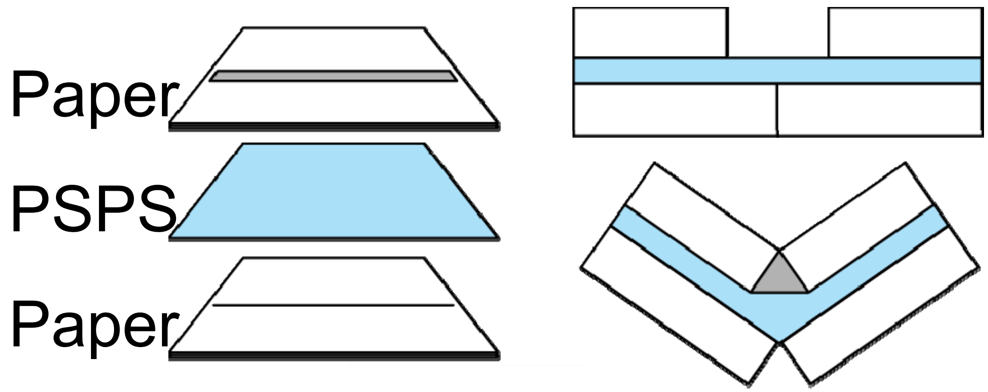
Cheaper Composites

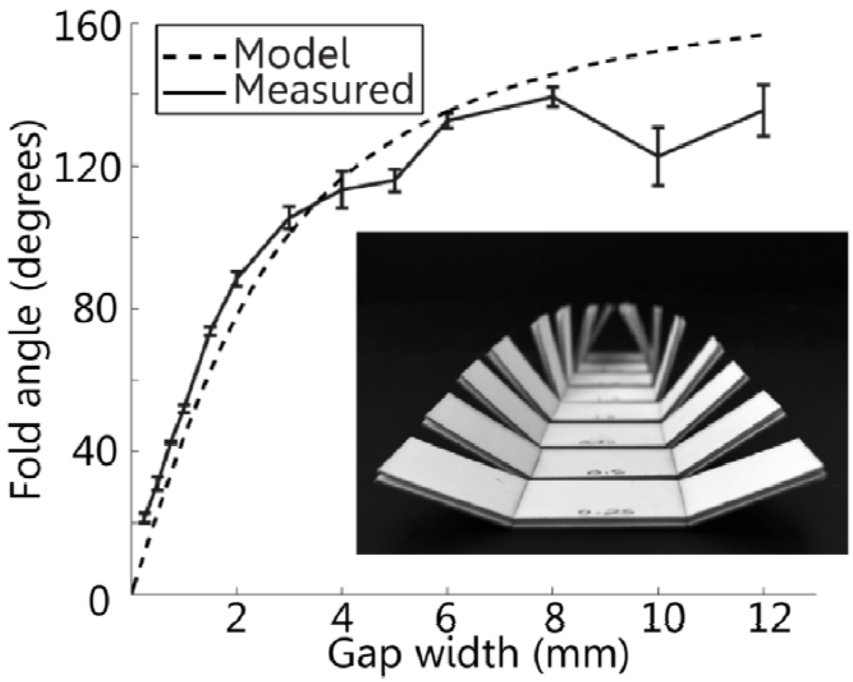
Centimeter-Scale Machines

Reversible Folding

`Easy-Bake' Self-Folding







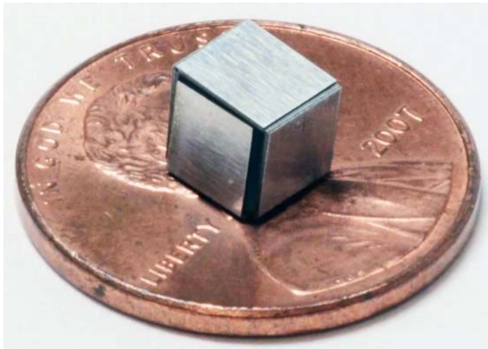
precision≈
3° - 8°

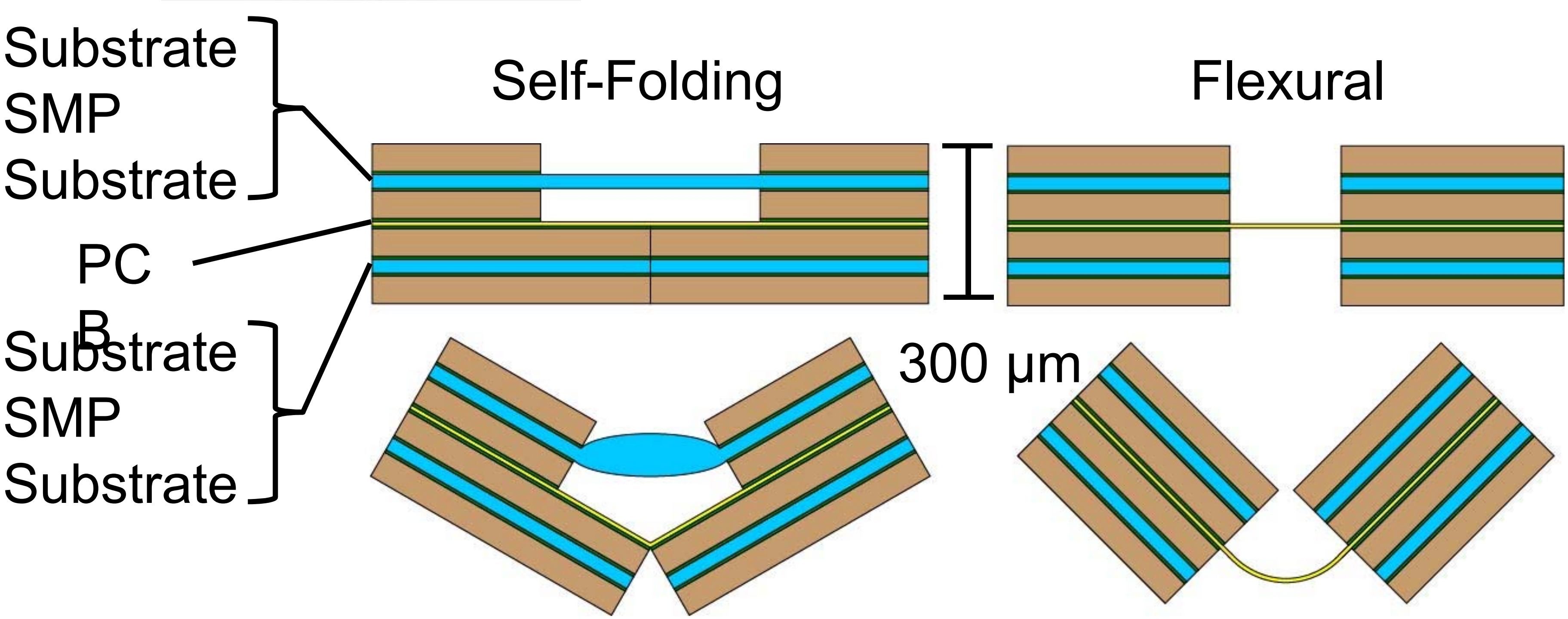
Tolley *et al.*, *SMS* 2014

`Easy-Bake' Self-Folding

Tolley *et al.*, *SMS* 2014

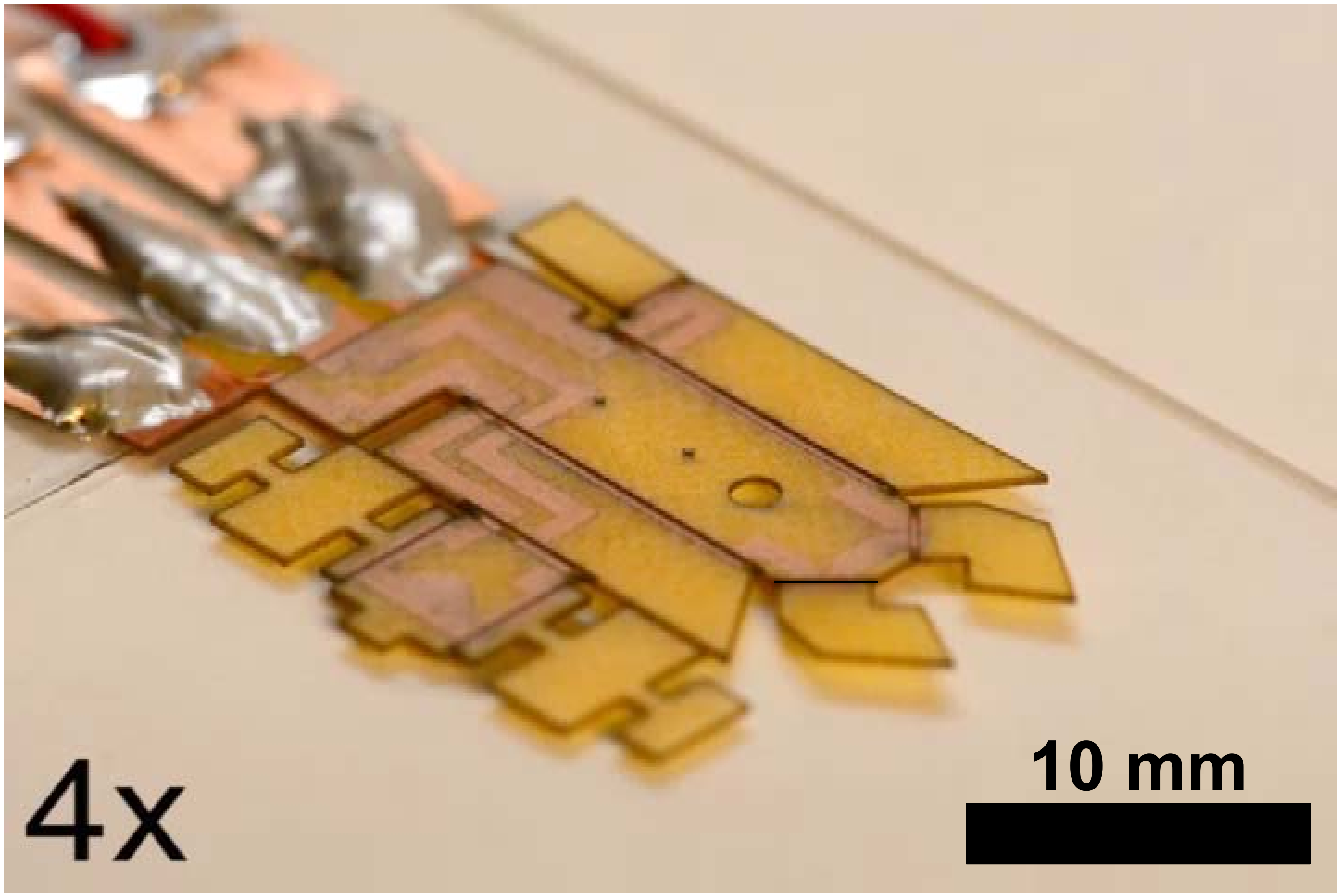
Millimeter Scale Folding





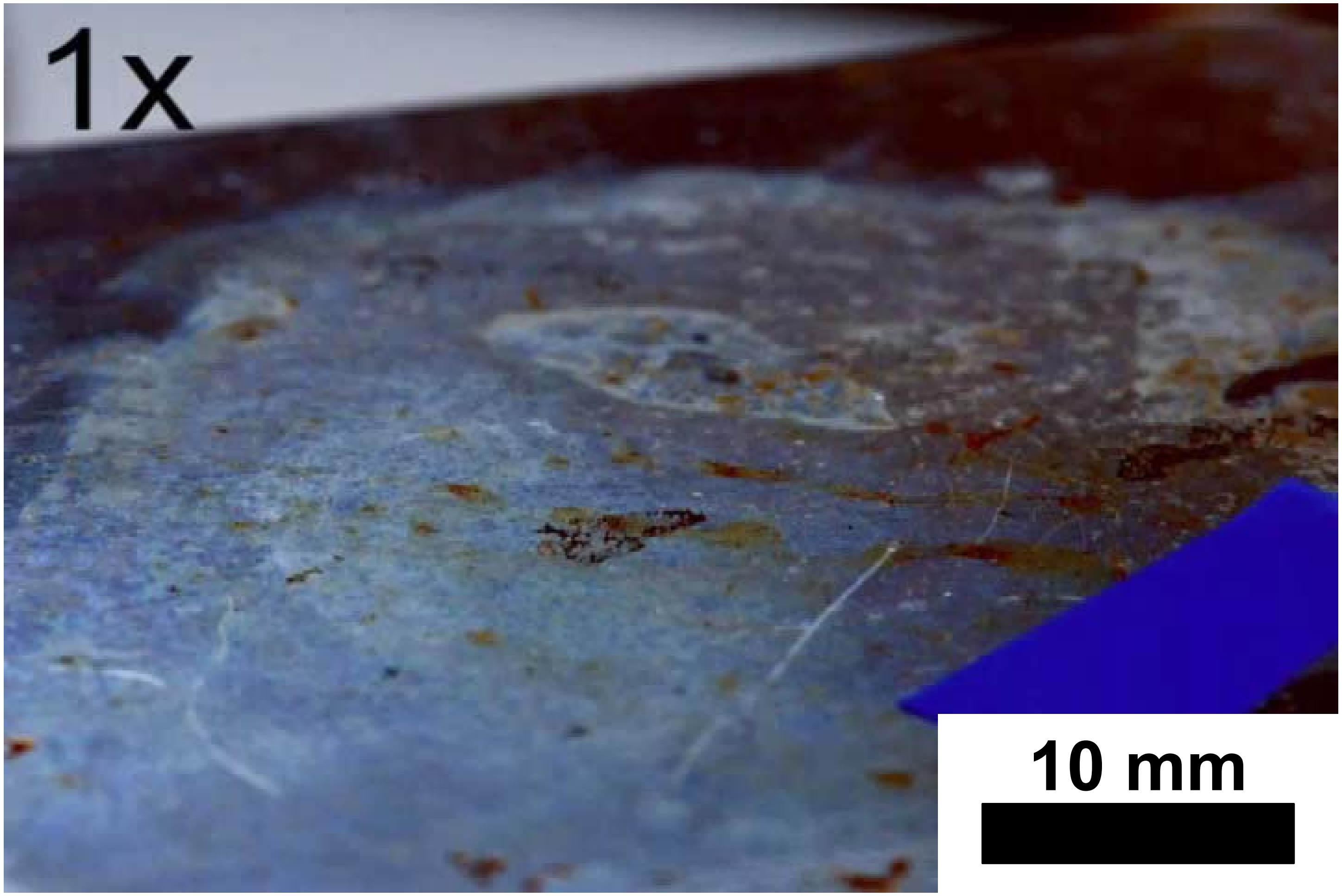
Felton *et al.*, *JMM* 2015

Ship



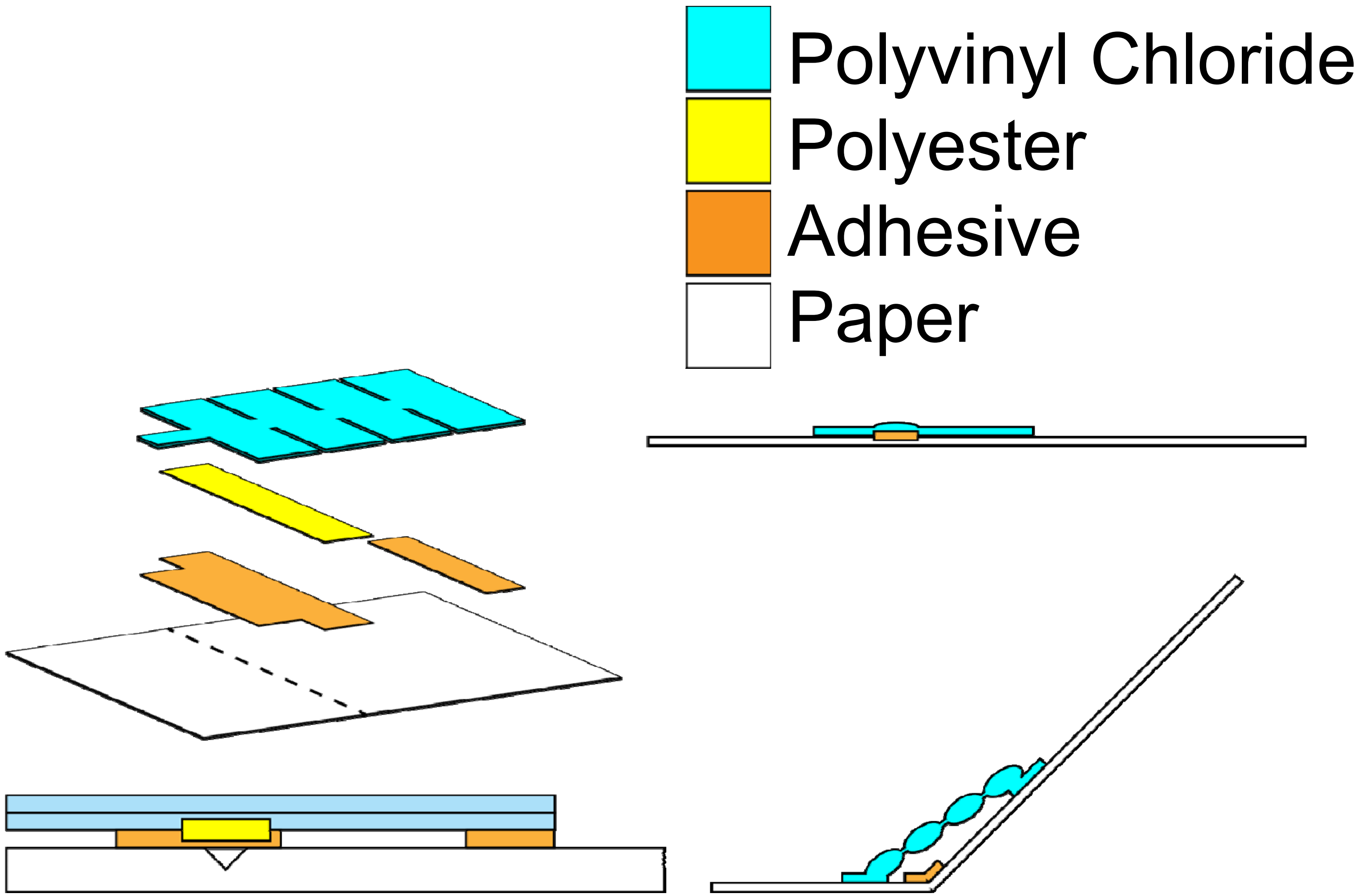
Felton *et al.*, *JMM* 2015

Bumblebee



Felton *et al.*, *JMM* 2015

Pneumatic Folding



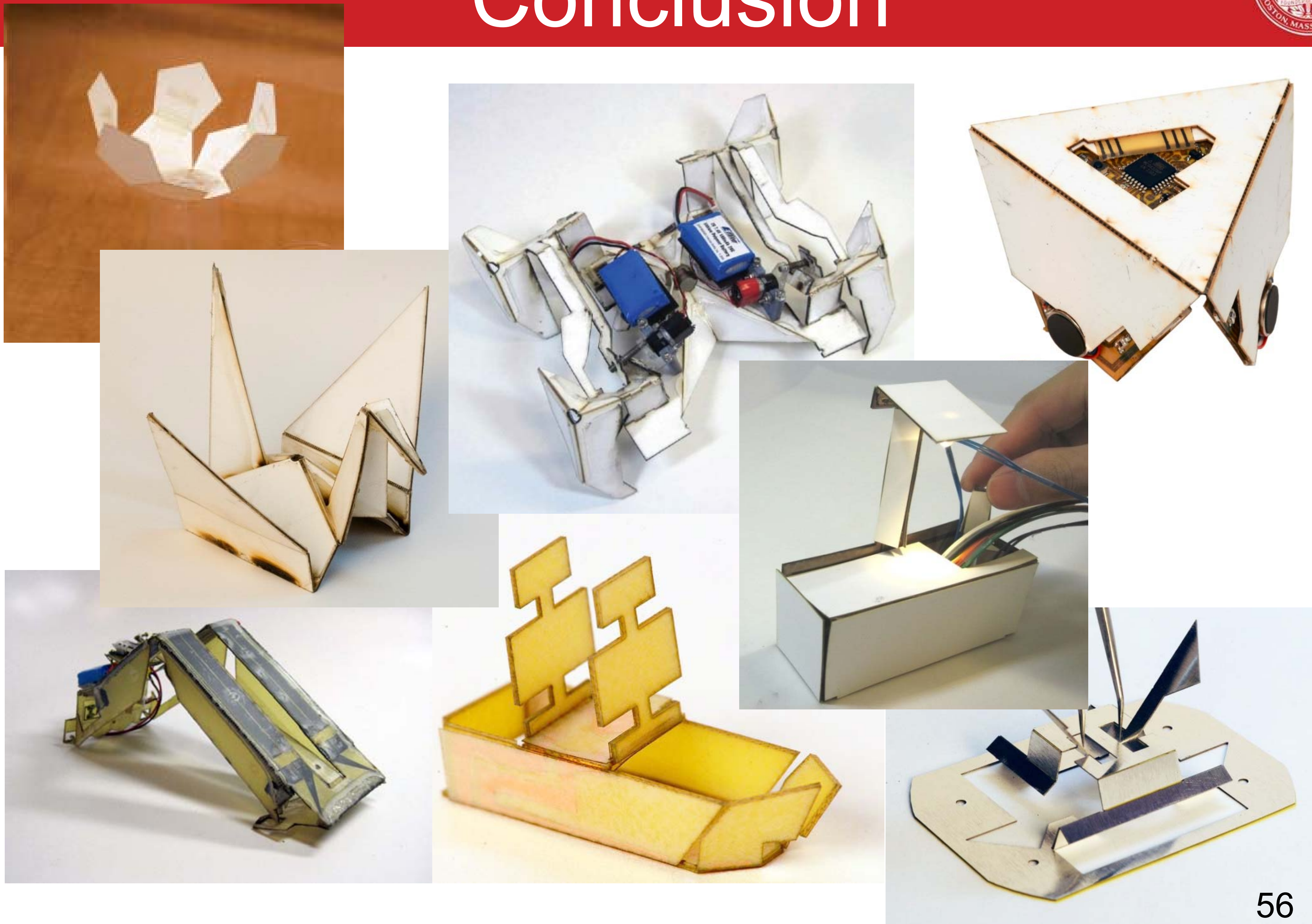
Sun *et al.*, ICRA 2015

Pneumatic Folding

A Self-folding
Dodecahedron

Sun *et al.*, *ICRA* 2015

Conclusion



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-Expedition in computing for Compiling Printable Programmable Machines
-Programmable Origami for Integration of Self-Assembling Systems in Engineered Structures

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Questions?