Architectural Origami

Architectural Form Design Systems based on Computational Origami

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Introduction
Background 1: Origami

Origami Teapot 2007
Tomohiro Tachi

Running Hare 2008
Tomohiro Tachi

Tetrapod 2009
Tomohiro Tachi
Background 2: Applied Origami

- Static:
  - Manufacturing
    - Forming a sheet
    - No Cut / No Stretch
    - No assembly
  - Structural Stiffness

- Dynamic:
  - Deployable structure
    - Mechanism
    - Packaging
  - Elastic Plastic Property
    - Textured Material
    - Energy Absorption

- Continuous surface

Potentially useful for
- Adaptive Environment
- Context Customized Design
- Personal Design
- Fabrication Oriented Design
Architectural Origami

- Origami Architecture
  Direct application of Origami for Design
  - Design is highly restricted by the symmetry of the original pattern
  - Freeform design results in losing important property (origami-inspired design)

- Architectural Origami
  Origami theory for Design
  - Extract characteristics of origami
  - Obtain solution space of forms from the required condition and design context
1. Origamizer
   - tucking molecules
   - layout algorithm

2. Freeform Origami
   - constraints of origami
   - perturbation based calculation
   - mesh modification

3. Rigid Origami
   - simulation
   - design by triangular mesh
   - design by quad mesh
   - non-disk?
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Origamizer

Related Papers:


Existing Origami Design Method by Circle Packing

Circle River Method [Meguro 1992]
Tree Method [Lang 1994]

CP: Parent and Children Crabs by Toshiyuki Meguro

Scutigera by Brian Chan
1D vs. 3D

- Circle River Method / Tree Method
  - Works fine for tree-like objects
  - Does not fit to 3D objects

- Origamizer / Freeform Origami
  - 3D Polyhedron, surface approximation
  - What You See Is What You Fold
3D Origami

Laptop PC 2003
by Tomohiro Tachi
not completed
3D Origami

Human 2004
Everything seems to be possible!
Problem: realize arbitrary polyhedral surface with a developable surface

- **Geometric Constraints**
  - Developable Surf
  - Piecewise Linear
  - Forget about Continuous Folding Motion

- **Potential Application**
  - Fabrication by folding and bending

Input: Arbitrary Polyhedron

Output: Crease Pattern

Folded Polyhedron
Approach: Make “Tuck”

- Tuck develops into
  - a plane
- Tuck folds into
  - a flat state hidden behind polyhedral surface

→ Important Advantage:
We can make Negative Curvature Vertex
Basic Idea

Origamize Problem
↓
Lay-outing Surface
Polygons Properly
↓
Tessellating Surface
Polygons and "Tucking Molecules"
↓
Parameter everything by Tucking Molecule:
  \[ \theta (i, j) \]
  \[ w(i, j) \]
\[ \theta (j, i) = -\theta (i, j) \]
\[ w(j, i) = w(i, j) + 2\lambda (i, j) \sin (0.5 \theta (i, j)) \]
Geometric Constraints (Equations)

\[ \sum_{n=0}^{N-1} \theta(i,j_n) = 2\pi - \sum_{n=0}^{N-1} \alpha(i,j_n) \quad \ldots (1) \]

\[ \sum_{n=0}^{N-1} w(i,j_n) \left[ \begin{array}{c} \cos \left( \sum_{m=1}^{n} \Theta_m \right) \\ \sin \left( \sum_{m=1}^{n} \Theta_m \right) \end{array} \right] = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \ldots (2) \]

where \( \Theta_m = \frac{1}{2} \theta(i,j_{m-1}) + \alpha(i,j_m) + \frac{1}{2} \theta(i,j_m) \)

Two-Step Linear Mapping

1. Mapping based on (1) (linear)
   \[ C_w w = b \]

2. Mapping based on (2) (linear)
   \[ w = C_w^+ b + \left( I_{N_{\text{edge}}} - C_w^+ C_w \right) w_0 \]
   where \( C_w^+ \) is the generalized inverse of \( C_w \)

   If the matrix is full-rank, \( C_w^+ = C_w^T (C_w C_w^T)^{-1} \)

gives \( (N_{\text{edge}} - 2N_{\text{vert}}) \) dimensional solution space

(within the space, we solve the inequalities)
**Geometric Constraints (Inequalities)**

- **2D Cond.**
  - Convex Paper
    \[ \theta(i,o) \geq \pi \]
    \[ w(i,o) \geq 0 \]
  - Non-intersection
    \[ -\pi < \theta(i,j) < \pi \]
    \[ \min(w(i,j), w(j,i)) \geq 0 \]
    \[ 0 \leq \Theta_m < \pi \]
  - Crease pattern non-intersection
    \[ \phi(i,j) \leq \arctan\left(\frac{2\ell(i,j)\cos\frac{1}{2}\theta(i,j)}{w(i,j)+w(j,i)}\right) + 0.5\pi \]

- **3D Cond.**
  for tuck proxy angle and depth
  - Tuck angle condition
    \[ \phi(i,j) - \frac{1}{2}\theta(i,j) \leq \pi - \tau'(i,j) \]
  - Tuck depth condition
    \[ w(i,j) \leq 2\sin\left(\tau'(i,j) - \frac{1}{2}\alpha(i,j)\right)d'(i) \]
Design System: Origamizer

- Auto Generation of Crease Pattern
- Interactive Editing (Search within the solution space)
  - Dragging Developed Facets
  - Edge
  - Boundary Editing

Developed in the project “3D Origami Design Tool” of IPA ESPer Project
0. Get a crease pattern using Origamizer
1. Fold Along the Crease Pattern
2. Done!
Proof?

Ongoing joint work with Erik Demaine
Freeform Origami

Related Papers:

Objective of the Study

1. freeform
   - Controlled 3D form
   - Fit function, design context, preference, ...

2. origami
   utilize the properties
   - Developability
     → Manufacturing from a sheet material based on Folding, Bending
   - Flat-foldability
     → Folding into a compact configuration or Deployment from 2D to 3D
   - Rigid-foldability
     → Transformable Structure
   - Elastic Properties
   ...
Proposing Approach

- Initial State: existing origami models (e.g. Miura-ori, Ron Resch Pattern, …) + Perturbation consistent with the origami conditions.
- Straightforward user interface.
Model

- Triangular Mesh (triangulate quads)
- Vertex coordinates represent the configuration
  - 3\(N_v\) variables, where \(N_v\) is the # of vertices

\[
X = \begin{bmatrix}
x_1 \\
y_1 \\
z_1 \\
\vdots \\
x_{N_v} \\
y_{N_v} \\
z_{N_v}
\end{bmatrix}
\]

- The configuration is constrained by developability, flat-foldability, …
Developability

Engineering Interpretation
→ Manufacturing from a sheet material based on Folding, Bending

• Global condition
  – There exists an isometric map to a plane.
⇔(if topological disk)

• Local condition
  – Every point satisfies
    • Gauss curvature = 0
Developable Surface

• Smooth Developable Surface
  – $G^2$ surface (curvature continuous)
    • "Developable Surface" (in a narrow sense)
    • Plane, Cylinder, Cone, Tangent surface
  – $G^1$ Surface (smooth, tangent continuous)
    • "Uncreased flat surface"
    • piecewise Plane, Cylinder, Cone, Tangent surface

• Origami
  – $G^0$ Surface
  – piecewise $G^1$ Developable $G^0$ Surface
Developability condition to be used

- **Constraints**
  - For every interior vertex $v$ ($k_v$-degree), gauss area equals 0.

\[
G_v = 2\pi - \sum_{i=0}^{k_v} \theta_i = 0
\]
Flat-foldability

Engineering Interpretation

→ Folding into a compact configuration or Deployment from 2D to 3D

• Isometry condition
  • isometric mapping with mirror reflection

• Layering condition
  • valid overlapping ordering
    • globally: NP Complete [Bern and Hayes 1996]
Flat-foldability condition to be used

- Isometry
  \[ \Leftrightarrow \text{Alternating sum of angles is 0 [Kawasaki 1989]} \]
  \[ F_v = \sum_{i=0}^{kv} \text{sgn}(i)\theta_i = 0 \]

- Layering
  \[ \Rightarrow \text{[Kawasaki 1989]} \]
  - If \( \theta_i \) is between foldlines assigned with MM or VV,
    \[ \theta_i \geq \min(\theta_{i-1}, \theta_{i+1}) \]
  + empirical condition [Tachi 2007]
    - If \( \theta_i \) and \( \theta_{i+1} \) are composed by foldlines assigned with MMV or VVM then, \( \theta_i \geq \theta_{i+1} \)
Other Conditions

- Conditions for fold angles
  - Fold angles \( \rho \)
  - V fold: \( 0 < \rho < \pi \)
  - M fold: \( -\pi < \rho < 0 \)
  - crease: \( -\alpha \pi < \rho < \alpha \pi \) \( (\alpha = 0: \text{planar polygon}) \)

- Optional Conditions
  - Fixed Boundary
    - Folded from a specific shape of paper
  - Rigid bars
  - Pinning
Settings

- Initial Figure:
  - Symmetric Pattern
- Freeform Deformation
  - Variables \((3N_v)\)
    - Coordinates \(\mathbf{X}\)
  - Constraints \((2N_{v_{in}}+N_c)\)
    - Developability
    - Flat-foldability
    - Other Constraints

\[
\mathbf{X} = \begin{bmatrix}
x_1 \\
y_1 \\
z_1 \\
\vdots \\
x_{N_v} \\
y_{N_v} \\
z_{N_v}
\end{bmatrix}
\]

Under-determined System

→ Multi-dimensional Solution Space
Solve Non-linear Equation

The infinitesimal motion satisfies:

\[
\frac{\partial G}{\partial X} \frac{\partial F}{\partial X} \frac{\partial H}{\partial X} \begin{bmatrix}
\frac{\partial \theta}{\partial \theta} \\
\frac{\partial \rho}{\partial \rho} \\
\frac{\partial \theta}{\partial \rho} \\
\frac{\partial \rho}{\partial \theta}
\end{bmatrix}
\begin{bmatrix}
\frac{\partial X}{\partial \theta} \\
\frac{\partial F}{\partial \rho} \\
\frac{\partial H}{\partial \theta} \\
\frac{\partial X}{\partial \rho}
\end{bmatrix}
\dot{X} = 0
\]

For an arbitrarily given (through GUI)
Infinitesimal Deformation \( \Delta X_0 \)

\[
\Delta X = -C^+ r + \left( I_{3N_v} - C^+ C \right) \Delta X_0
\]

\( G_v = 2\pi - \sum_{i=0}^{kv} \theta_i = 0 \)

\( F_v = \sum_{i=0}^{kv} \text{sgn}(i) \theta_i = 0 \)

\[
\frac{\partial \theta_{ijk}}{\partial x_i} = -\frac{1}{\ell_{ij}} \mathbf{b}_{ij}^T
\]

\[
\frac{\partial \theta_{ijk}}{\partial x_j} = \frac{1}{\ell_{ij}} \mathbf{b}_{ij}^T + \frac{1}{\ell_{jk}} \mathbf{b}_{jk}^T
\]

\[
\frac{\partial \theta_{ijk}}{\partial x_k} = -\frac{1}{\ell_{jk}} \mathbf{b}_{jk}^T
\]
Freeform Origami

Get A Valid Value
- Iterative method to calculate the conditions
- Form finding through User Interface

Implementation
- Lang
  - C++, STL
- Library
  - BLAS (intel MKL)
- Interface
  - wxWidgets, OpenGL

To be available on web
Mesh Modification

Edge Collapse

• Edge Collapse [Hoppe et al 1993]

• Maekawa’s Theorem [1983] for flat foldable pattern
  \[ M - V = \pm 2 \]
Mesh Modification
Miura-Ori

- **Original**
  - [Miura 1970]

- **Application**
  - bidirectionally expansible (one-DOF)
  - compact packaging
  - sandwich panel

- **Conditions**
  - Developable
  - Flat-foldable
  - op: (Planar quads) → Rigid Foldable

ISAS Space Flyer Unit
zeta core
[Koryo Miura 1972]
Miura-ori Generalized

- Freeform Miura-ori
Miura-ori Generalized
Ron Resch Pattern

• Original
  – Resch [1970]

• Characteristics
  – Flexible (multiDOF)
  – Forms a smooth flat surface
    + scaffold

• Conditions
  – Developable
  – 3-vertex coincide
Ron Resch Pattern
Generalized
Generalized Ron Resch Pattern
Crumpled Paper

- Origami
  = crumpled paper
  = buckled sheet

- Conditions
  - Developable
  - Fixed Perimeter
crumpled paper example
Waterbomb Pattern

- “Namako” (by Shuzo Fujimoto)
- Characteristics
  - Flat-foldable
  - Flexible (multi DOF)
  - Complicated motion
- Application
  - packaging
  - textured material
  - cloth folding...

S. Mabona “Fugu”

Kuribayashi & You 2006
Waterbomb Pattern Generalized
Rigid Origami

Rigid Origami?

- **Rigid Origami** is
  - Plates and Hinges model for origami

- **Characteristics**
  - Panels do not deform
    - Do not use Elasticity
  - synchronized motion
    - Especially nice if One-DOF
  - watertight cover for a space

- **Applicable for**
  - self deployable micro mechanism
  - large scale objects under gravity using thick panels
Study Objectives

1. Generalize rigid foldable structures to freeform
   1. Generic triangular-mesh based design
      • multi-DOF
      • statically determinate
   2. Singular quadrilateral-mesh based design
      • one-DOF
      • redundant constraints

2. Generalize rigid foldable structures to cylinders and more
Examples of Rigid Origami
Basics of Rigid Origami
Angular Representation

• Constraints
  – [Kawasaki 87]
    [belcastro and Hull 02]
    \[ \chi_1 \cdots \chi_{n-1} \chi_n = I \]
  – 3 equations per interior vertex

• \( V_{in} \) interior vert + \( E_{in} \) foldline model:
  – constraints:
    \[ \begin{bmatrix} C \end{bmatrix} \dot{\rho} = 0 \]
    \( 3V_{in} \times E_{in} \) matrix

Generic case:
DOF = \( E_{in} - 3V_{in} \)

\[ \dot{\rho} = \left[ I_N - C^+ C \right] \dot{\rho}_0 \]
\[ \text{where } C^+ \text{ is the pseudo-inverse of } C \]
DOF in Generic Triangular Mesh

Euler’s: \((V_{in} + E_{out}) - (E_{out} + E_{in}) + F = 1\)

Triangle: \(3F = 2E_{out} + E_{in}\)

Mechanism: \(\text{DOF} = E_{in} - 3V_{in}\)

Disk with \(E_{out}\) outer edges

\(\text{DOF} = E_{out} - 3\)

with \(H\) generic holes

\(\text{DOF} = E_{out} - 3 - 3H\)

\((V_{in} + E_{out}) - (E_{out} + E_{in}) + F = 1 - H\)

\(\text{DOF} = E_{in} - 3V_{in} - 6H\)
Hexagonal Tripod Shell

Hexagonal boundary:

\[ E_{\text{out}} = 6 \]

\[ \therefore \text{DOF} = 6 - 3 = 3 \]

+ rigid DOF = 6

3 pin joints \((x,y,z)\):

\[ \therefore 3 \times 3 = 9 \text{ constraints} \]
Generalize Rigid-Foldable Planar Quad-Mesh

• One-DOF
  – Every vertex transforms in the same way
  – **Controllable with single actuator**

• Redundant
  – Rigid Origami in General
    • \( \text{DOF} = N - 3M \)
    • \( N: \) num of foldlines
    • \( M: \) num of inner verts
  – \( n \times n \) array \( N=2n(n-1), M=(n-1)^2 \)
    -> \( \text{DOF}=-(n-2)^2+1 \)
    -> \( n>2 \), then overconstrained if not singular
  – Rank of Constraint Matrix is \( N-1 \)
    • Singular Constraints
  – **Robust structure**
  – **Improved Designability**
Idea: Generalize Regular pattern

- Original
  - Miura-ori
  - Eggbox pattern

- Generalization
  To:
  Non Symmetric forms

(Do not break rigid foldability)
Flat-Foldable Quadrivalent Origami

MiuraOri Vertex

- one-DOF structure
  - x,y in the same direction

- Miura-ori

- Variation of Miura-ori
Flat-Foldable Quadrivalent Origami

MiuraOri Vertex

• Intrinsic Measure:

\[ \theta_0 = \pi - \theta_2 \]
\[ \theta_1 = \pi - \theta_3 \]

• Folding Motion
  – Opposite fold angles are equal
  – Two pairs of folding motions are linearly related.

\[ \rho_1 = -\rho_3 \]
\[ \rho_0 = \rho_2 \]

\[ \tan \frac{\rho_0}{2} = \frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)} \tan \frac{\rho_1}{2} \]
Flat-Foldable Quadrivalent Origami

MiuraOri Vertex

$$\begin{bmatrix}
\tan \frac{\rho_1(t)}{2} \\
\tan \frac{\rho_2(t)}{2} \\
\vdots \\
\tan \frac{\rho_N(t)}{2}
\end{bmatrix} = \lambda(t) \begin{bmatrix}
\tan \frac{\rho_1(t_0)}{2} \\
\tan \frac{\rho_2(t_0)}{2} \\
\vdots \\
\tan \frac{\rho_N(t_0)}{2}
\end{bmatrix}$$

$$\rho_1 = -\rho_3$$
$$\rho_0 = \rho_2$$

$$\tan \frac{\rho_0}{2} = \sqrt{\frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)}} \tan \frac{\rho_1}{2}$$
Get One State and Get Continuous Transformation

Finite Foldability: Existence of Folding Motion ⇔

There is one static state with

- Developability
- Flat-foldability
- Planarity of Panels

\[
\begin{bmatrix}
\tan \frac{\rho_1(t)}{2} \\
\tan \frac{\rho_2(t)}{2} \\
\vdots \\
\tan \frac{\rho_N(t)}{2}
\end{bmatrix} = \lambda(t)
\begin{bmatrix}
\tan \frac{\rho_1(t_0)}{2} \\
\tan \frac{\rho_2(t_0)}{2} \\
\vdots \\
\tan \frac{\rho_N(t_0)}{2}
\end{bmatrix}
\]
Built Design

- **Material**
  - 10mm Structural Cardboard (double wall)
  - Cloth
- **Size**
  - 2.5m x 2.5m
- exhibited at NTT ICC
Rigid Foldable Curved Folding

- Curved folding is rationalized by Planar Quad Mesh
- Rigid Foldable Curved Folding = Curved folding without ruling sliding
Discrete Voss Surface
Eggbox-Vertex

- one-DOF structure
  - Bidirectionally Flat-Foldable

- Eggbox-Pattern
- Variation of Eggbox Pattern
Discrete Voss Surface
Eggbox-Vertex

• Intrinsic Measure:

\[ \theta_0 = \theta_2 \]
\[ \theta_1 = \theta_3 \]

• Folding Motion
  – Opposite fold angles are equal
  – Two pairs of folding motions are linearly related.
  [SCHIEF et.al. 2007]

\[ \rho_1 = \rho_3 \]
\[ \rho_0 = \rho_2 \]

\[
\tan \frac{\rho_0}{2} = \sqrt{\frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)}} \cdot \cot \frac{\rho_1}{2}
\]
\[ = \frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)} \cdot \tan \frac{\rho_1}{2} \]
Eggbox: Discrete Voss Surface

- Use Complementary Folding Angle for “Complementary Foldline”

\[
\begin{bmatrix}
\tan \frac{\rho_0(t)}{2} \\
\tan \frac{\rho_1(t)}{2} \\
\vdots \\
\tan \frac{\rho_N(t)}{2}
\end{bmatrix} = \lambda(t) \begin{bmatrix}
\tan \frac{\rho_0(t_0)}{2} \\
\tan \frac{\rho_1(t_0)}{2} \\
\vdots \\
\tan \frac{\rho_N(t_0)}{2}
\end{bmatrix}
\]

Complementary Folding Angle

\[
\rho_1 = \rho_3 = \pi - \rho'_1 = \pi - \rho'_3
\]

\[
\rho_0 = \rho_2
\]

\[
\tan \frac{\rho_0}{2} = \sqrt{\frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)}} \cot \frac{\rho_1}{2}
\]

\[
= \sqrt{\frac{1 + \cos(\theta_0 - \theta_1)}{1 + \cos(\theta_0 + \theta_1)}} \tan \frac{\rho'_1}{2}
\]
Hybrid Surface: BiDirectionally Flat-Foldable PQ Mesh

- use 4 types of foldlines
  - mountain fold
    - $0^\circ \rightarrow -180^\circ$
  - valley fold
    - $0^\circ \rightarrow 180^\circ$
  - complementary mountain fold
    - $-180^\circ \rightarrow 0^\circ$
  - complementary valley fold
    - $180^\circ \rightarrow 0^\circ$

“developed” state  flat-folded state

3D

DeveToped

Flat-folded
Developability and Flat-Foldability

- **Developed State:**
  - Every edge has fold angle complementary fold angle to be $0^\circ$

\[
\sum_{i=0}^{3} \sigma^{\text{dev}}(i)\theta_i = 0 \quad \cdots 4CF \quad \text{or} \quad 2F + 2CF
\]

\[
2\pi - \sum_{i=0}^{3} \theta_i = 0 \quad \cdots \quad 4F
\]

- **Flat-folded State:**
  - Every edge has fold angle complementary fold angle to be $\pm 180^\circ$

\[
\sum_{i=0}^{3} \sigma^{\text{ff}}(i)\theta_i = 0 \quad \cdots 4F \quad \text{or} \quad 2F + 2CF
\]

\[
2\pi - \sum_{i=0}^{3} \theta_i = 0 \quad \cdots \quad 4CF
\]
Hybrid Surface:
BiDirectionally Flat-Foldable PQ Mesh
Rigid-foldable Cylindrical Structure
Topologically Extend Rigid Origami

• Generalize to the **cylindrical**, or higher genus rigid-foldable polyhedron.

• But it is not trivial!
Rigid-Foldable Tube Basics

Miura-Ori Reflection

(Partial Structure of Thoki Yenn’s “Flip Flop”)

\[
\begin{align*}
\phi & \quad \xi \\
\frac{\ell_0}{2} & \quad \ell
\end{align*}
\]
Symmetric Structure Variations
Parametric design of cylinders and composite structures
Cylinder -> Cellular Structure
[Miura & Tachi 2010]
Isotropic Rigid Foldable Tube Generalization

- Rigid Foldable Tube based on symmetry

- Based on
  - “Fold”
  - “Elbow”

= special case of BDFFPQ Mesh
Generalized Rigid Folding Constraints

• For any closed loop in Mesh

\[ T_{0,1} \cdots T_{k-2,k-1} T_{k-1,0} = I \]

where \( T_{i,j} \) is a 4x4 transformation matrix to translate facets coordinate \( i \) to \( j \)

• When it is around a vertex: \( T \) is a rotation matrix.
Generalized Rigid Folding Constraints

• If the loop surrounds no hole:
  – constraints around each vertex
• If there is a hole,
  – constraints around each vertex
+ 1 Loop Condition
Loop Condition: Sufficient Condition

Loop condition for finite rigid foldability

→ Sufficient Condition: start from symmetric cylinder and fix 1 loop
Manufactured From Two Sheets of Paper
Thickening

- Rigid origami is ideal surface (no thickness)
- Reality:
  - There is thickness
  - To make “rigid” panels, thickness must be solved geometrically
- Modified Model:
  - Thick plates
  - Rotating hinges at the edges
Hinge Shift Approach

• Main Problem
  – non-concurrent edges $\rightarrow 6$ constraints (overconstrained)

• Symmetric Vertex:
  – [Hoberman 88]
  – use two levels of thickness
  – works only if the vertex is symmetric ($a = b$, $c = d = \pi - a$)

• Slidable Hinges
  – [Trautz and Kunstler 09]
  – Add extra freedom by allowing „slide“
  – Problem: global accumulation of slide (not locally designable)
Our Approach

Hinge Shift

Volume Trim

Non-concurrent edges

Concurrent edges
Trimming Volume

• folds up to \( \pi - \delta \)

• offsetting edges by \( t \cot \left( \frac{\delta}{2} \right) \)

→ Different speed for each edge: Weighed Straight Skeleton
Variations

- Use constant thickness panels
  - if both layers overlap sufficiently
- use angle limitation
  - useful for defining the "deployed 3D state"
Example

• **Constant Thickness Model**
  - the shape is locally defined
  - cf: Slidable Hinge →
厚板のカッティングパターン生成

- 実装
  - Grasshopper + C# components (Rhinoceros Plugin)

- 二次元パターン
  - 2軸 CNC マシンで構築可能

- カッティングプロッタ
- レーザーカッター
- ユッードルータ

組み立ての合理化の可能性
Example: Construct a foldable structure that temporarily connects existing buildings.

- **Space: Flexible**
  - Connects when opened
    - Openings: different position and orientation
    - Connected gallery space
  - Compactly folded
    - to fit the facade

- **Structure: Rigid**
  - Rigid panels and hinges
Panel Layout