Creating Foldable Polyhedral Nets Using Evolution Control

http://masc.cs.gmu.edu/wiki/LinearlyFoldableNets

Yue Hao¹, Yun-hyeong Kim², Zhonghua Xi¹ and Jyh-Ming Lien¹

¹ Dept. of Computer Science, George Mason University
² Seoul National University

Background

Polyhedral nets are 2D unfoldings of 3D meshes. Have many applications in Robotics:
- Self-folding robots using active material or mechanically driven hinges
- Fabricating 3D structures using 2D materials
- Transporting and storing in compact forms

A Very Challenging Problem

Designing the foldable nets is similar to designing the structure of a robot that would perform certain required motion

Motivation: The foldability of the nets created from a single polyhedron varies significantly. We seek to finding nets that are linearly foldable.

Our Approach

- Geometric and Topological Features
  - Problem: evaluating foldability \( f^* \) is computationally expensive.
  - Idea: Extract features of Number of Leaf Nodes, Cut Length, Border Cut Length, Hull Area etc. as \( x_i \).
  - Construct a fitness function \( f(x_i) \) to replace \( f^* \), and optimize \( f \) in a low dimensional feature space.
  - Genetic-based Unfolder

  \[ f = -(x_0 + x_1) \]  
  \[ f = f(x_1) \]

  An exemplar unfolder generating nets with minimum sized convex hull bounding it.

  - Genetic Algorithm to evolve the unfoldings by mutating the weights on the dual edges.
  - When the net is invalid, minimizes the number of overlapping faces.
  - If the net is flattened, use \( f \) to further evolve the net towards higher foldability

Results

- Learning Curve: Median Folding Path Planning Time (Foldability) – Iteration

  Foldability optimized in 50 iter. for simple models.

- Handling Complex Models

  Transfer learning accelerates the optimization for complex models by simplifying the polyhedron

  The total time cost to optimize \( f_{64} \), \( f_{128} \) is still lower than directly using \( f_{128} \) from the beginning.

- Evolution Control Learning Strategy
  - Generate a set of hypothesis fitnesses \( \tilde{f} \)\_init used in multiple genetic-based unfolder.
  - Each unfolder produce the individuals in the last generation that have highest fitness.
  - Use a motion planner to evaluate the foldability of the nets \( f^*_i \).
  - CMA-ES to generate a new set of fitness \( (f_i)_{new} \) according to evaluation \( (f_i f^*_i)_{out} \).

- Linearly & Uniformly Foldable Nets

  - Linearly Foldable Nets have a collision-free linear folding path in C-Space
  - Uniformly Foldable Nets can fold under the constraint that all hinges rotate uniformly at the same speed (good for active material self-folding)

Conclusion

- Proposed a computational design of polyhedral nets for complex foldable structures
- The linearly and uniformly foldable nets limit the self-collision issues for foldable structures satisfying material constraints
- The generally foldable nets simplifies the design of the control mechanisms when making deployable shape morphing devices
- Our method can be adapted to find foldable nets that satisfy other user-defined motion constraints
- Limitations in scalability: Large nets with distinct foldability may be mapped to similar spots in the feature space, which makes optimization difficult