DSCarver: Decompose-and-Spiral-Carve for Subtractive Manufacturing

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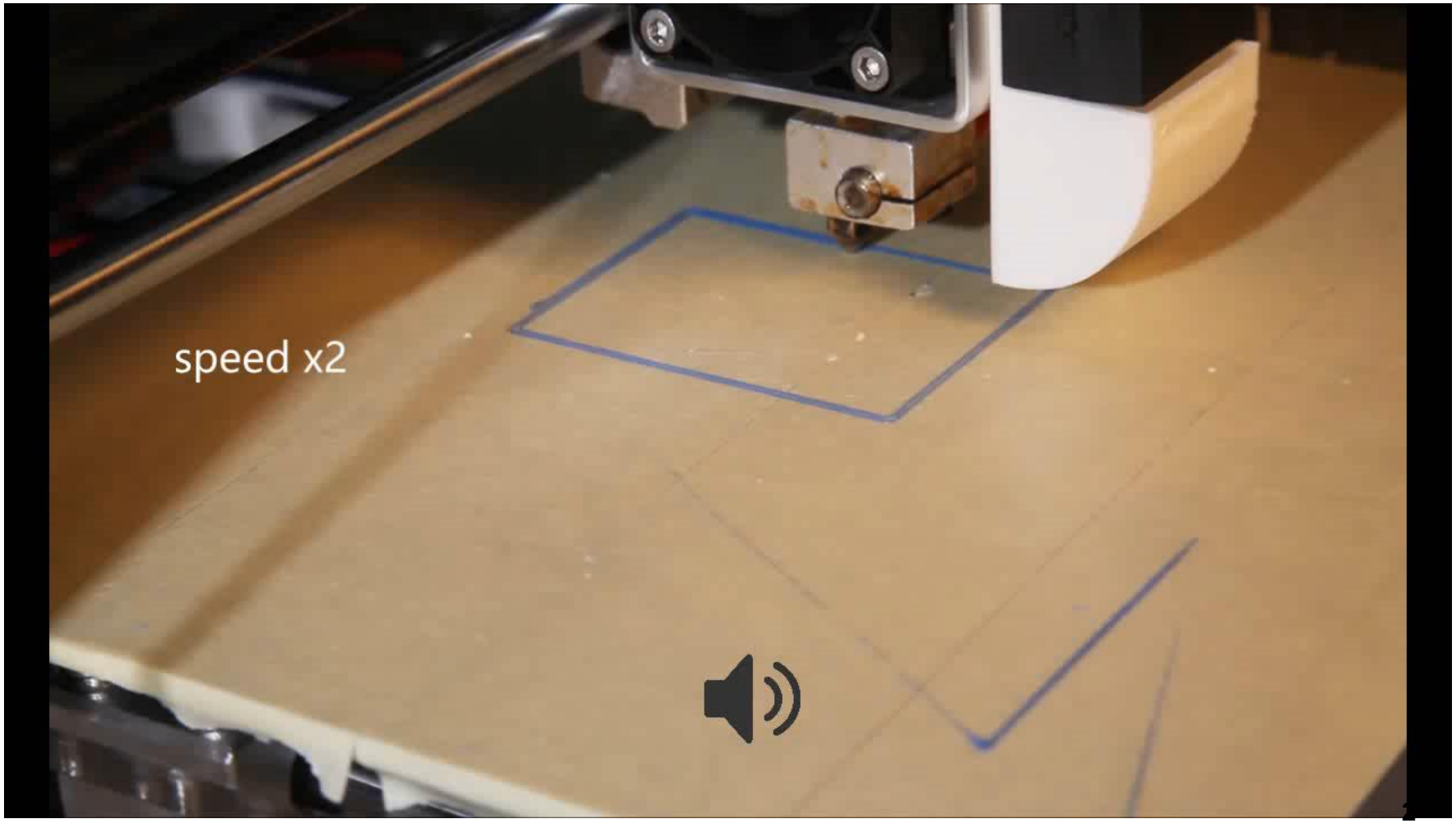
Inspiration

- Connected Fermat Spirals for Layered Fabrication, SIG 2016



Connected Fermat spirals: continuous

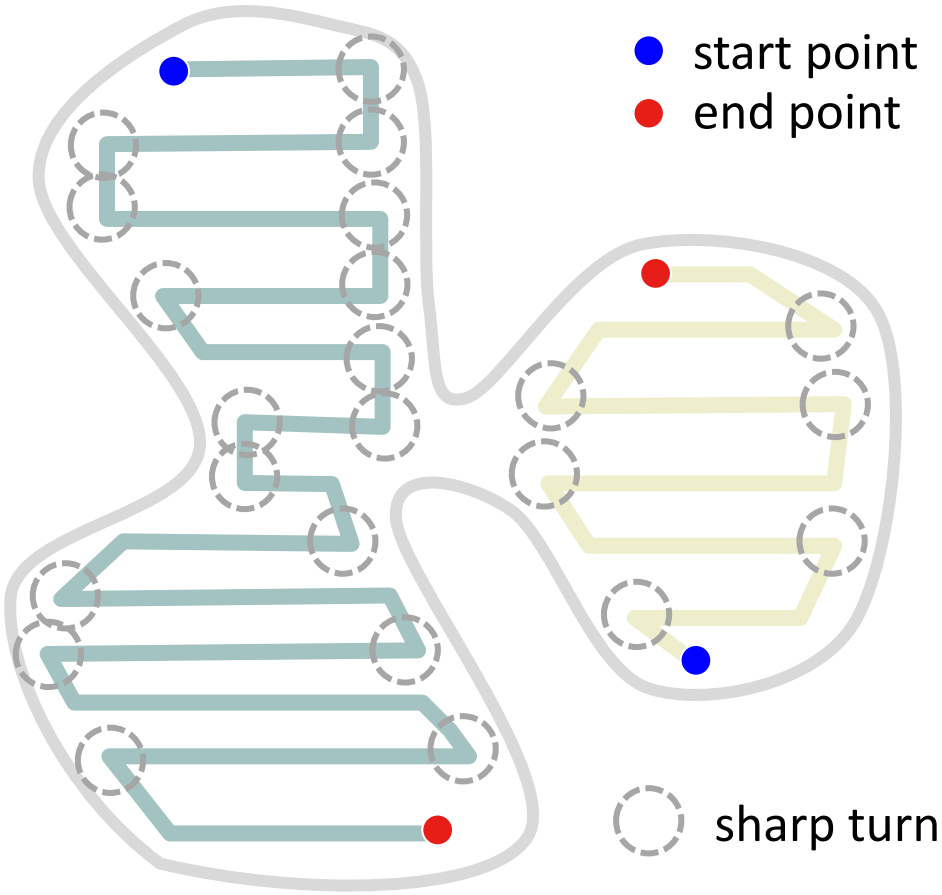
A Fermat spiral

Connected Fermat Spirals
(globally continuous space filling curves)

Connected Fermat spirals: lower curvature

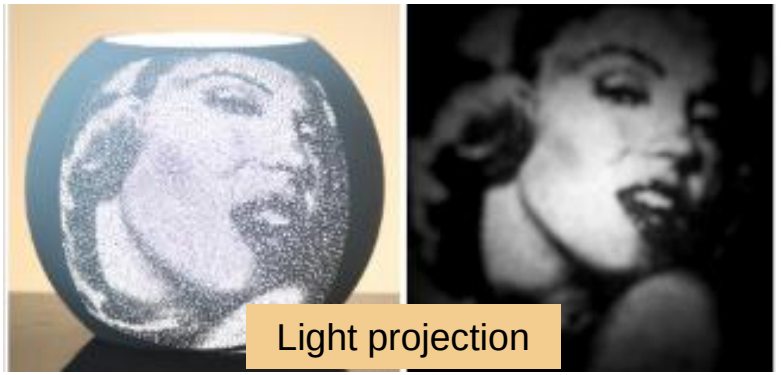
Connected Fermat spirals

(lower curvature and less number of sharp turns)

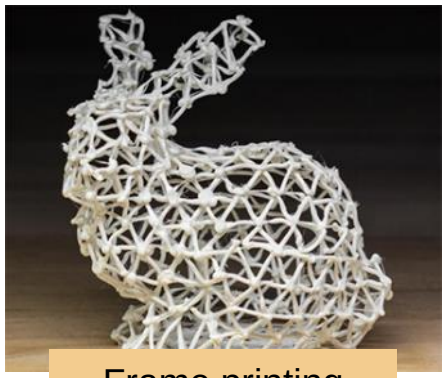


Zigzag

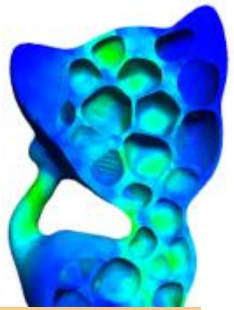
Additive manufacturing is popular!


Light projection


Designs


Frame printing

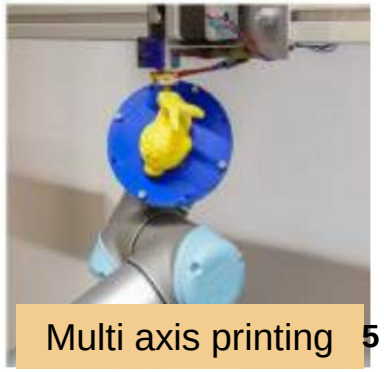

Decomposition and packing


Hollowing


Clever support


Improving stability

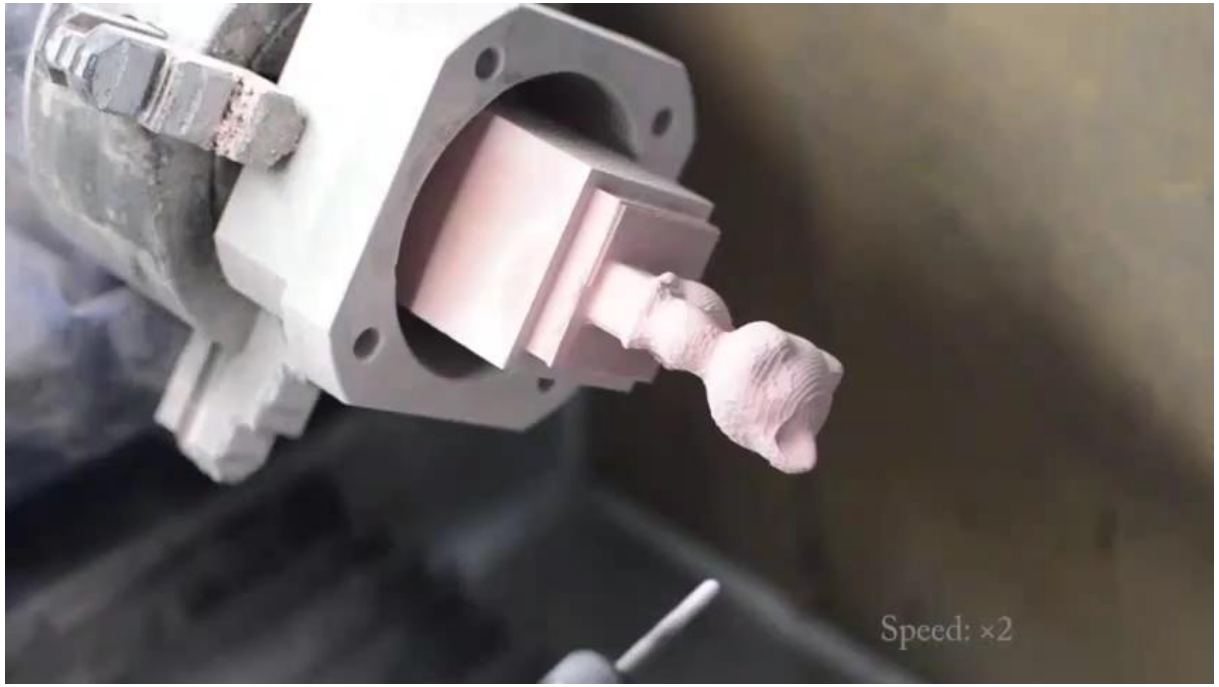
Large object


Multi axis printing

Subtractive manufacturing

- Still a **more dominant** fabrication technology

A CNC machine

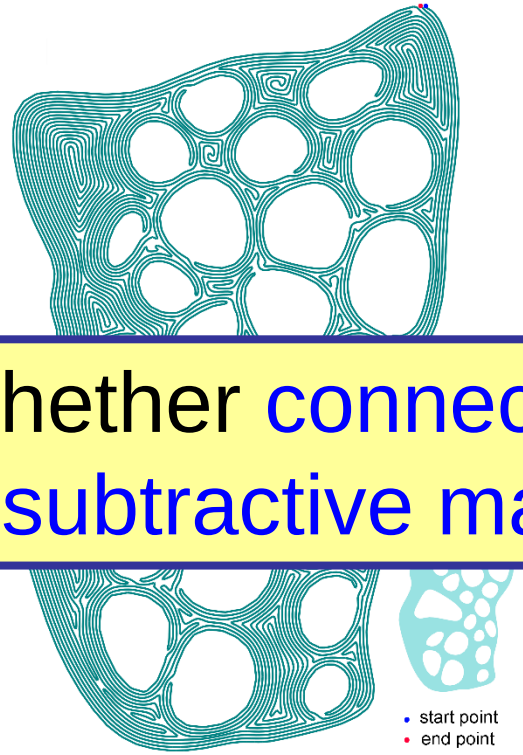


CNC machining process

Subtractive manufacturing

- Tool path planning
  - Space filling curves to cover surface regions

carving



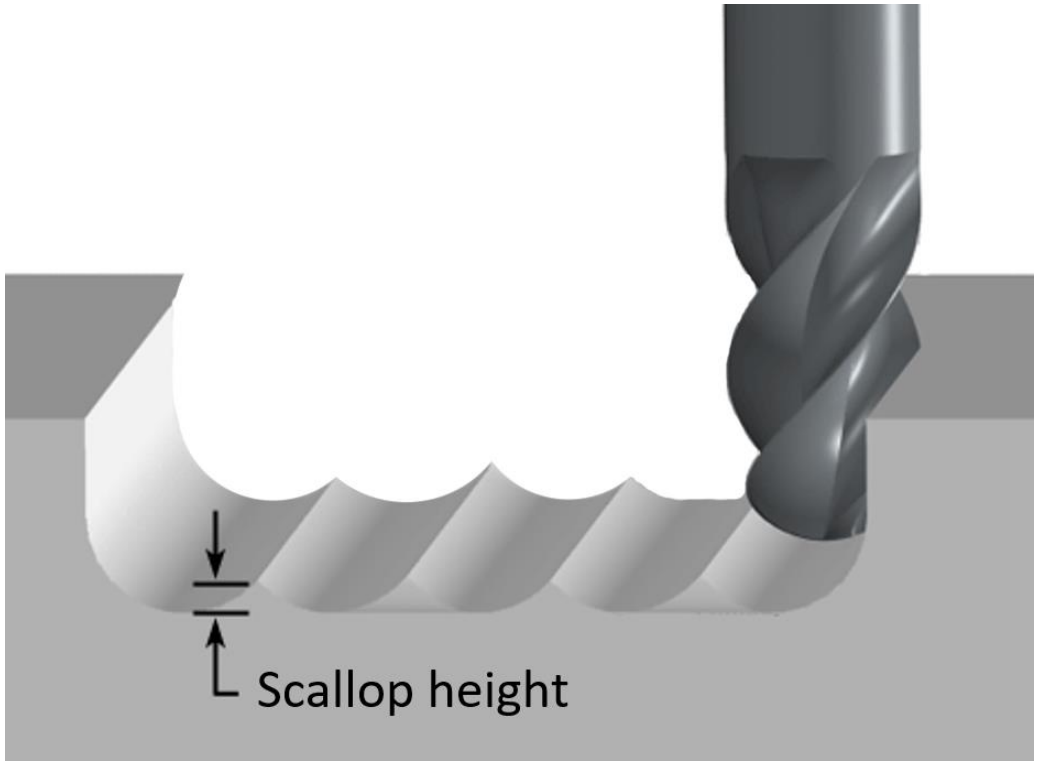
2D layers in 3D printing

Curved surfaces

Whether connected Fermat spirals can be extended to subtractive manufacturing of freeform 3D objects?

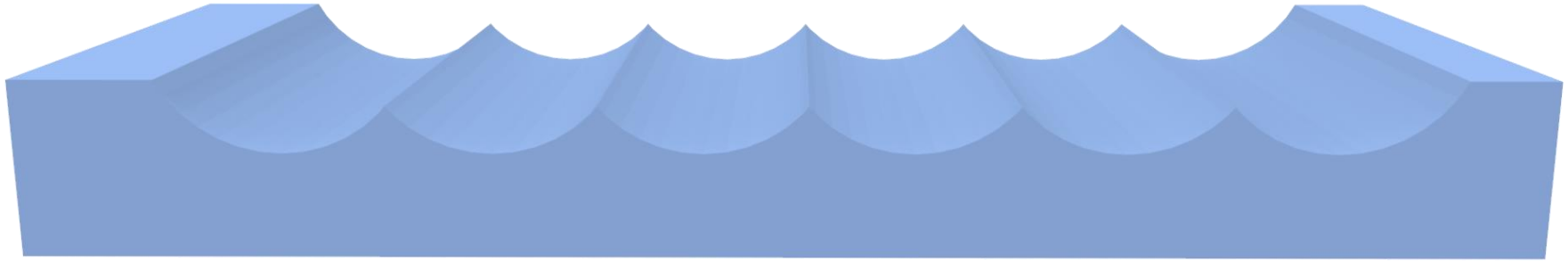
Carved surface quality

- Carved surface exposed outside
  - Visual quality is very important
- Critical measures of quality
  - Scallop: residual material after carving
- High-quality surface finishes
  - Scallop to be uniform distribution
- ISO-scallop tool paths

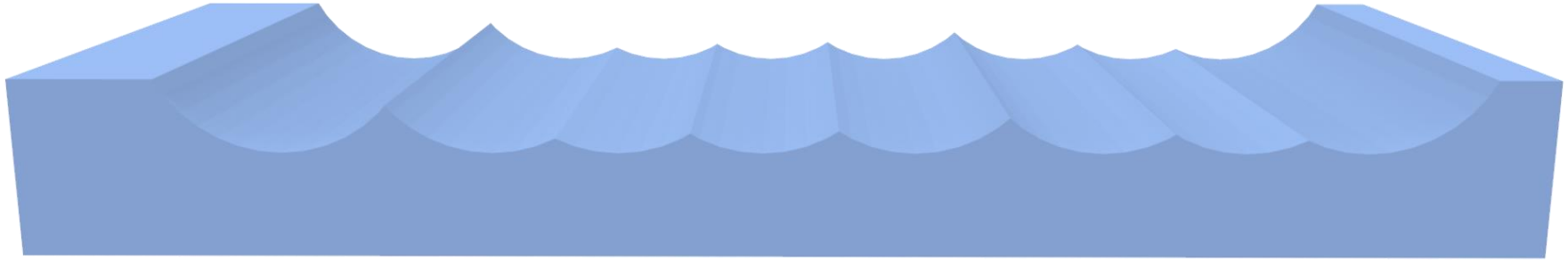


Carved surface efficiency

- Uniform scallop distribution also increase machining efficiency
- Maximal scallop height

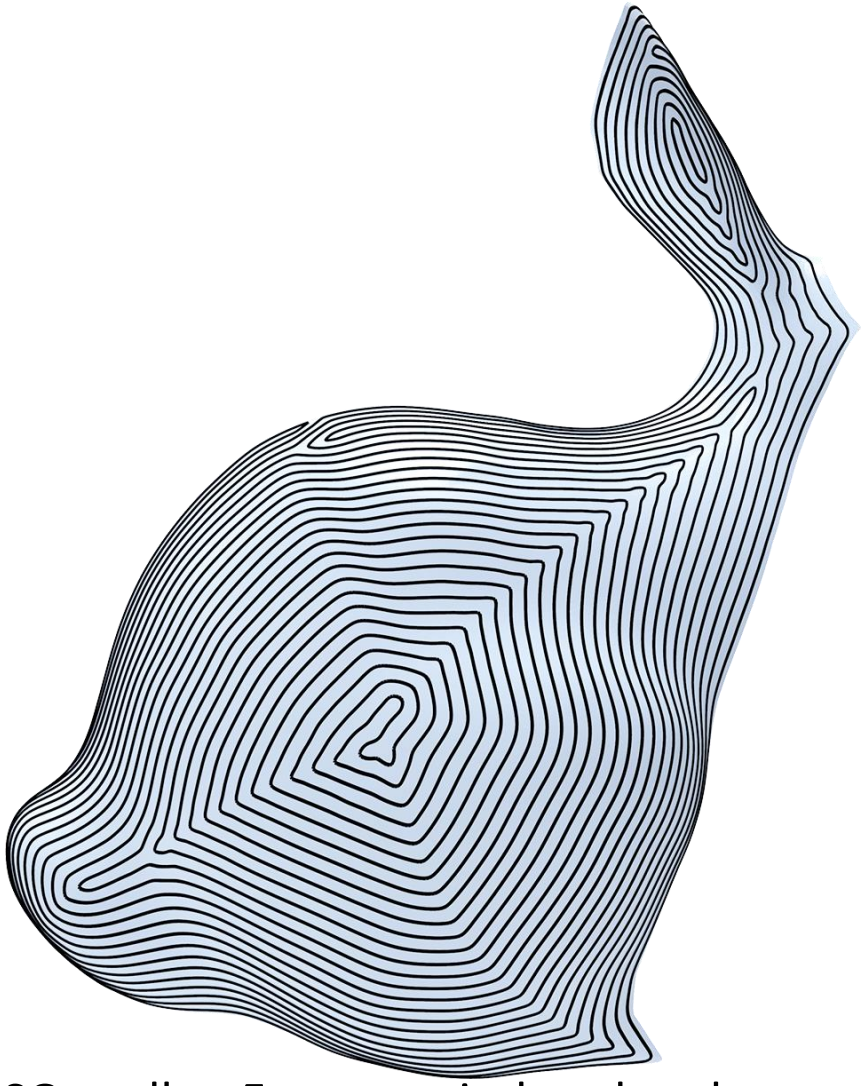


ISO-scallop tool path

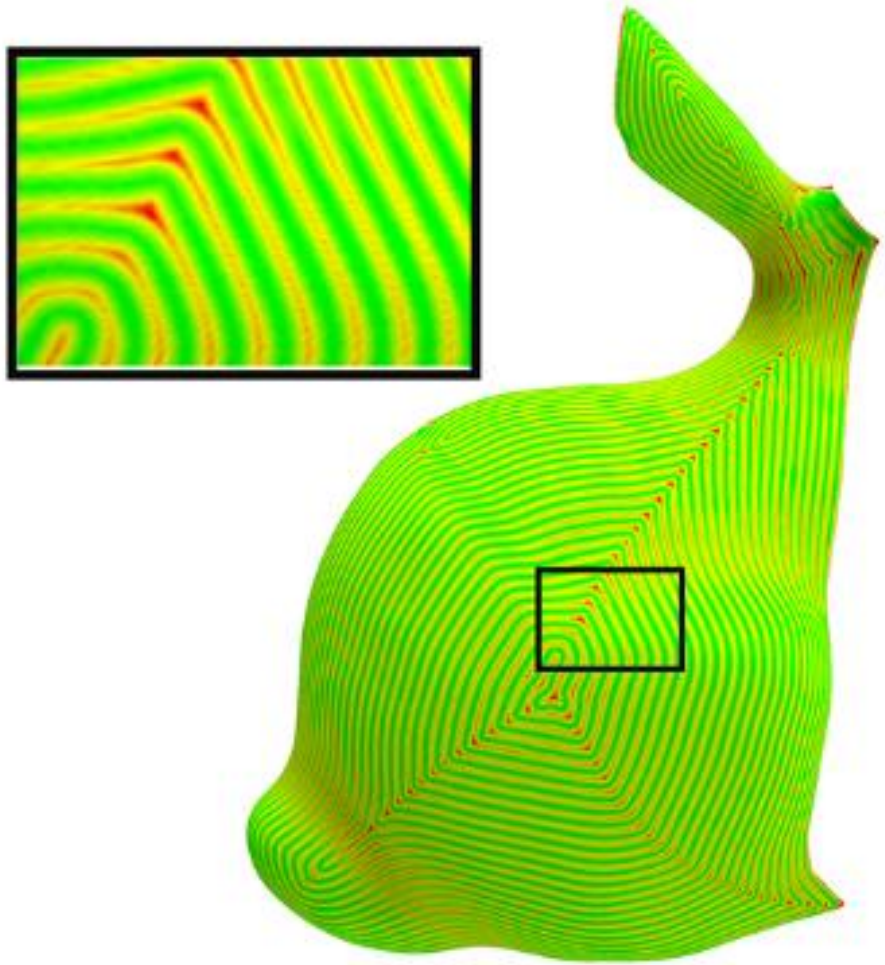


Non-uniform scallop tool path

ISO-scallop Fermat spiral tool path



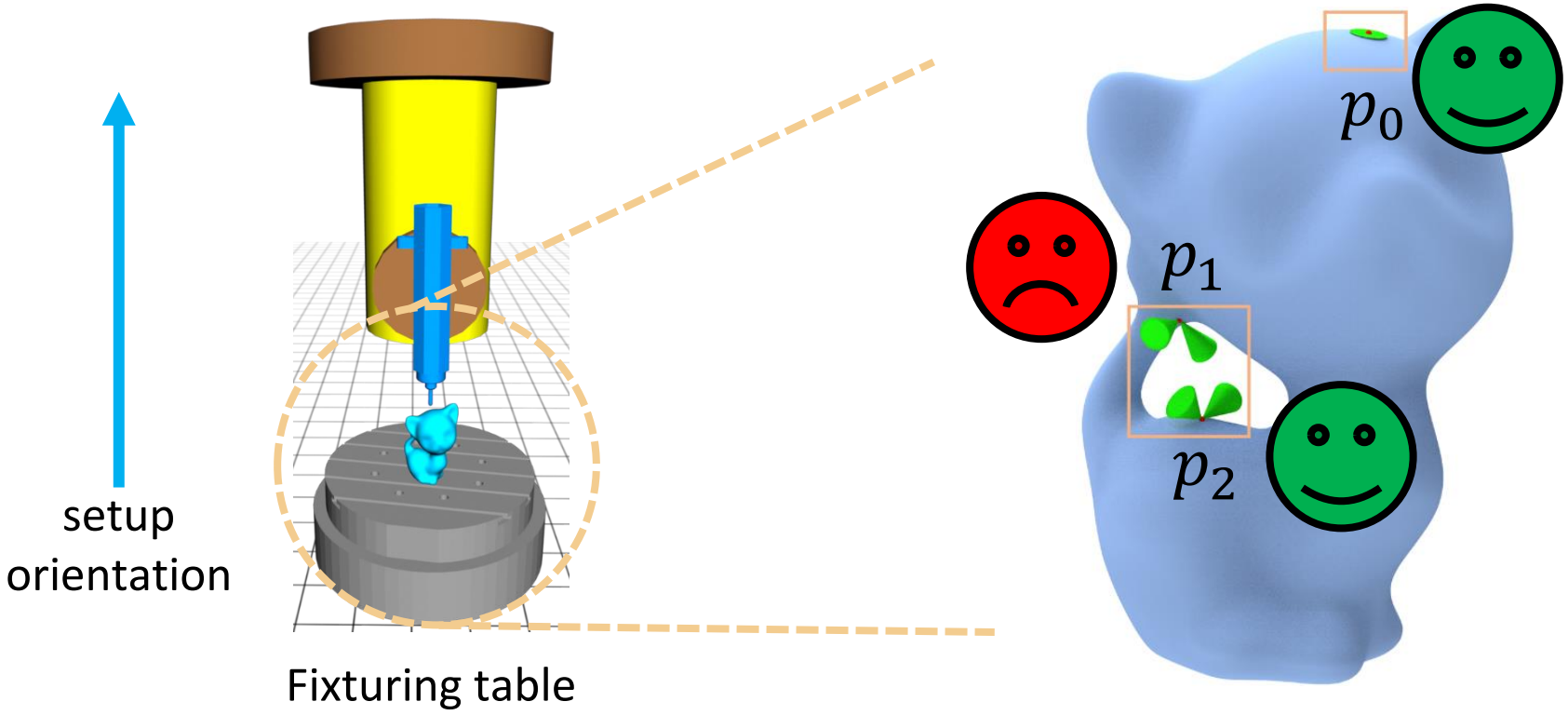
ISO-scallop Fermat spiral tool path



Scallop height visualization

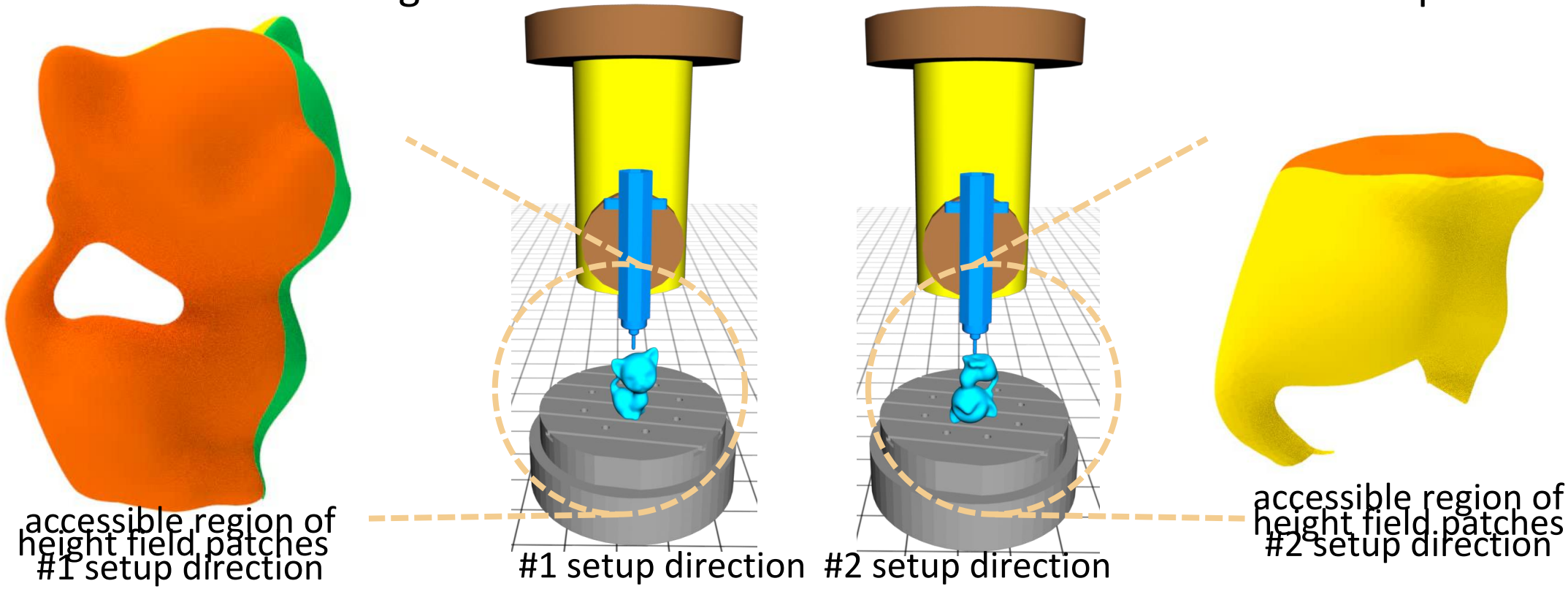
Problems before surface carving

- Ensure that all surface regions are accessible by the CNC cutter
- In general, the cutter cannot access all regions of an arbitrary 3D object



Decomposition problem

- Decompose the surface of an input 3D object into a small number of accessible regions by the cutter
- Minimizing the number of accessible regions
  - Each accessible region => CNC machine needs to be calibrated and set up



Contributions

- Connected Fermat spirals from additive to subtractive manufacturing
  - Accessibility-based decomposition
  - ISO-scallop tool path planning over curved surface regions

- Contributions in this work
  - A decomposition algorithm
  - A tool path planning process based on ISO-scallop connected Fermat spirals

Contributions

- CAD models
  - much attention in CNC machining
  - many efficient methods for each planning step

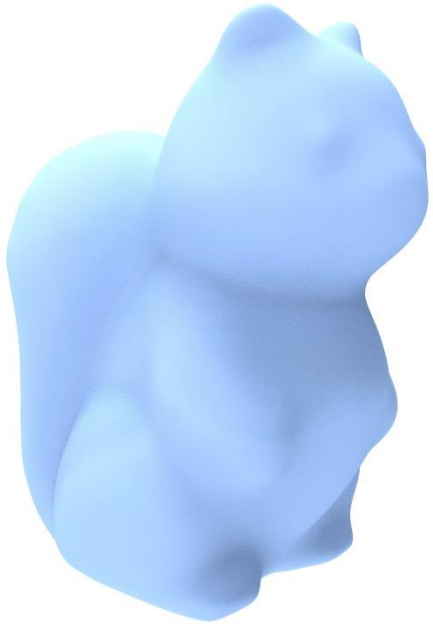
CAD models
(planes and other parameterizable patches)

- Free-form 3D objects
  - hard to apply an automatic process of CNC machining

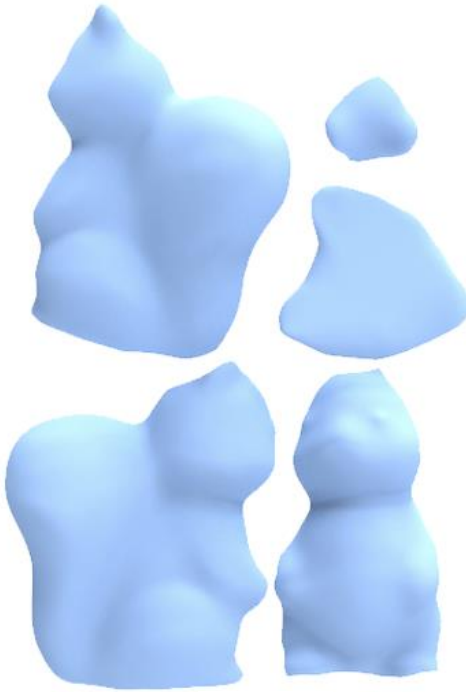
Free-form 3D objects
(formed by free-form or sculpted surfaces)

Pipeline

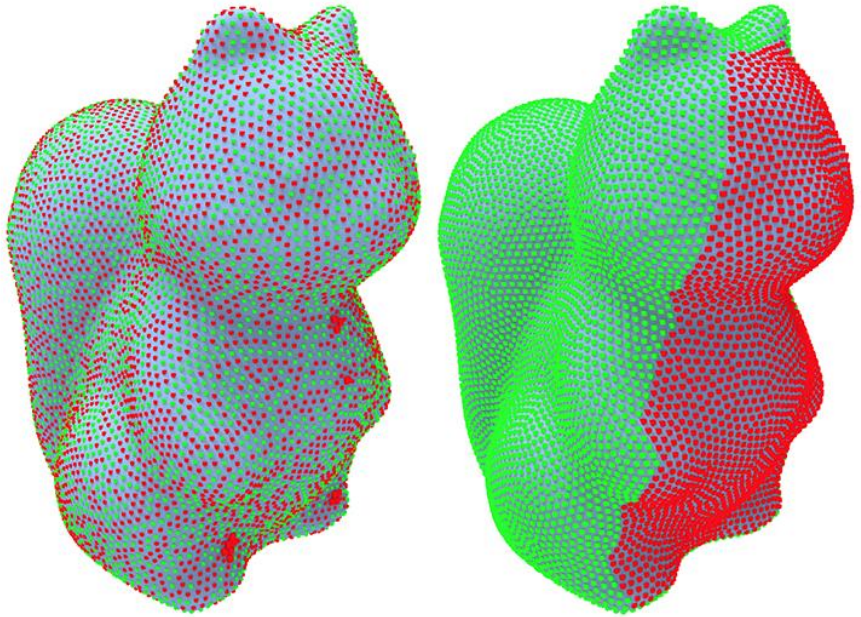
- *DSCarver*: Decompose-and-Spiral-Carve
- Subtractive manufacturing of freeform 3D objects



Freeform 3D object



Height fields

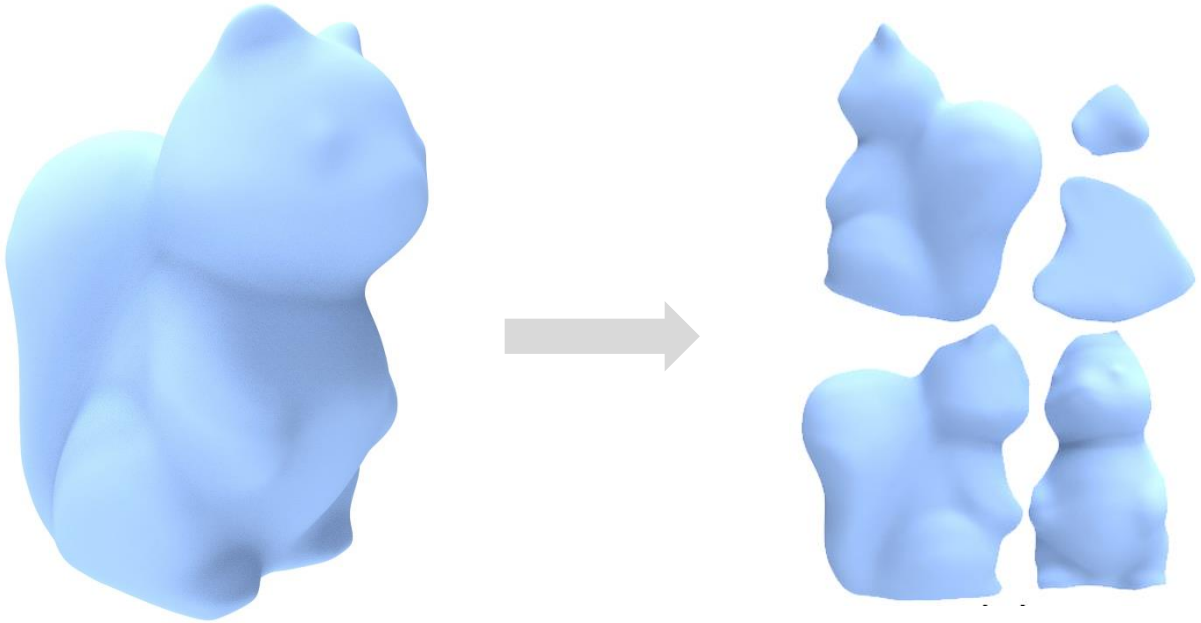


Minimum number of accessible regions

Tool path generation

Height fields decomposition

- Approximated height fields decomposition method for 3-axis milling[Philipp et al. 2015]
- Pre-computing stage (3+2 machining mode)



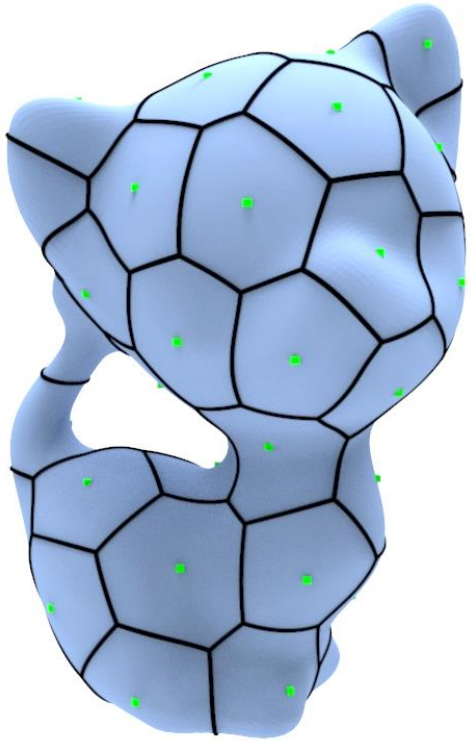
Input surface

A small number of height fields

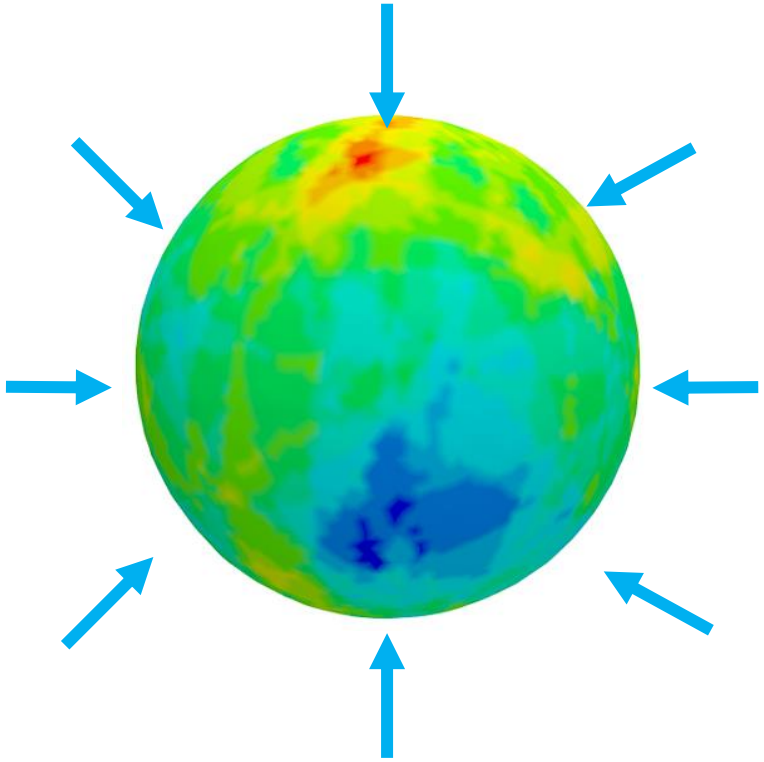
Philipp Herholz, Wojciech Matusik, and Marc Alexa. 2015. Approximating Free-form Geometry with Height Fields for Manufacturing. Computer Graphics Forum (Eurographics) 34, 2 (2015), 239–251.

Setup directions sampling

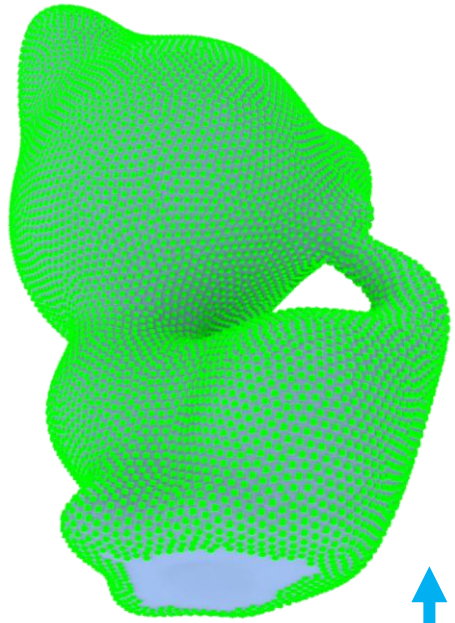
- Select a set of candidate setup directions



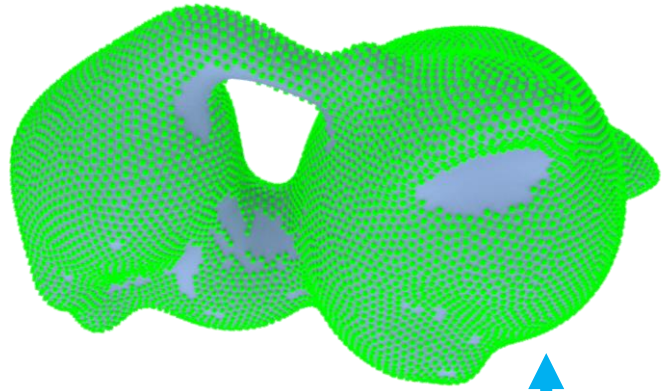
Voronoi tesselation



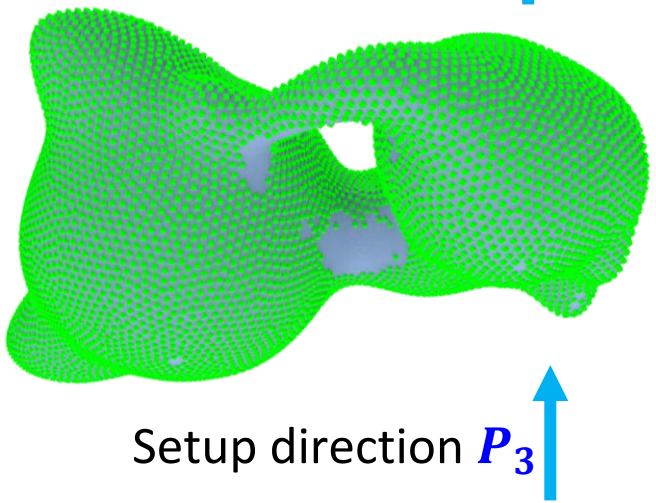
Gaussian sphere



Setup direction P_1



Setup direction P_2



Setup direction P_3

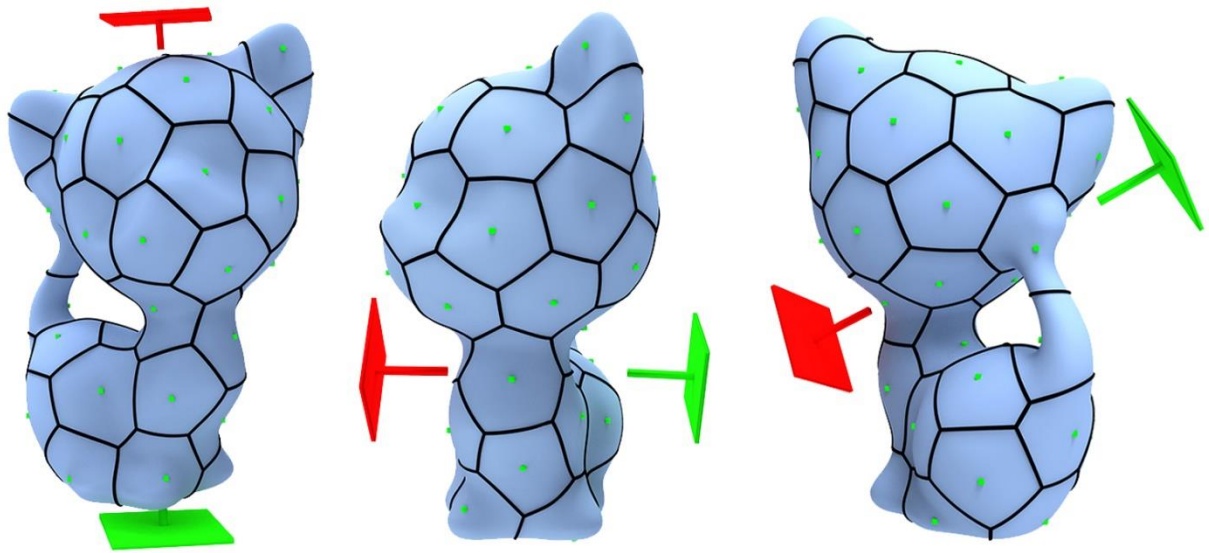
Accessible region

Set cover to MINORI

Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, and Clifford Stein. 2001. Introduction to Algorithms. MIT Press and McGraw-Hill.

- Accessible regions computing problem as a set-cover problem[Chvatal 1979]
  - Voronoi cells c_i as elements of the universe U;
  - Accessible region S_i of each setup direction P_i is a subset of universe U;

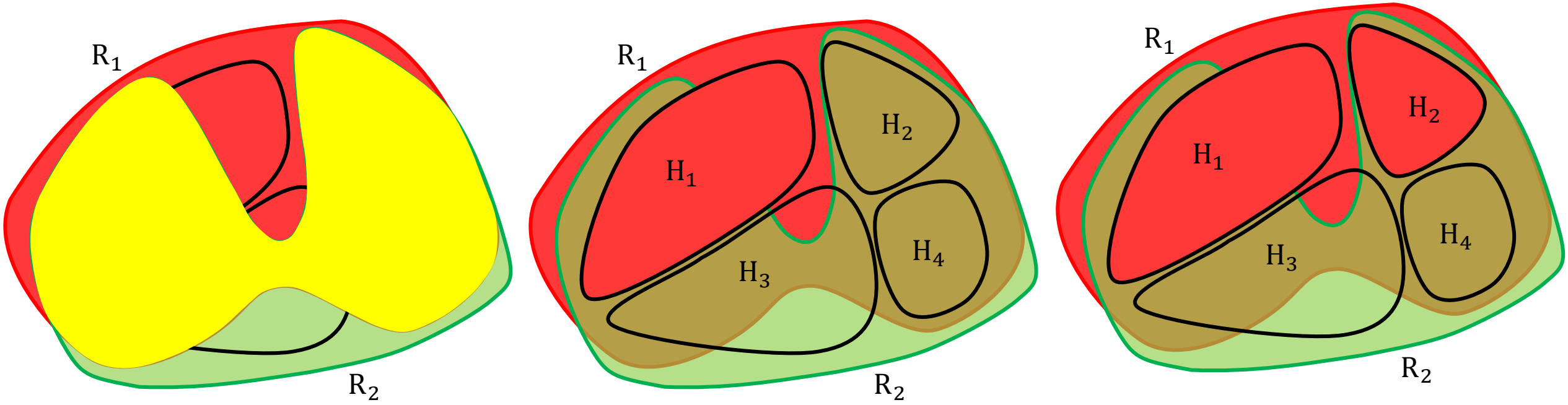
- MINORI: a set of minimal number of orientations



Three MINORIs with two setup directions

Label assignment and propagation

- A MINORI solution typically contains many cells that are accessible from more than one setup direction.



- Unassigned height fields are split by a graph cut process!

Overlap resolution by graph cut

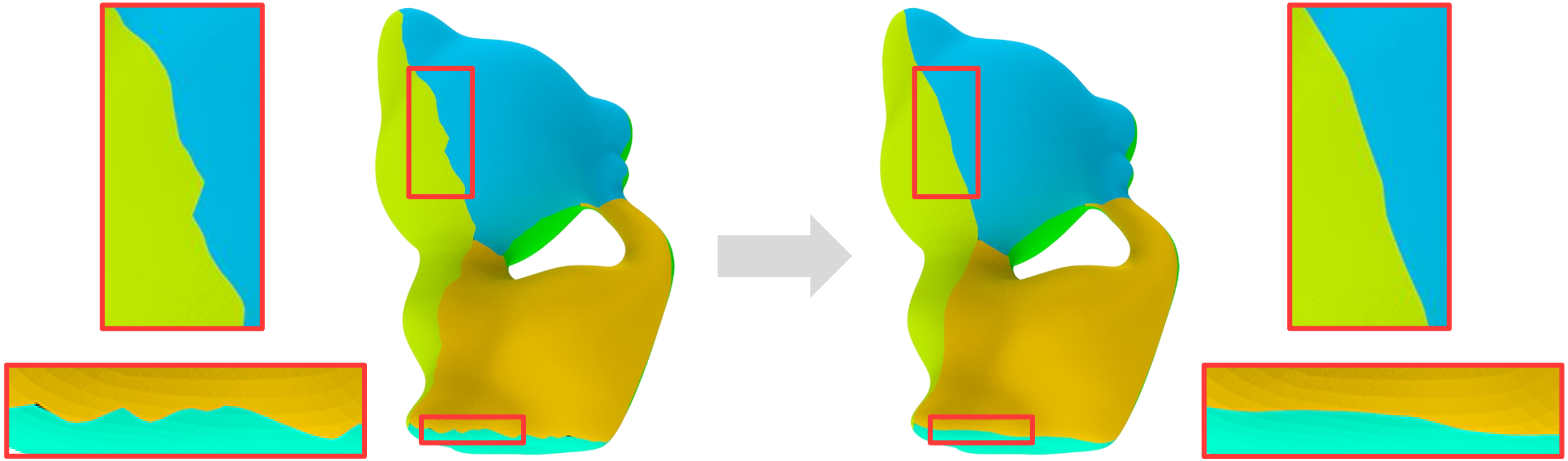
- Graph cut [Boykov et al. 2001] to split unassigned height fields
  - boundary smoothness
  - along low curvature paths
- Energy minimization defined over the cells $\boldsymbol{c_i},\ \boldsymbol{i = \{1, 2, \cdots, n\}}$ in the overlapping region:

$$E(r) = \sum_{i=1}^{m} D(r(c_i)) + \alpha \sum_{(ij)} S(r(c_i), r(c_j)),$$

Yuri Boykov, Olga Veksler, and Ramin Zabih. 2001. Fast Approximate Energy Minimization via Graph Cuts. *IEEE Trans. Pat. Ana. & Mach. Int.* 23, 11 (2001), 1222–1239

Boundary smoothness

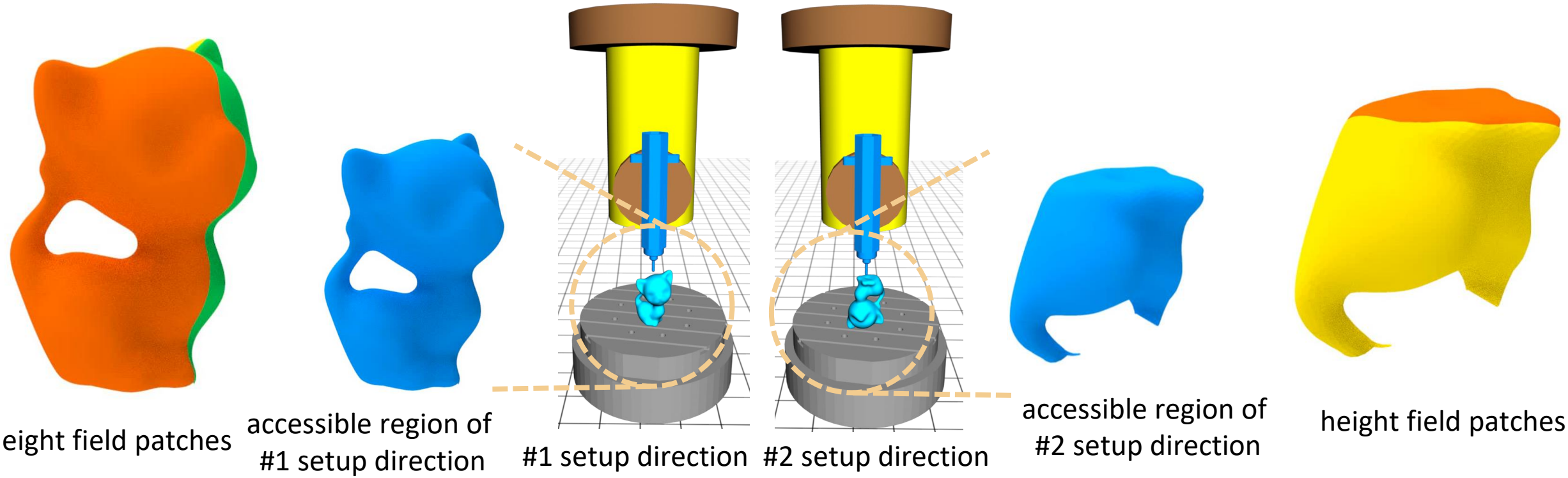
- Geometric snake method[Lee and Lee 2002].



Yunjin Lee and Seungyong Lee. 2002. Geometric Snakes for Triangular Meshes. *Computer Graphics Forum* 21, 3 (2002), 229–238.

Accessible regions decomposition

- Minimal number of accessible regions corresponding to setup directions

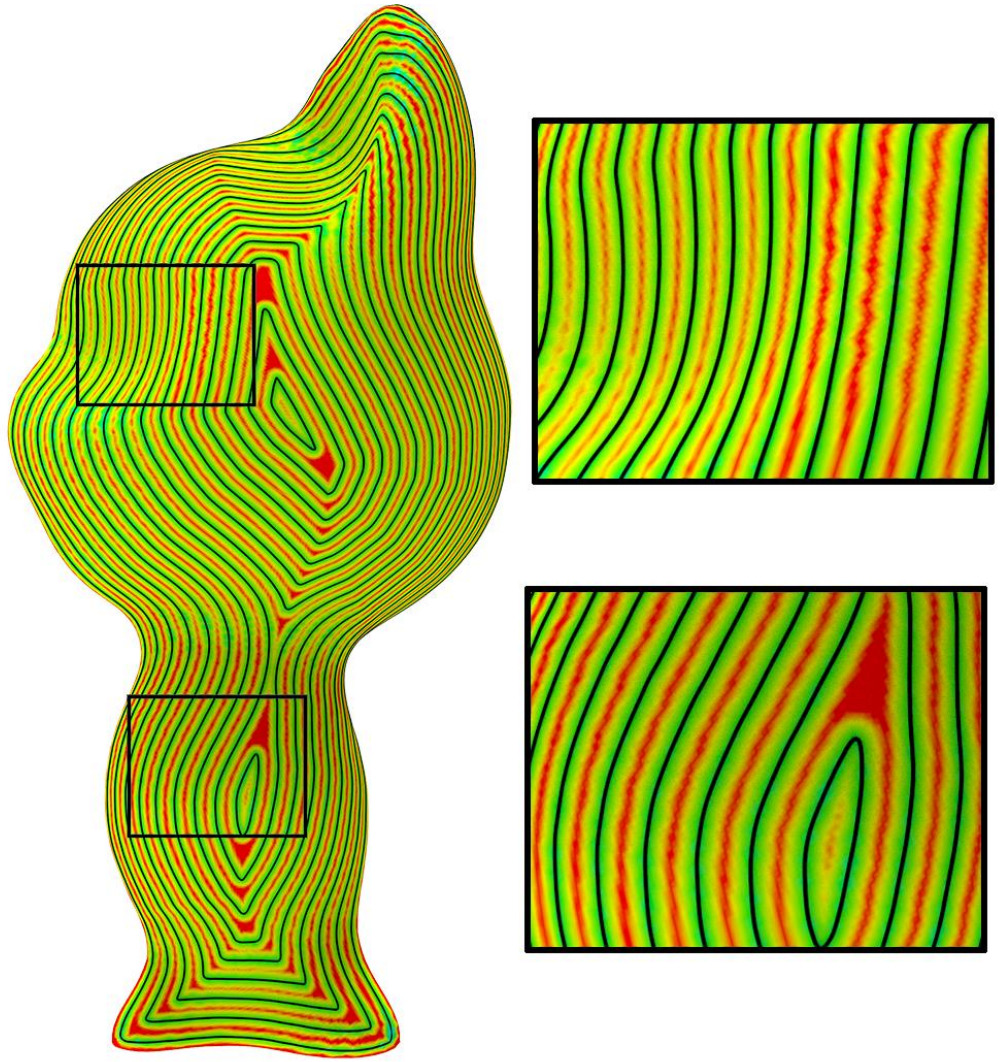


Tool path planning

- Designed for each accessible region
  - Smoothness, continuous
  - maximal uniform scallop distribution

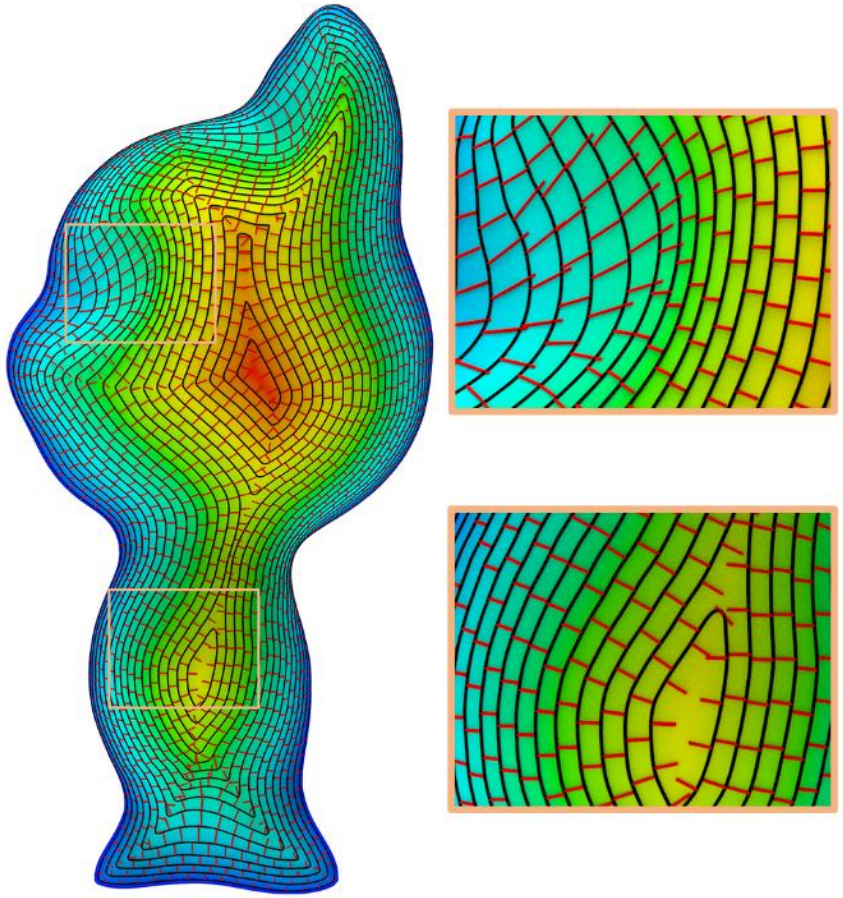
- Equally-spaced curves ≠
  uniform scallop distribution

- The gap between neighboring paths
  to be **adaptive**!



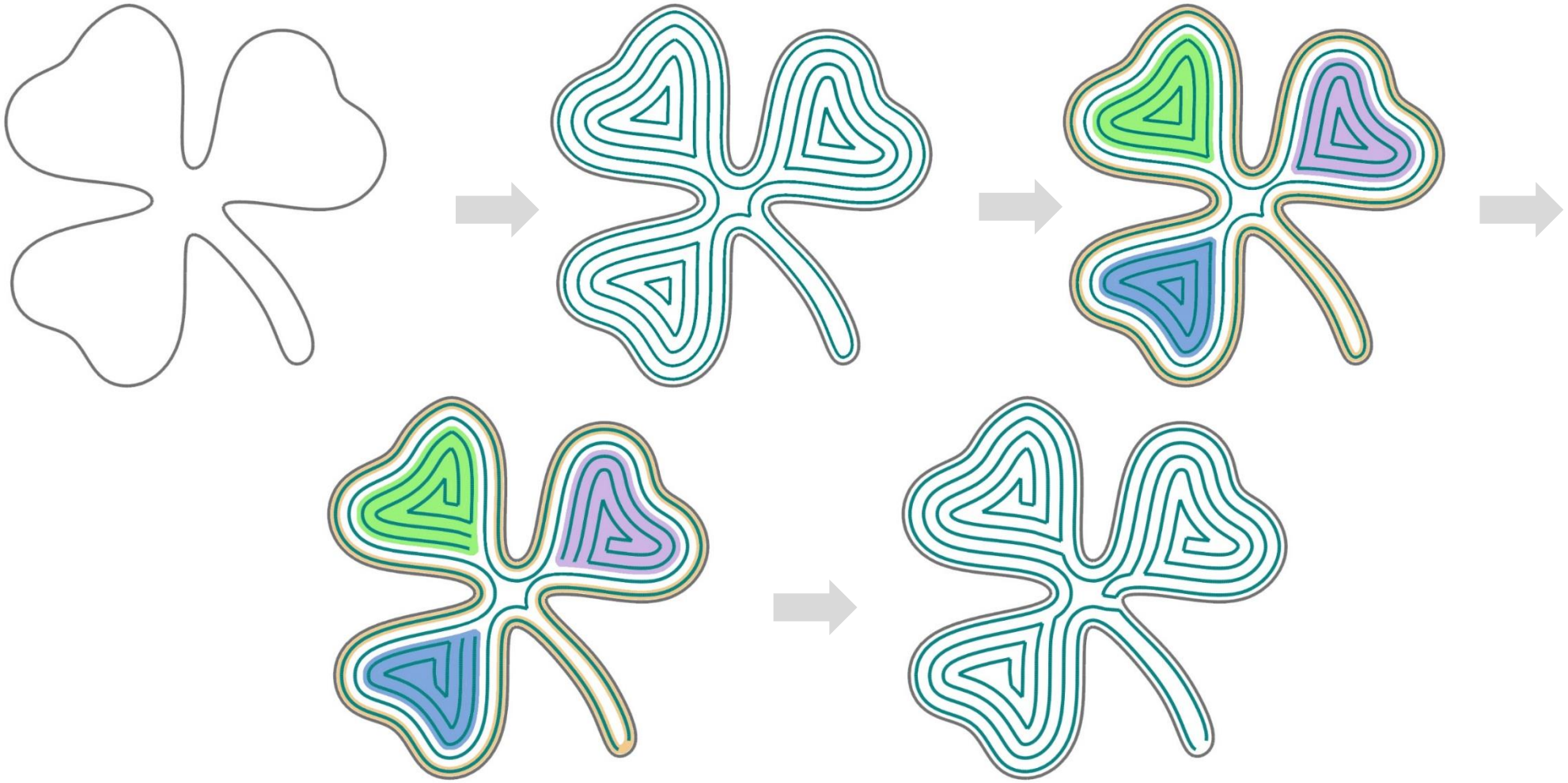
Scallop distribution

- Adaptive scalar field whose isolines meet the gap requirement



Keenan Crane, Clarisse Weischedel, and Max Wardetzky. 2013a. Geodesics in Heat: A New Approach to Computing Distance Based on Heat Flow. ACM Trans. on Graph 32, 5 (2013), 152:1–152:11.

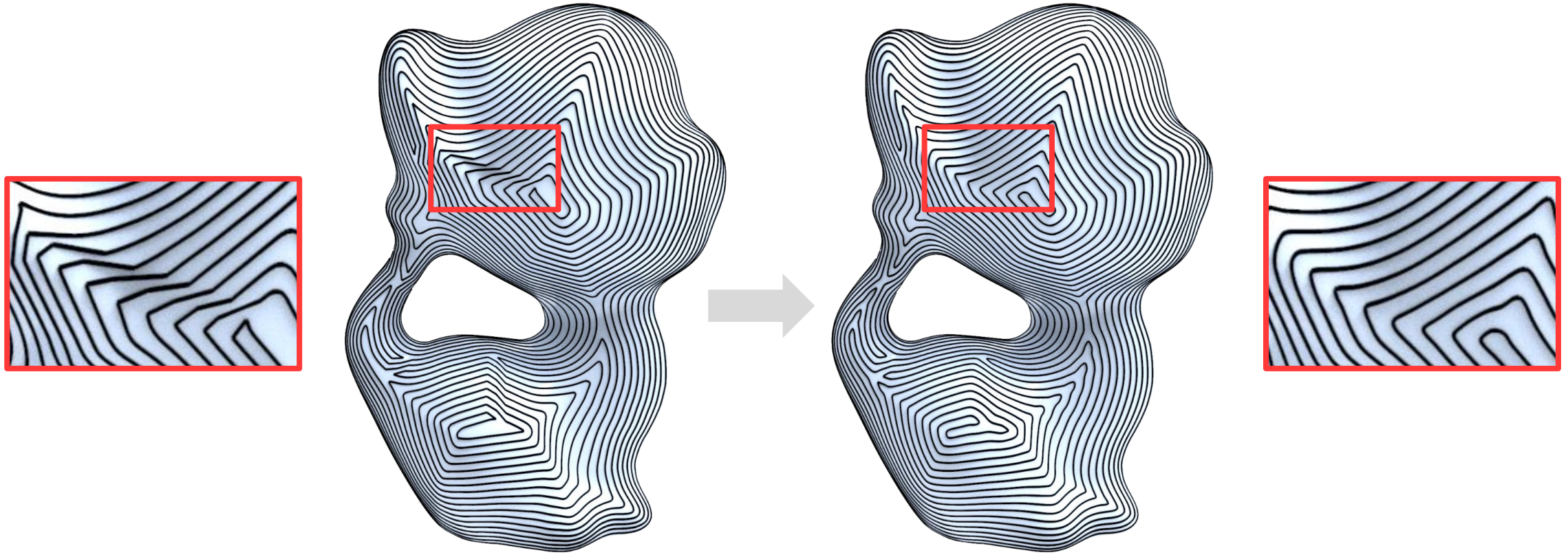
Connected Fermat Spirals (CFS)



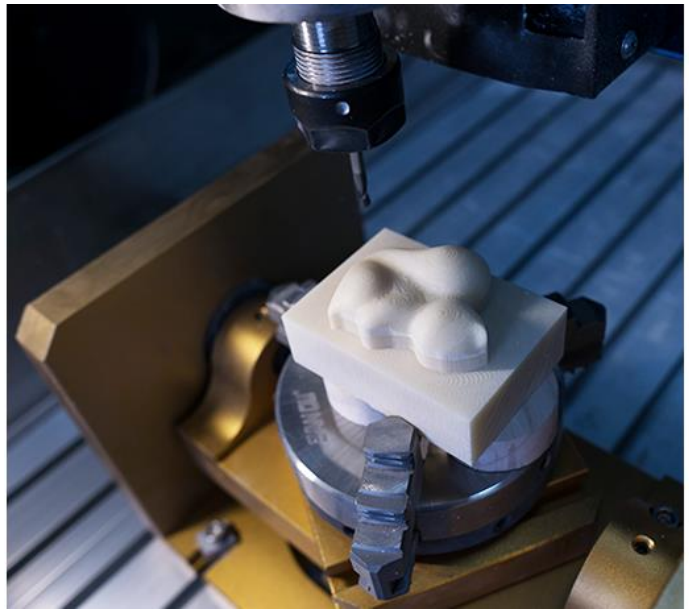
Haisen Zhao, Fanglin Gu, Qi-Xing Huang, Jorge Garcia, Hao Zhang, Daniel Cohen-Or, Yong Chen, Changhe Tu, and Baoquan Chen. 2016. Connected Fermat Spirals for Layered Fabrication. *ACM Trans. on Graph* 35, 4 (2016)

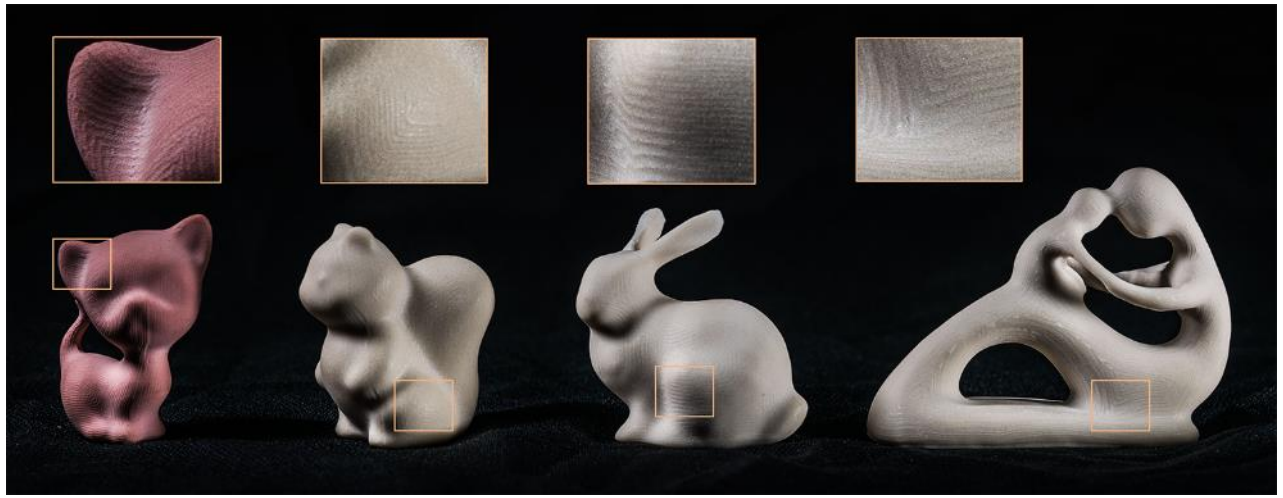
Tool path refinement

- Locally optimize continuous path
  - fairness and uniform scallop distribution



Experiments environment

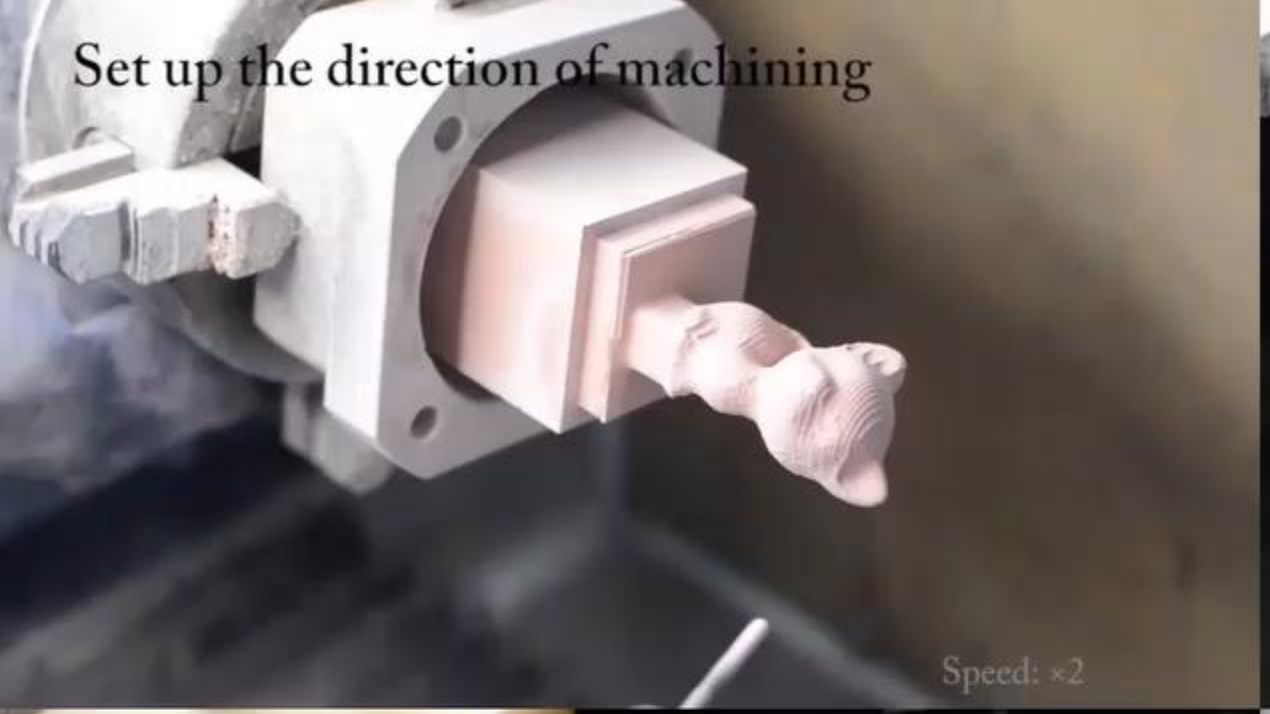




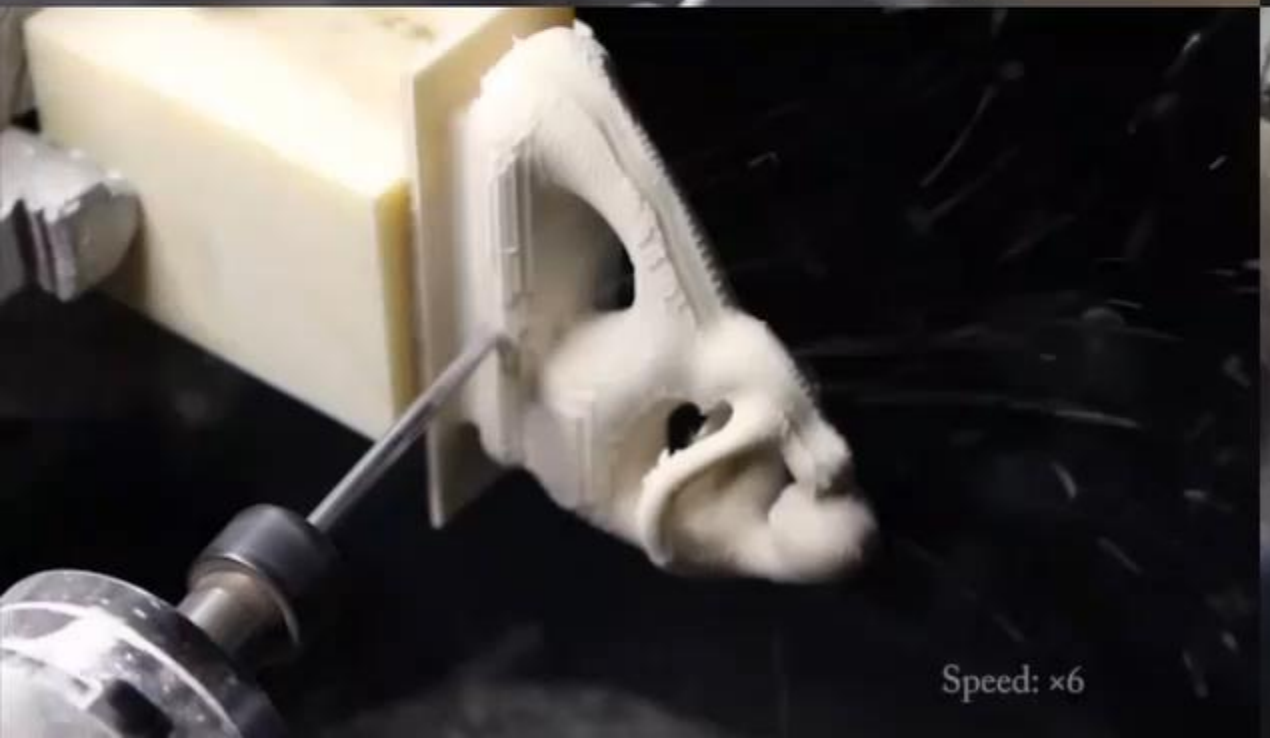
CNC 6040 2200W 5-axis machine

- Max scallop height: 0.045mm
- Cutter diameter: 4.0mm
- Feed rate: 500mm/min
- Chord error: 0.001mm
- Spindle speed: 15000r/min
- G-code is used to transfer the tool paths.

Real machining results of full 3D objects, with machinable resin boards as testing material.

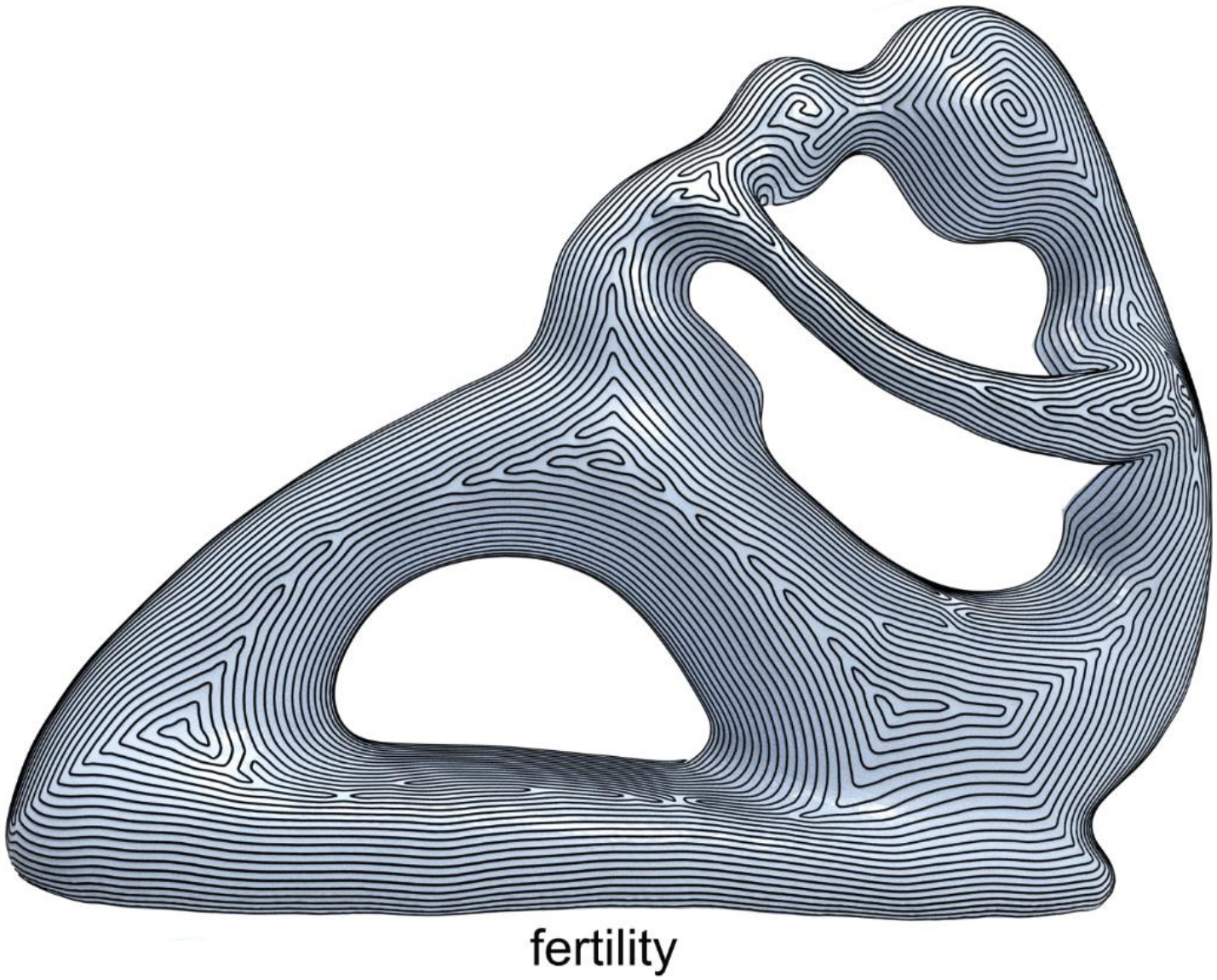

Set up the direction of machining
Speed: ×2


1st piece
Speed: ×2


Speed: ×6


Set up the direction of machining
Speed: ×2

Results



Results

F: ISO-scallop connected Fermat spirals **Z**: zigzag paths  **C**: contour-parallel paths 

Patch	#sgZ	#sC	#sgF	%tnZ	%tnC	%tnF	t_Z	t_C	t_F
#1 (BUNNY)	9	4	**1**	7.1%	4.7%	**1.5%**	450	368	**342**
#2 (FERTILITY)	18	6	**1**	6.6%	4.0%	**3.8%**	1908	1054	**1034**
#3 (MAXPLANK)	5	**1**	**1**	7.6%	6.0%	**2.5%**	245	232	**205**
#4 (SQUIRREL)	6	**1**	**1**	6.0%	2.8%	**1.9%**	539	428	**416**
#5 (KITTEN)	11	2	**1**	7.4%	3.7%	**2.8%**	469	381	**370**

#disconnected segments % sharp turns Real machining time

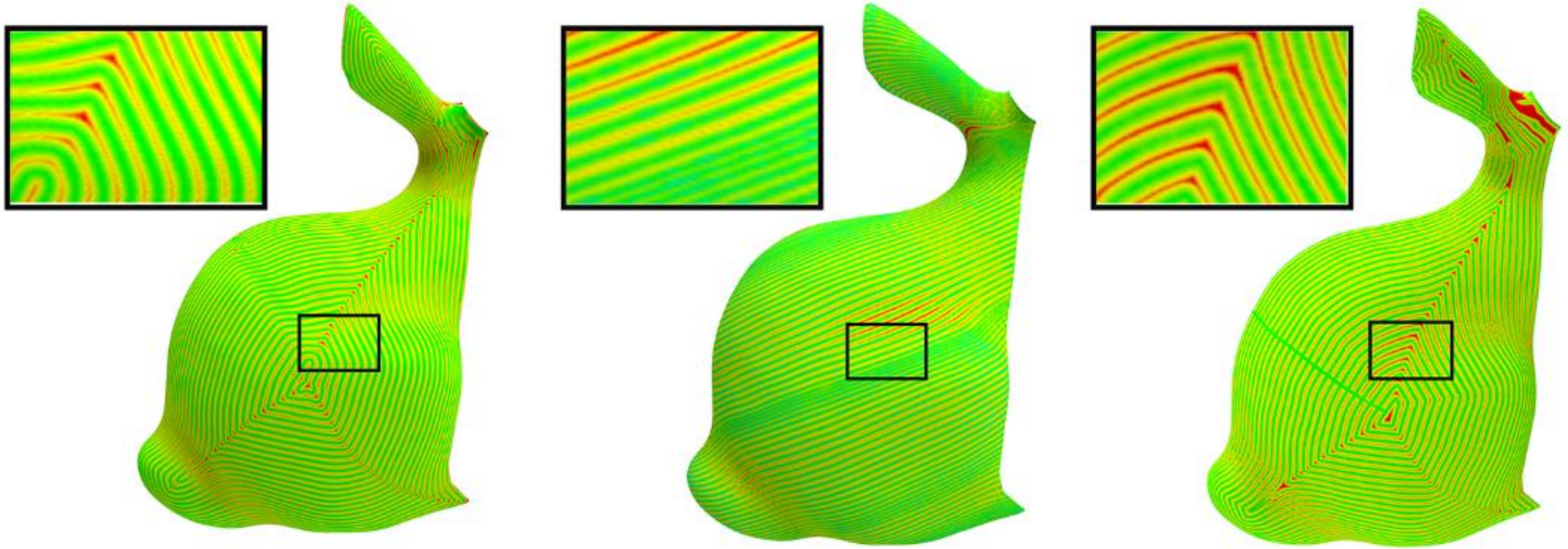
Results

Z: zigzag paths
C: contour-parallel paths
F: ISO-scallop connected Fermat spirals

Our path

Zigzag

Contour-parallel

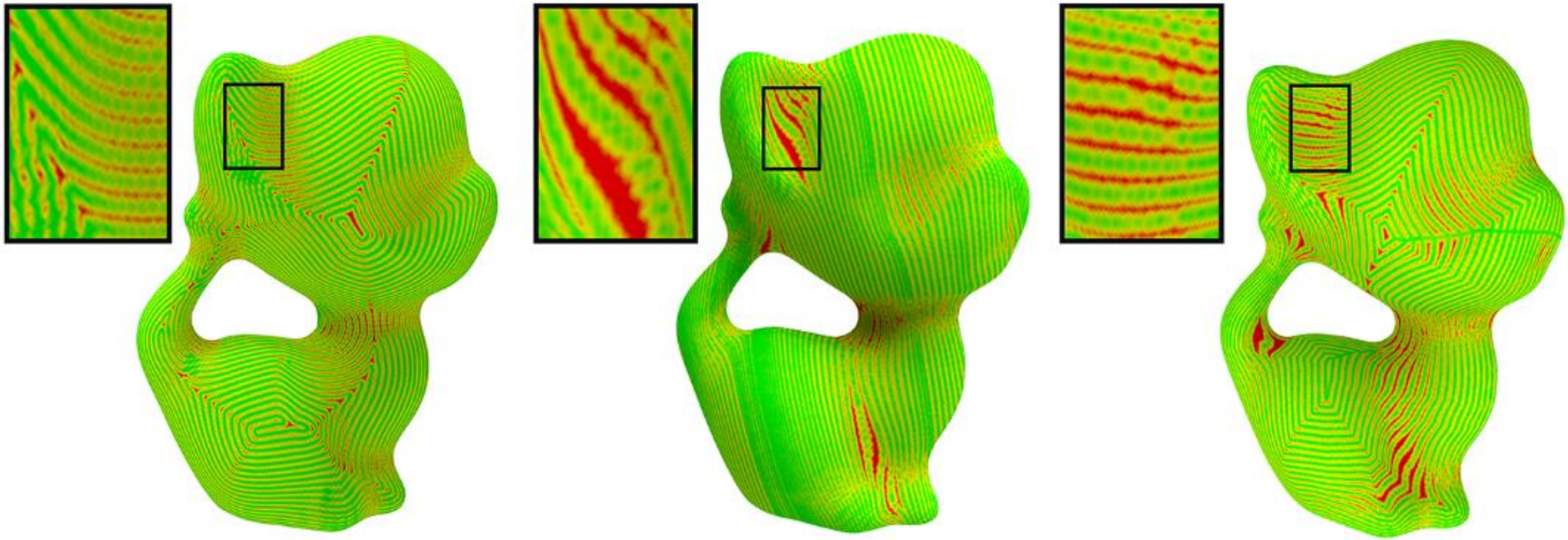


Scallop heights visualization

Results

Z: zigzag paths
C: contour-parallel paths
F: ISO-scallop connected Fermat spirals

Our path Zigzag Contour-parallel



Scallop heights visualization

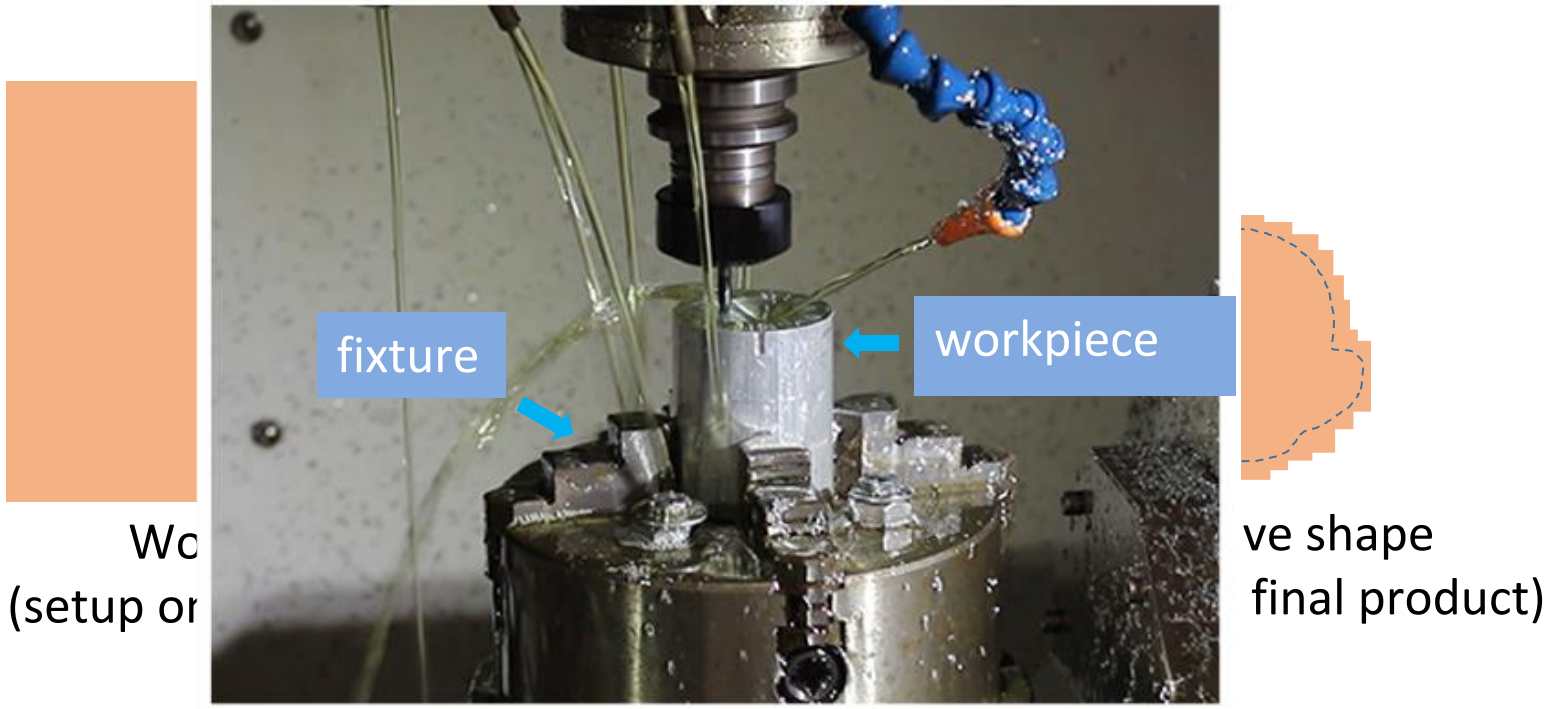
Conclusion and limitation

- A fully automatic algorithm
  - Accessibility decomposition for setup planning
  - Iso-scallop connected Fermat spirals for tool path planning

- Practical CNC machining issues
  - Fixture design, cutter switching
  - Rough machining
  - Do not address **inaccessibility** from tunnels or hollow parts
- Do not produce a globally continuous carving path for one setup

Future works

- Rough machining stage for free-form 3D objects
- Fixture design considering setup planning
- Full 5-axis machining tool path generation



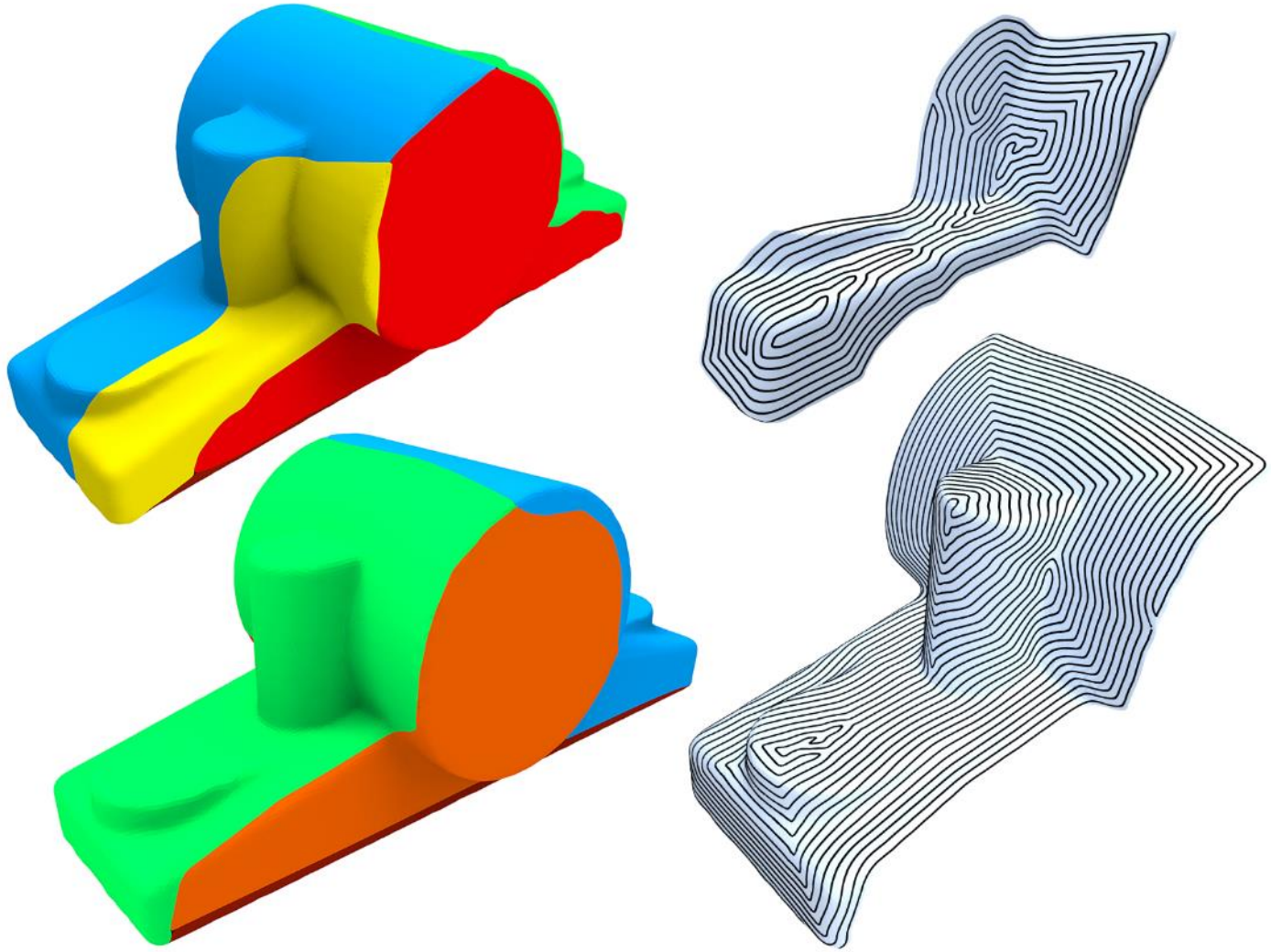
Acknowledgements

- Reviewers
- Jinjie Lin
- Jibin Zhao, Libin Sun, Haoyuan Yu…

Thank you!

http://irc.cs.sdu.edu.cn/DSCarver/

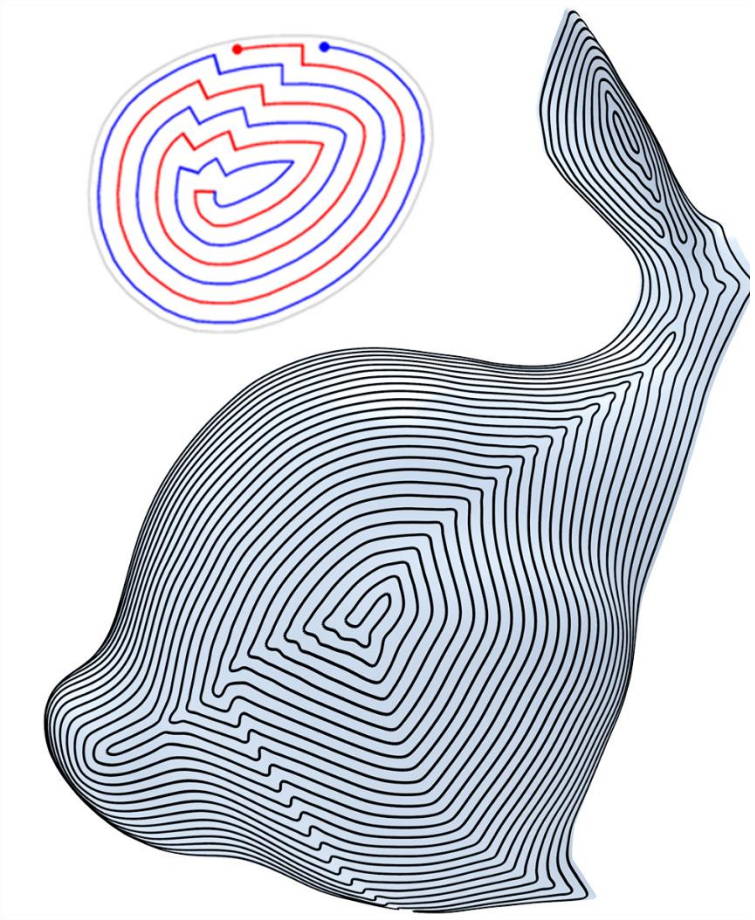
Conclusion



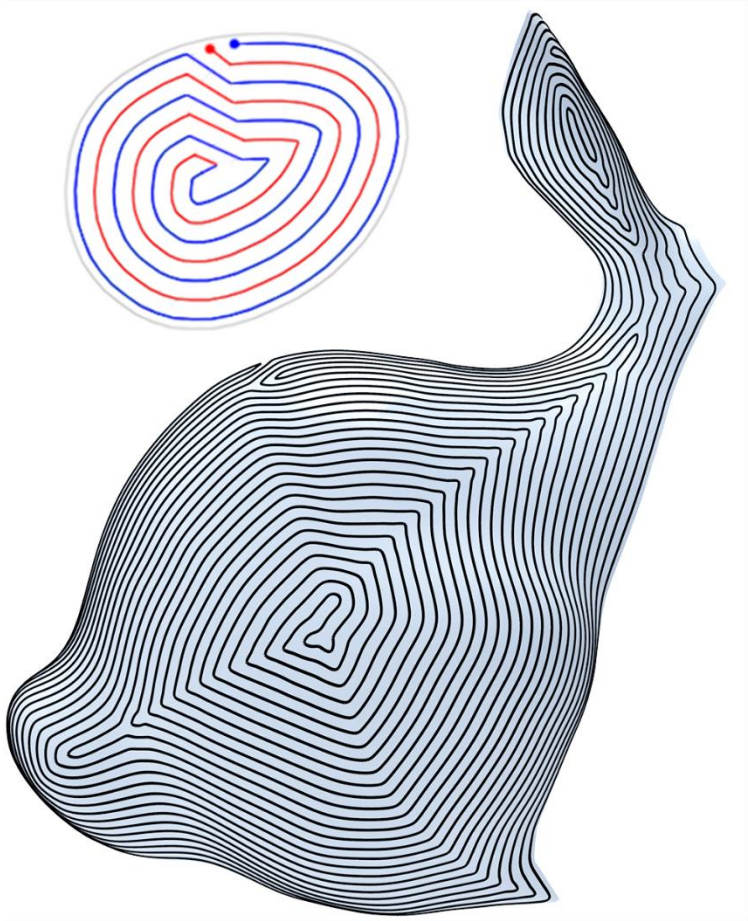
CAD/Engineering parts

Connected Fermat Spirals (CFS)

- Trick: short **“oblique”** curves instead of zigzag connections



zigzag connections



Short “oblique” connections