GAMES Webinar 51期

图形学可能的新机遇
减材制造

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2018.06.21

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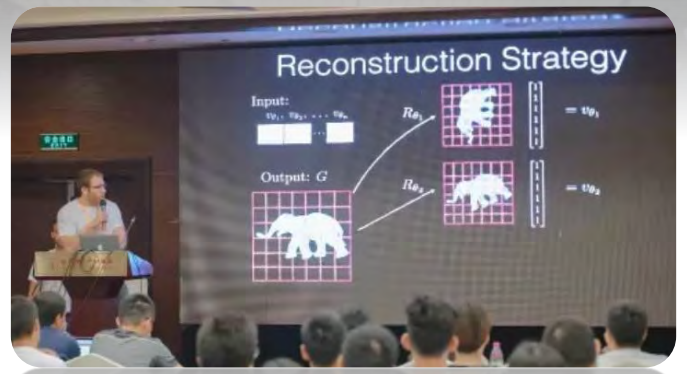
"可视计算"暑期学校
Visual Computing Summer School
暨国际研讨会


任务驱动的自动可视化


IRC第三届"可视计算"暑期学校
三维视觉研究成果介绍
李扬彦
http://yangyan.li
2017年7月11日


Reconstruction Strategy
Input:
Output: G

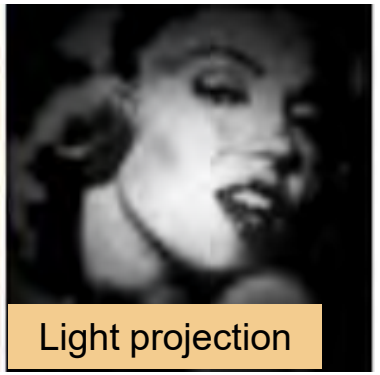
增材制造

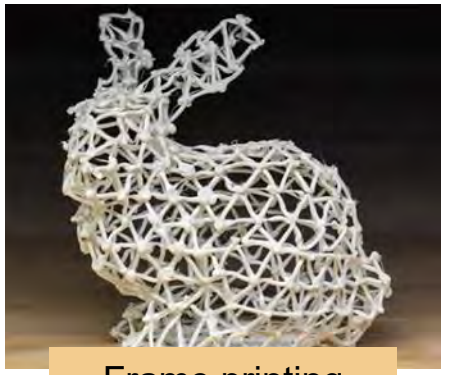
Personal Fabrication Research in HCI and Graphics:
An Overview of Related Work

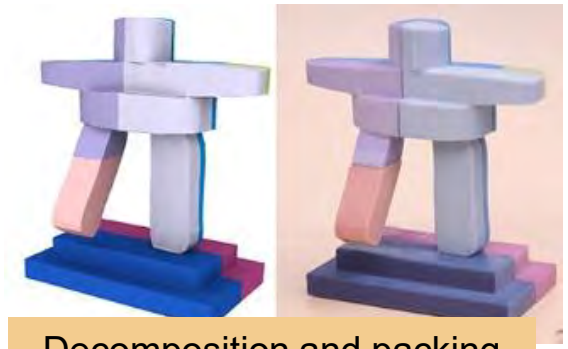
Webpage maintained by Stefanie Mueller, Parinya Punpongsanon, and Dishita Turakhia, HCI Engineering Group , MIT CSAIL
For feedback and changes, please email: stefanie.mueller/at/mit.edu

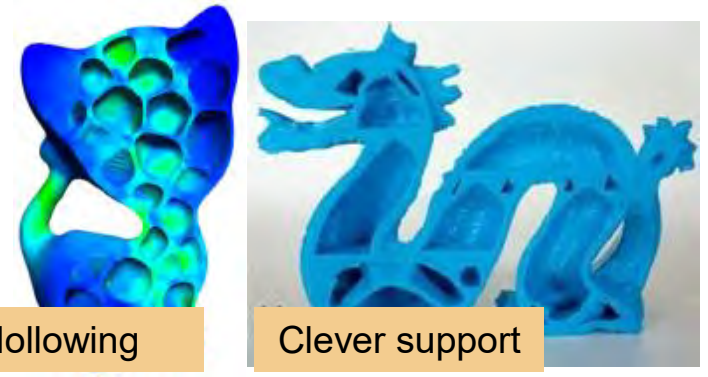
The goal of this website is to provide a resource for newcomers in the field of computational fabrication so that they can quickly access recent contributions made in the field. This database serves as a related work directory - the creators of this webpage do not hold the rights for these works, please contact the authors directly

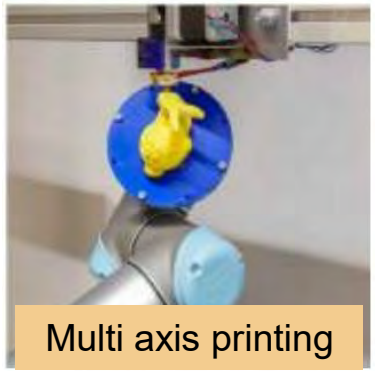
http://hcie.csail.mit.edu/fabpub/





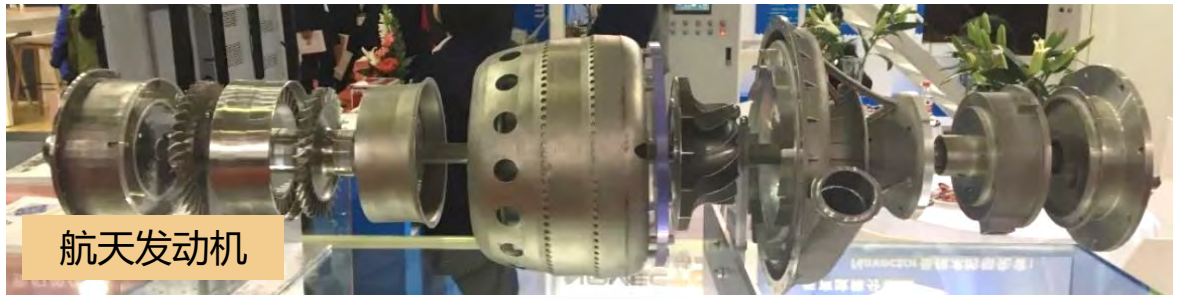




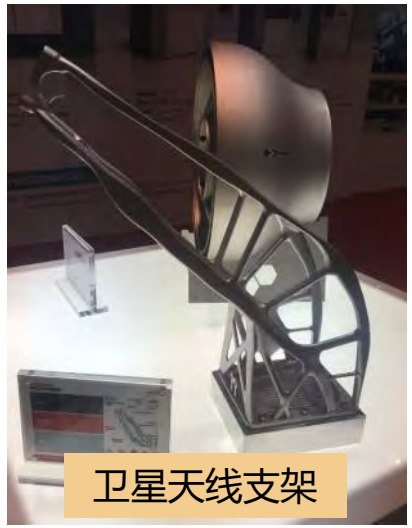


增材制造

福特汽车排气管



航天发动机



卫星天线支架

骨骼修复

头部模型

金属打印模具
及其制品

定制跑鞋

轮胎模具

陶瓷打印

减材制造

- CNC：**$81.5 billion** (2016)
- “Global and China CNC Machine Tool Industry Report, 2017-2021”
- 3DPrinting：**$6.1 billion** (2016)
- “Wohlers 2017 Report on 3D Printing Industry Points to Softened Growth”

- 批量生产
- 原材料范围广
- 加工效率高
- 零件强度，表面平整度高

减材制造

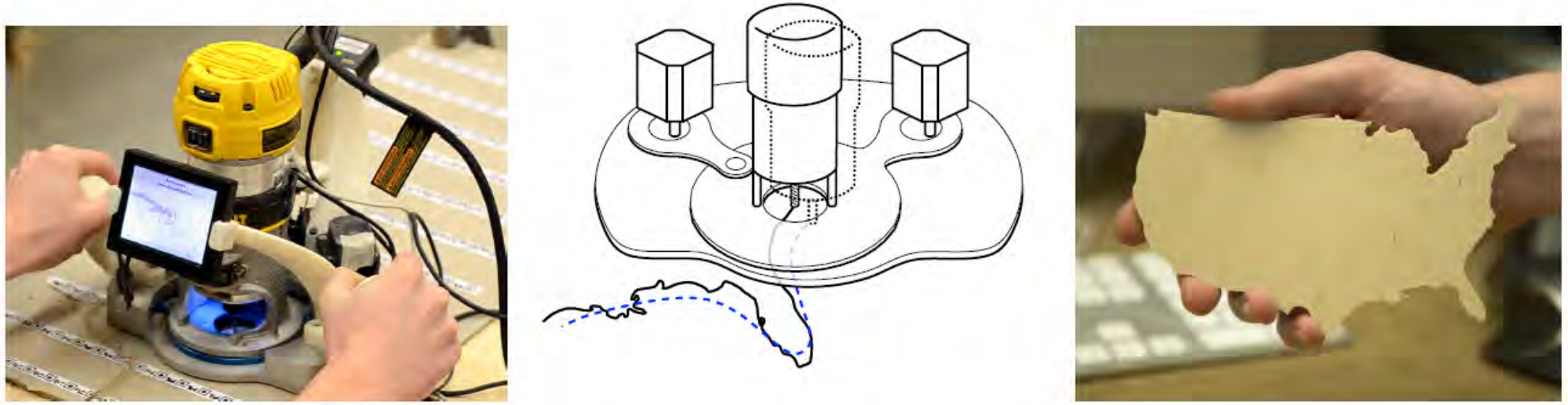
Rivers, Alec, Ilan E. Moyer, and Frédo Durand. "Position-correcting tools for 2D digital fabrication." *ACM Transactions on Graphics (TOG)* 31.4 (2012): 88.

Position-Correcting Tools for 2D Digital Fabrication

Alec Rivers
MIT CSAIL

Ilan E. Moyer
MIT

Frédo Durand
MIT CSAIL



(a) (b) (c)

Figure 1: Overview: (a): *A position-correcting tool. The device consists of a frame and a tool (in this case a router) mounted within that frame. The frame is positioned manually by the user. A camera on the frame (top right in the figure) is used to determine the frame's location. The device can adjust the position of the tool within the frame to correct for error in the user's coarse positioning.* **(b):** *To follow a complex path, the user need only move the frame in a rough approximation of the path. In this example, the dotted blue line shows the path that the tool would take if its position were not adjusted; the black line is its actual path.* **(c):** *An example of a shape cut out of wood using this tool.*

减材制造

Herholz, Philipp, Wojciech Matusik, and Marc Alexa. "Approximating Free-form Geometry with Height Fields for Manufacturing." *Computer Graphics Forum*. Vol. 34. No. 2. 2015.

Approximating Free-form Geometry with Height Fields for Manufacturing

Philipp Herholz[1] Wojciech Matusik[2] Marc Alexa[1]

[1]Technische Universität Berlin [2]MIT CSAIL

Figure 1: *To fabricate a mesh, possibly acquired by laser scanning, in a molding process, we automatically decompose and deform the shape (center left). A reusable multi-piece mold for the object can be produced by CNC milling (center right). Physical copies can be fabricated by mold casting in different materials like resin or plaster (right).*

減材制造

Alessandro et al. "Axis-Aligned Height-Field Block Decomposition of 3D Shapes." ACM Transactions on Graphics (TOG) (2018)

Axis-Aligned Height-Field Block Decomposition of 3D Shapes

ALESSANDRO MUNTONI, University of Cagliari and New York University
MARCO LIVESU, CNR IMATI
RICCARDO SCATENI, University of Cagliari
ALLA SHEFFER, University of British Columbia
DANIELE PANOZZO, New York University

Fig. 1. We decompose general 3D geometries into height-field blocks (left), enabling their fabrication using single pass 3-axis CNC machining (right).

减材制造

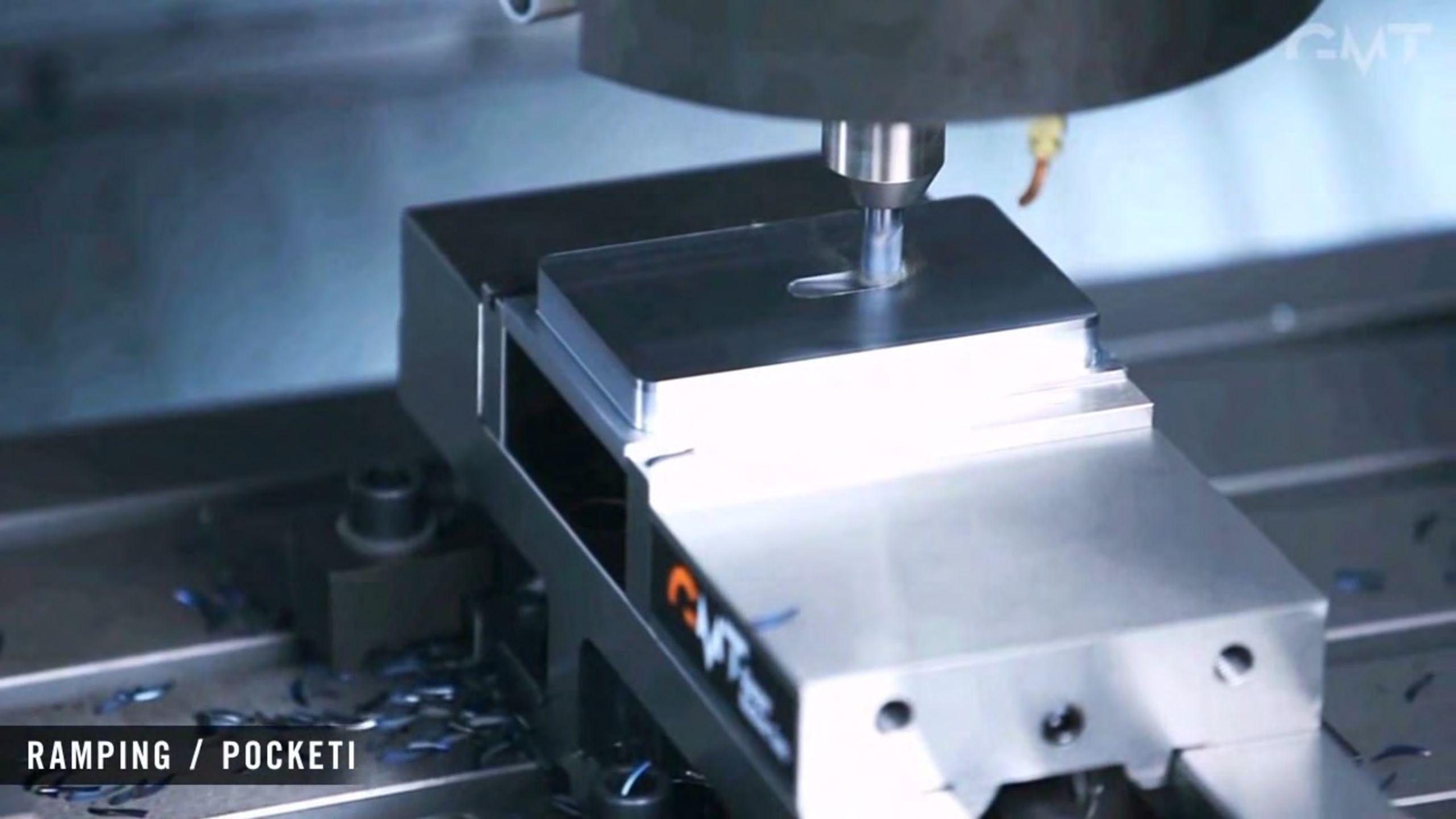
- 减材制造(数控加工)的概念
- 常见减材制造工艺
- 铣床设备, 刀具, CAM软件
- 数控加工误差来源
- 数控加工vs三维打印
- 数控加工流程
- 路径规划考虑因素
- 机器操作

减材制造

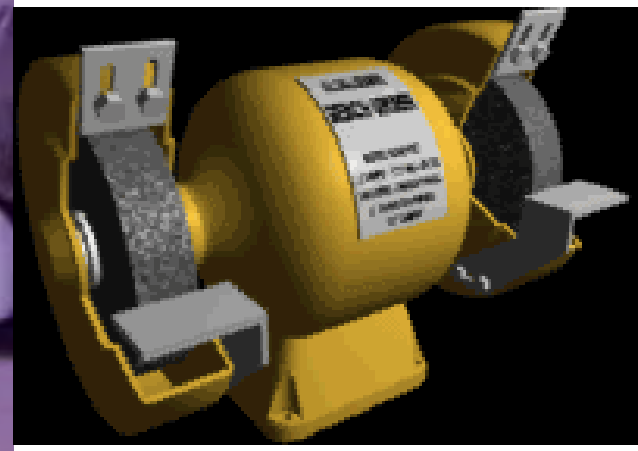
- 减材制造
  - 相对于“增材制造”，将材料固定于设备上，通过刀具减去或去除材料的加工方式，最终成型为所需部件的工艺类型。

- 数控加工（Computer Numerical Control, CNC）
  - 通过编程，数控机床以无需手工干预的自动连续的方式去除余料，适合于大批量、形状复杂的零件；
  - 上世纪40年代，第一台手动控制机床诞生。

http://www.ach-wisdom.com/h-col-121.html
http://www.wisegeek.org/what-are-cnc-machines.htm


RAMPING / POCKETI

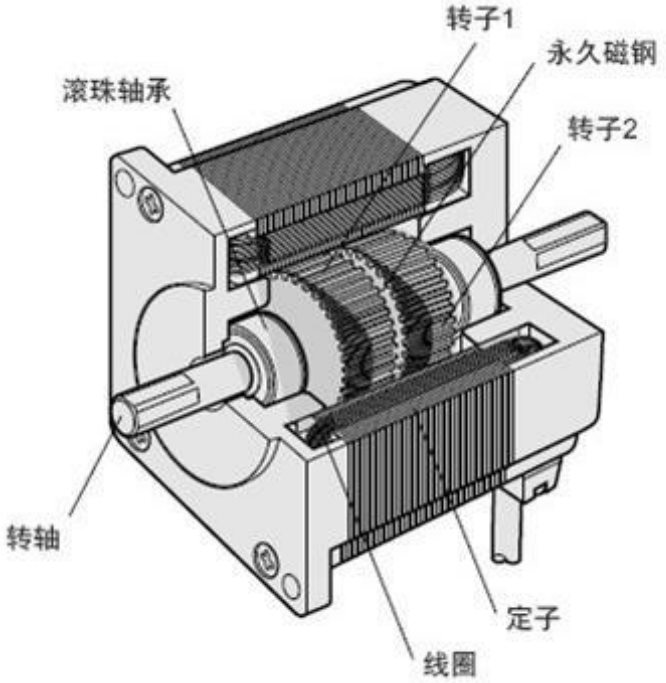

GRINDEX

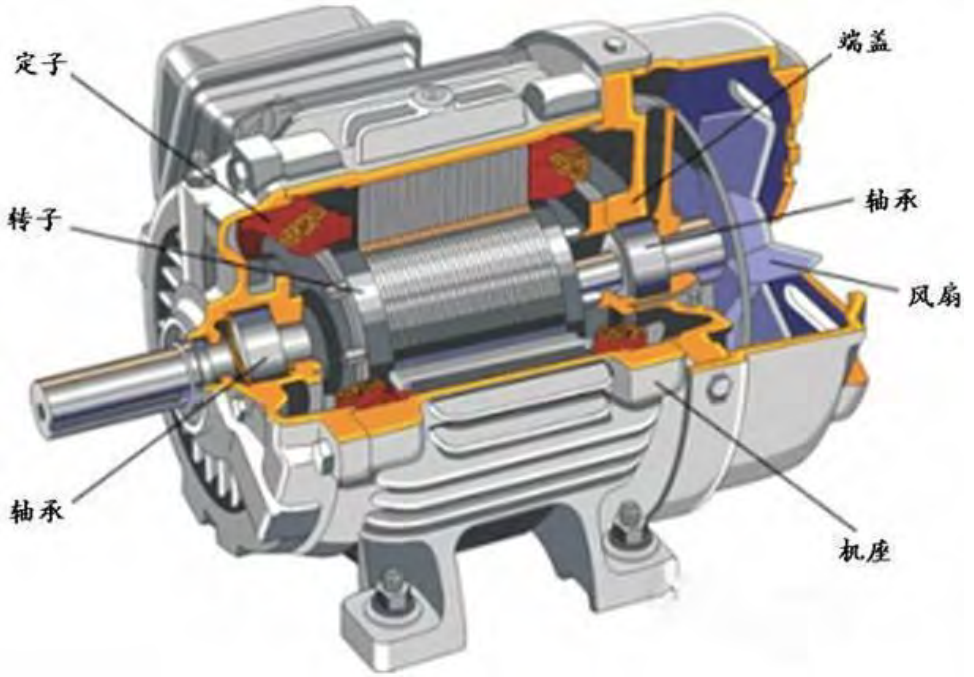


数控机床

数控机床

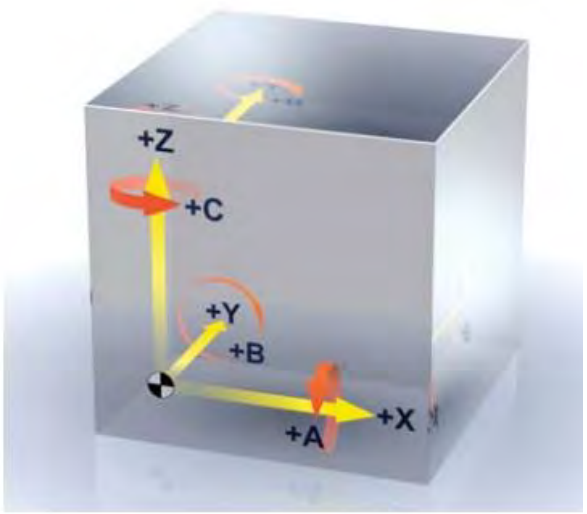
- 轴数：2，3，4，5，5+
- 电机：步进电机，伺服电机

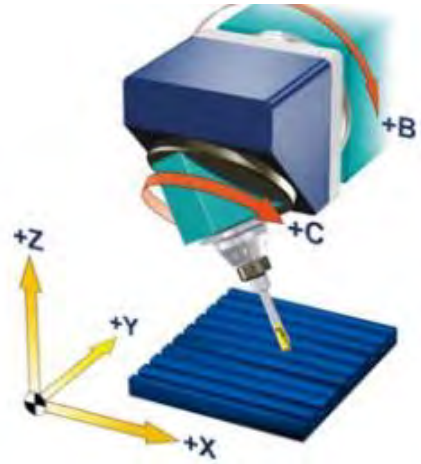


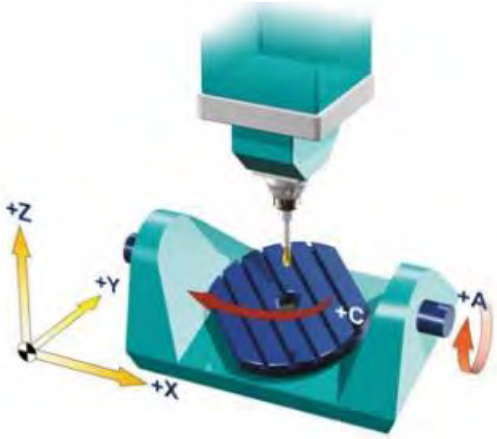


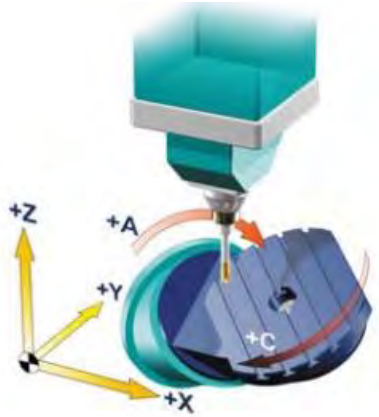
- 用途：雕刻机，大型机床

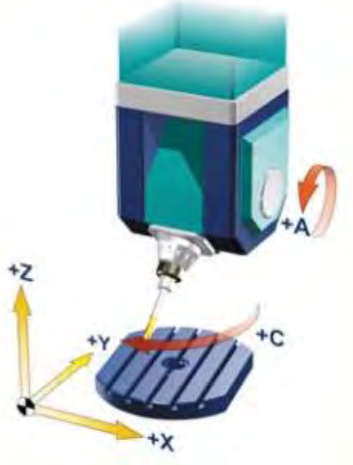
数控机床



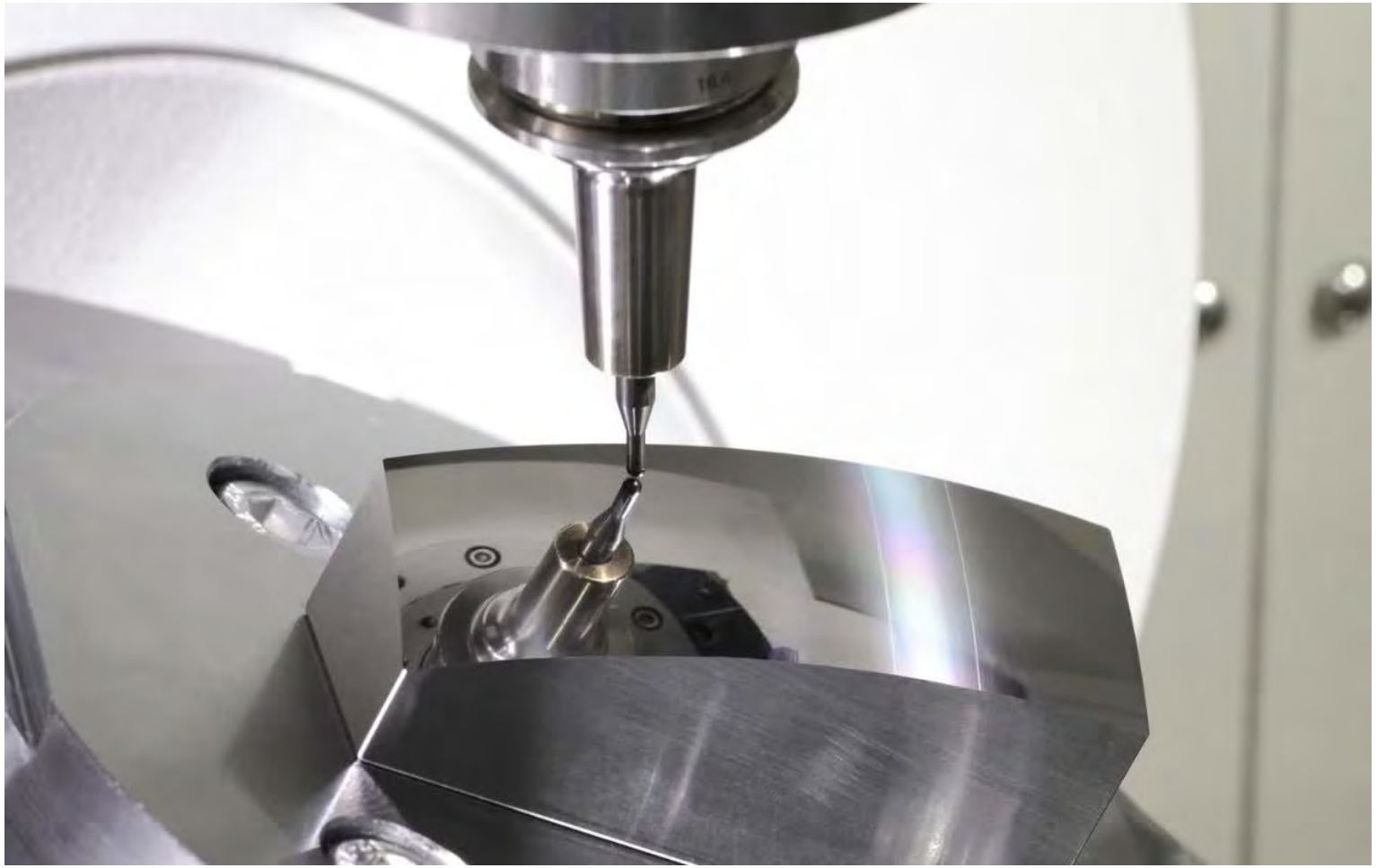








数控机床



北京精雕实现0.1μ进给和1.0μ切削

刀具

平底刀

尖刀

球头刀

误差因素

- 刀具磨损/变形/尺寸误差
- 工件热变形和弹性变形误差
- 机床运动误差
- 编程中计算误差
- 加工系统震动(振纹)
- 加工铣削温度变化
- 切削力的变化
- 残留应力
- 刀具端点切削力为0
- 进给速度优化(恒定切削力)

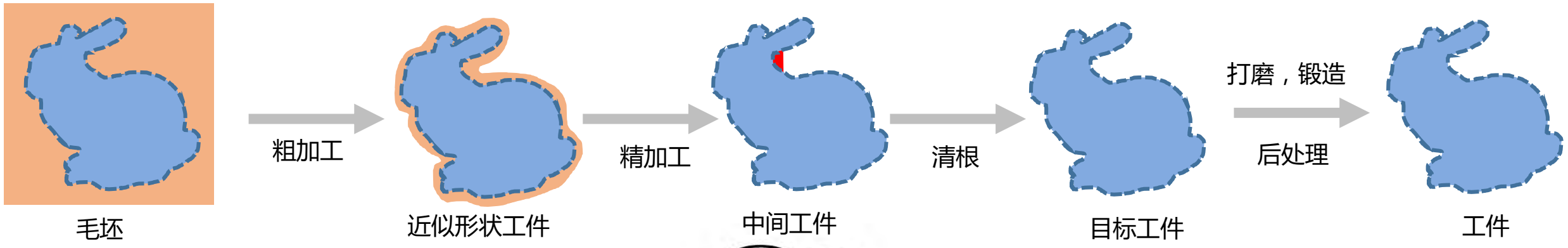
恒定切削力路径

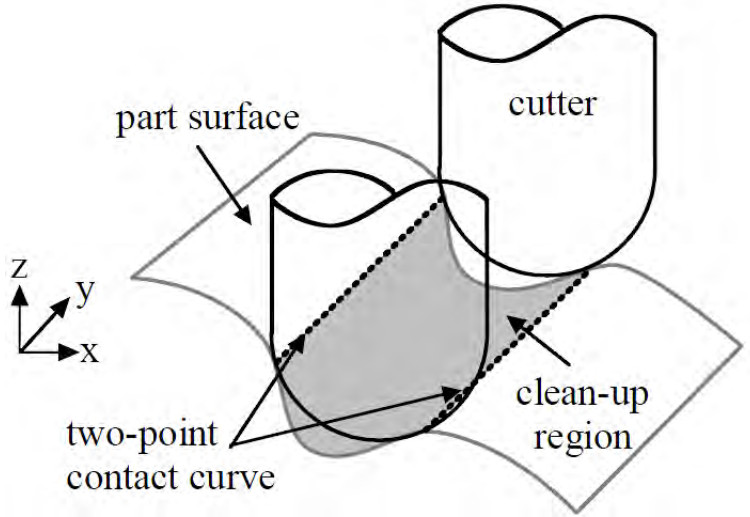
https://www.365yg.com/group/6551255016399700484/

数控加工vs三维打印

- “减” vs “增” 路径是否可重复
- 机械运动能力不同
- Gcode
- 可加工的工件复杂度
- 应用场景
- 碰撞检测
- 路径：二维 =》五维

数控加工流程


毛坯
粗加工
近似形状工件
精加工
中间工件
清根
目标工件
打磨，锻造
后处理
工件

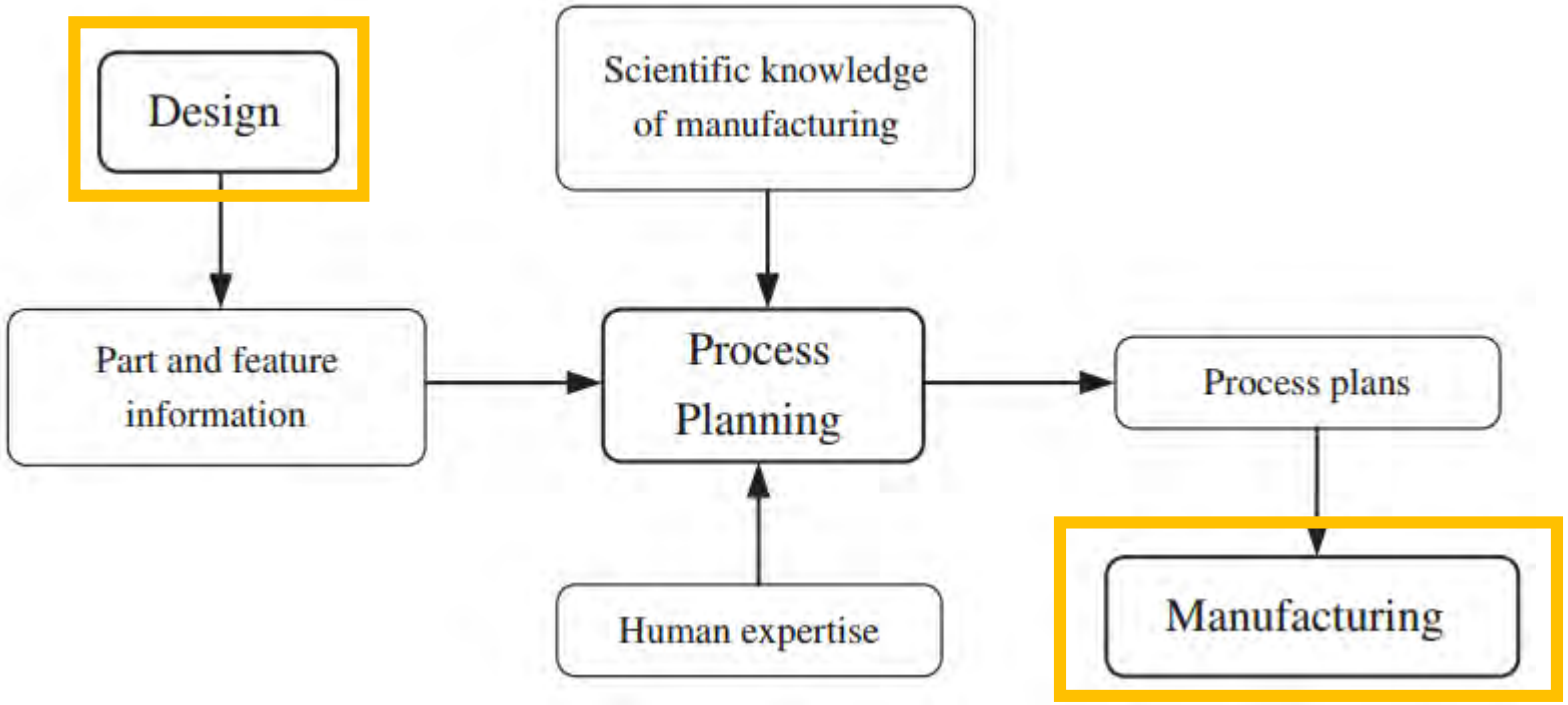

part surface
cutter
z
y
x
clean-up
region
two-point
contact curve

规划流程

- Process planning
- Setup planning
- Tool path planning
- Trajectory planning

Process planning

- The act of preparing detailed manufacturing instructions to produce a part with the available resources at the lowest possible cost and of the best quality.



Hazarika M, Dixit U S. Setup planning for machining[M]. Heidelberg: Springer, 2015

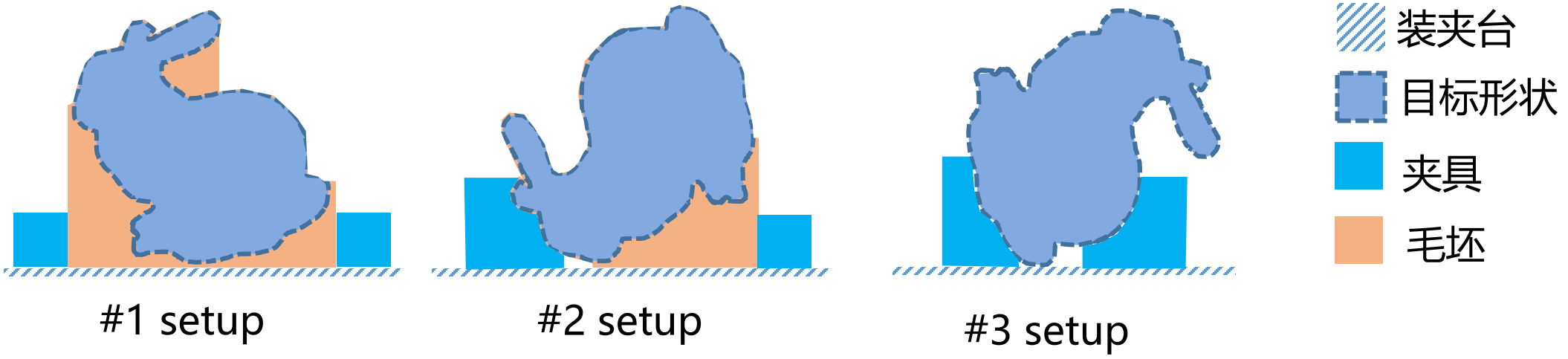
Process planning

- The act of preparing detailed manufacturing instructions to produce a part with the available resources at the lowest possible cost and of the best quality.
  - Design interpretation
  - Process selection and machine selection
  - **Setup planning**
  - Process parameters selection
  - Cycle time estimation and scheduling
  - Cost evaluation
  - Documentation

Hazarika M, Dixit U S. Setup planning for machining[M]. Heidelberg: Springer, 2015

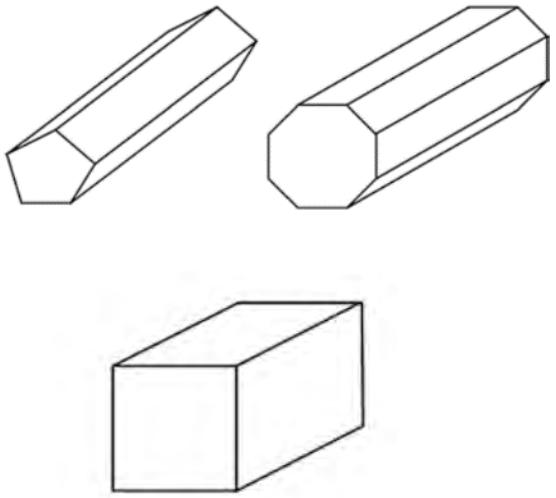
Setup planning

- Orient and stabilize the shape stock with fixtures for carving.
  - Highly critical to minimize the number of setups (NP-hard)

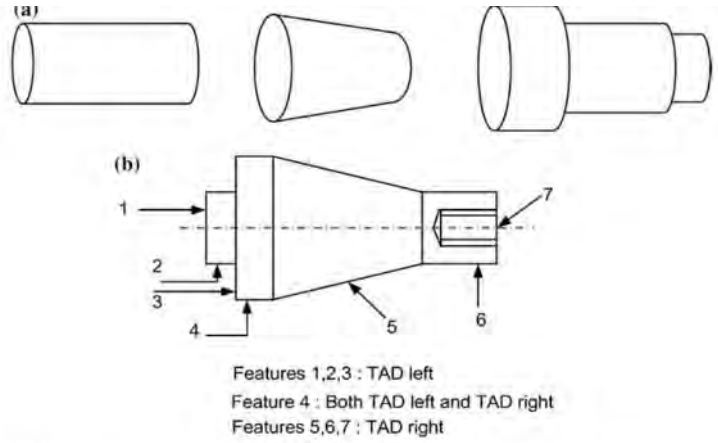


[1]Xu N, Huang S H, Rong Y K. Automatic setup planning: current state-of-the-art and future perspective[J]. International journal of manufacturing technology and management, 2007, 11(2): 193-208.
[2]Gupta P, Janardan R, Majhi J, et al. Efficient geometric algorithms for workpiece orientation in 4-and 5-axis NC machining[J]. Computer-Aided Design, 1996, 28(8): 577-587.

Setup planning—Related works



Prismatic parts
(箱体工件)



Rotational parts
（回转体工件）

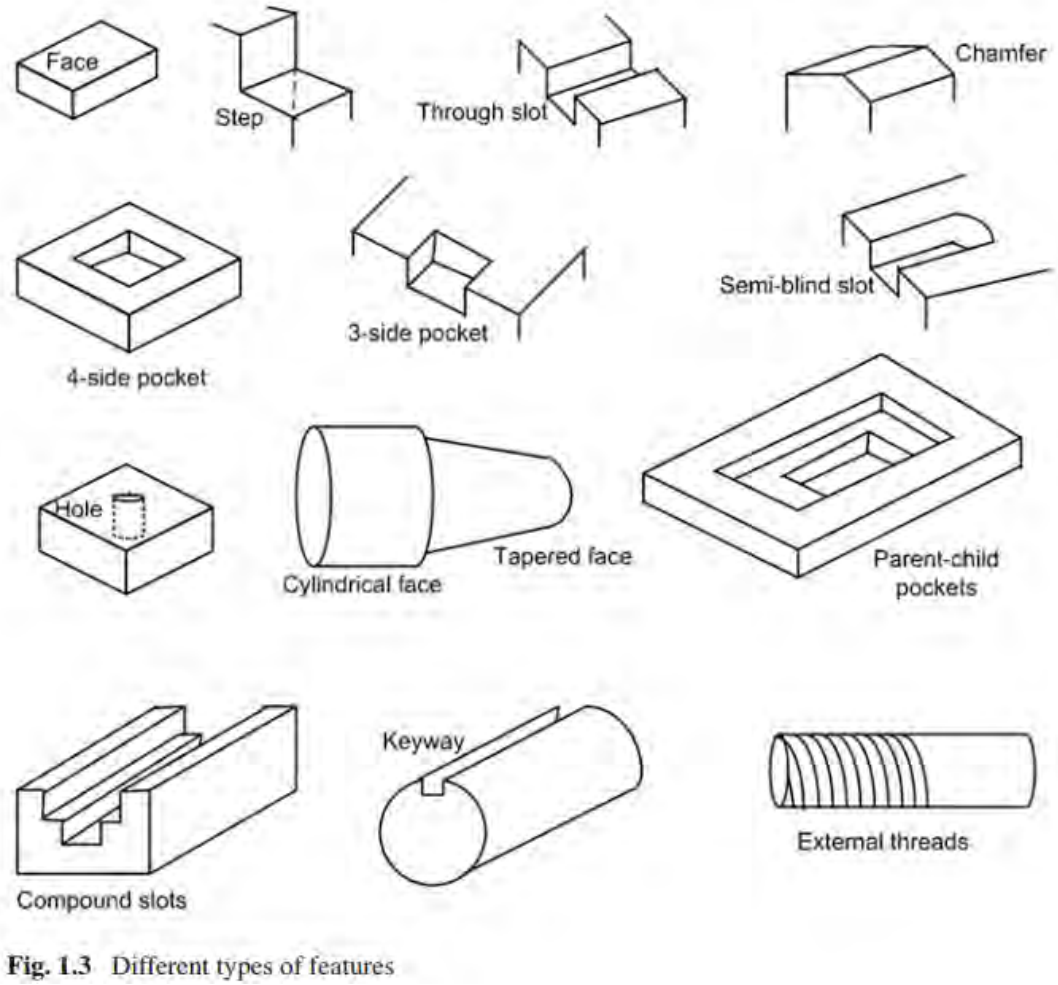
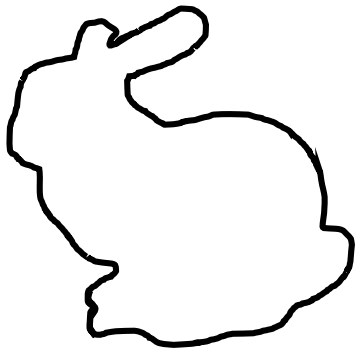


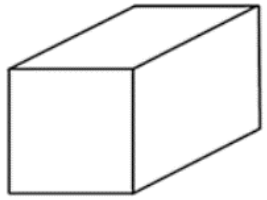
Fig. 1.3 Different types of features

Setup planning—Industry area

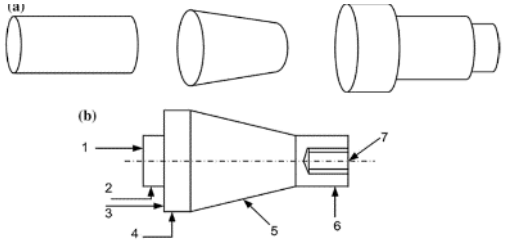
- In practice, a **manual** process
  - Heavily rely on experts' domain knowledge and experience;



自由曲面3D工件



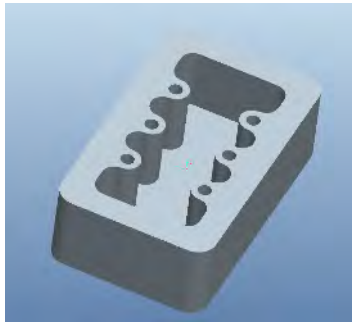
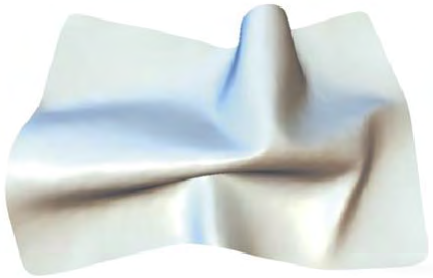
箱体工件



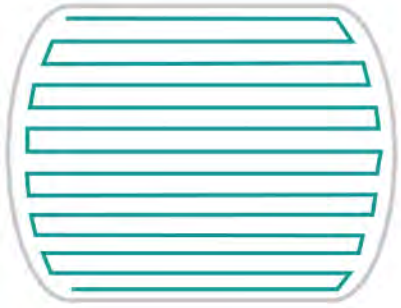
回转体工件

Tool path planning

- 工件类型：平面型腔，复杂自由曲面

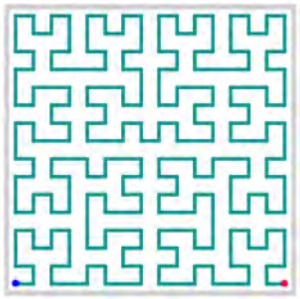




- 不同机床: 3轴, 4轴, 5轴, 机器人加工
- 加工阶段：粗加工, 精加工, 清根, 后处理
- 常用路径：


Zigzag


Contour parallel


Spiral


Space filling curve

Lasemi, Ali, Deyi Xue, and Peihua Gu. "Recent development in CNC machining of freeform surfaces: A state-of-the-art review." *Computer-Aided Design* 42.7 (2010): 641-654.

Tool path planning

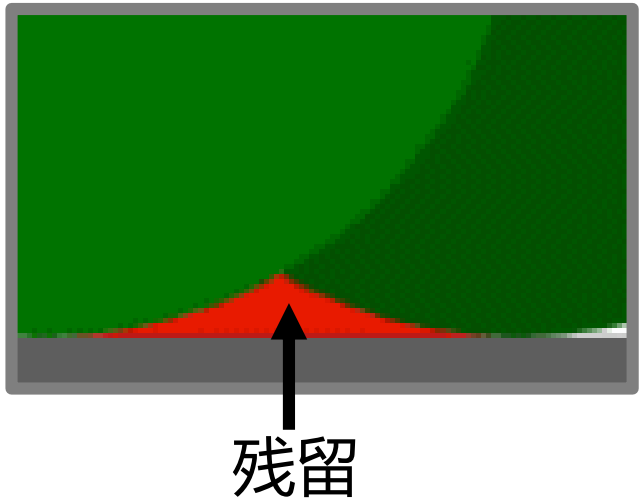
- 路径光顺性 》加工效率
- 路径连续性 》撤刀次数 》加工效率 +加工精度
- 路径长度 》加工效率
- 刀具姿态 》刀头负载均衡 》刀具寿命

  》去材料率 》加工效率+加工精度

  》刀具干涉
- 残留高度均匀性 》加工效率 + 加工精度

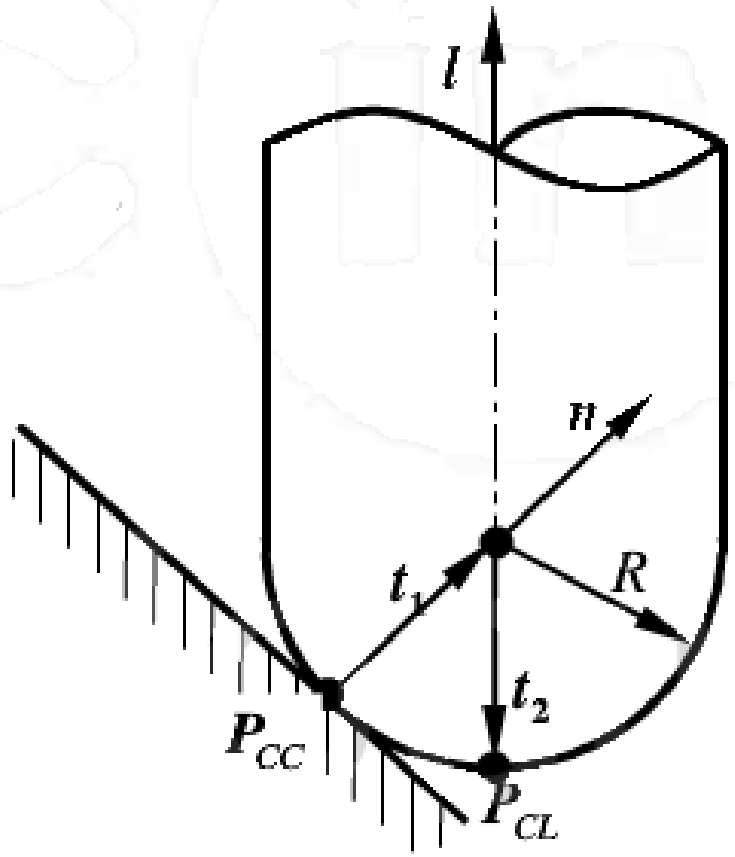
Scallop height

- **Scallop distribution** （残留分布）
  - Residual material after carving.
  - **Maximize uniformity** of the scallop within maximal scallop height (最大残留高度)



CC/CL

- Cutter Contact Point刀触点
- Cutter Location Point 刀位点



Gcode代码

https://en.wikipedia.org/wiki/G-code
https://reprap.org/wiki/G-code

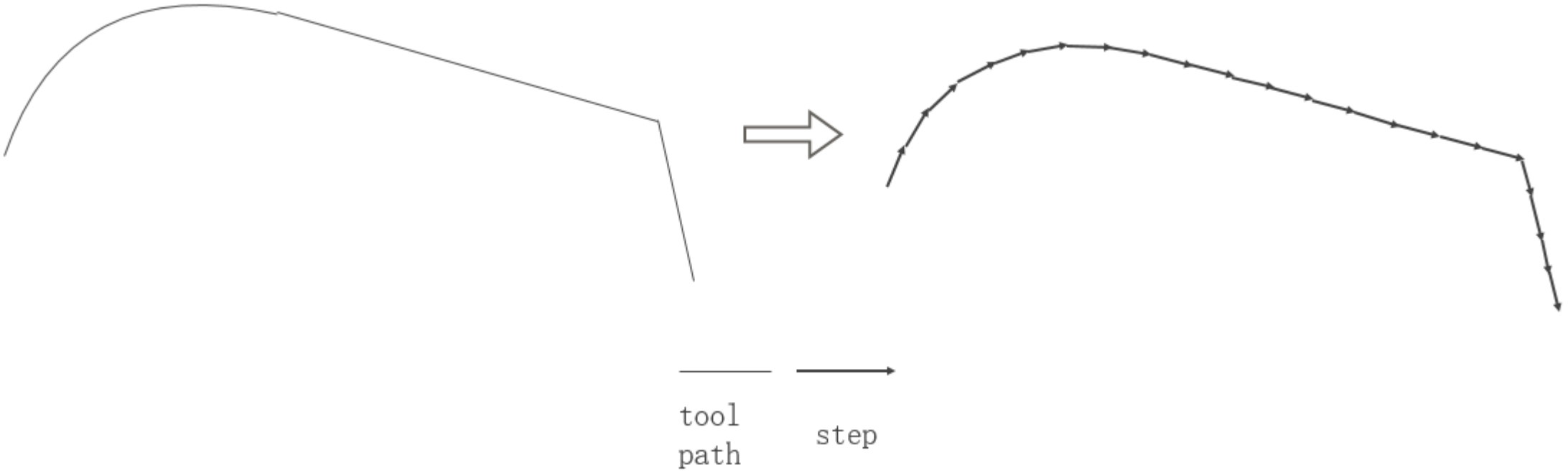
```
M107 ; disable fan
M104 S200 ; set temperature
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle

M109 S200 ; wait for temperature to be reached
G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0 ; reset extrusion distance
G1 Z0.300 F9000.000 ; move to next layer (0)
G1 E-2.00000 F2400.00000 ; retract
G92 E0 ; reset extrusion distance
G1 X-7.095 Y13.895 F9000.000 ; move to first skirt point
G1 E2.00000 F2400.00000 ; unretract
G1 X-8.832 Y13.008 E2.02778 F4800.000 ; skirt
G1 X-10.719 Y11.537 E2.06185 ; skirt
G1 X-11.212 Y10.970 E2.07256 ; skirt
G1 X-12.973 Y8.835 E2.11198 ; skirt
G1 X-13.990 Y7.100 E2.14063 ; skirt
G1 X-15.299 Y3.719 E2.19227 ; skirt
G1 X-15.699 Y1.287 E2.22738 ; skirt
G1 X-15.592 Y-1.969 E2.27378 ; skirt
G1 X-15.236 Y-3.864 E2.30125 ; skirt
G1 X-14.222 Y-6.746 E2.34476 ; skirt
G1 X-13.193 Y-8.601 E2.37498 ; skirt
G1 X-12.800 Y-9.082 E2.38383 ; skirt
G1 X-10.932 Y-11.217 E2.42423 ; skirt
G1 X-10.324 Y-11.845 E2.43669 ; skirt
G1 X-8.902 Y-12.914 E2.46203 ; skirt
G1 X-6.287 Y-14.355 E2.50457 ; skirt
G1 X-4.603 Y-14.991 E2.53019 ; skirt
G1 X-0.981 Y-15.717 E2.58282 ; skirt
G1 X1.441 Y-15.721 E2.61731 ; skirt
G1 X4.483 Y-15.134 E2.66144 ; skirt
G1 X6.378 Y-14.441 E2.69019 F4800.000 ; skirt
```

Code	Description	Milling (M)	Turning (T)
G00	Rapid positioning	M	T
G01	Linear interpolation	M	T
G02	Circular interpolation, clockwise	M	T
G03	Circular interpolation, counterclockwise	M	T

Trajectory planning

- 路径规划后，由控制系统生成的速度规划
- 机器相关



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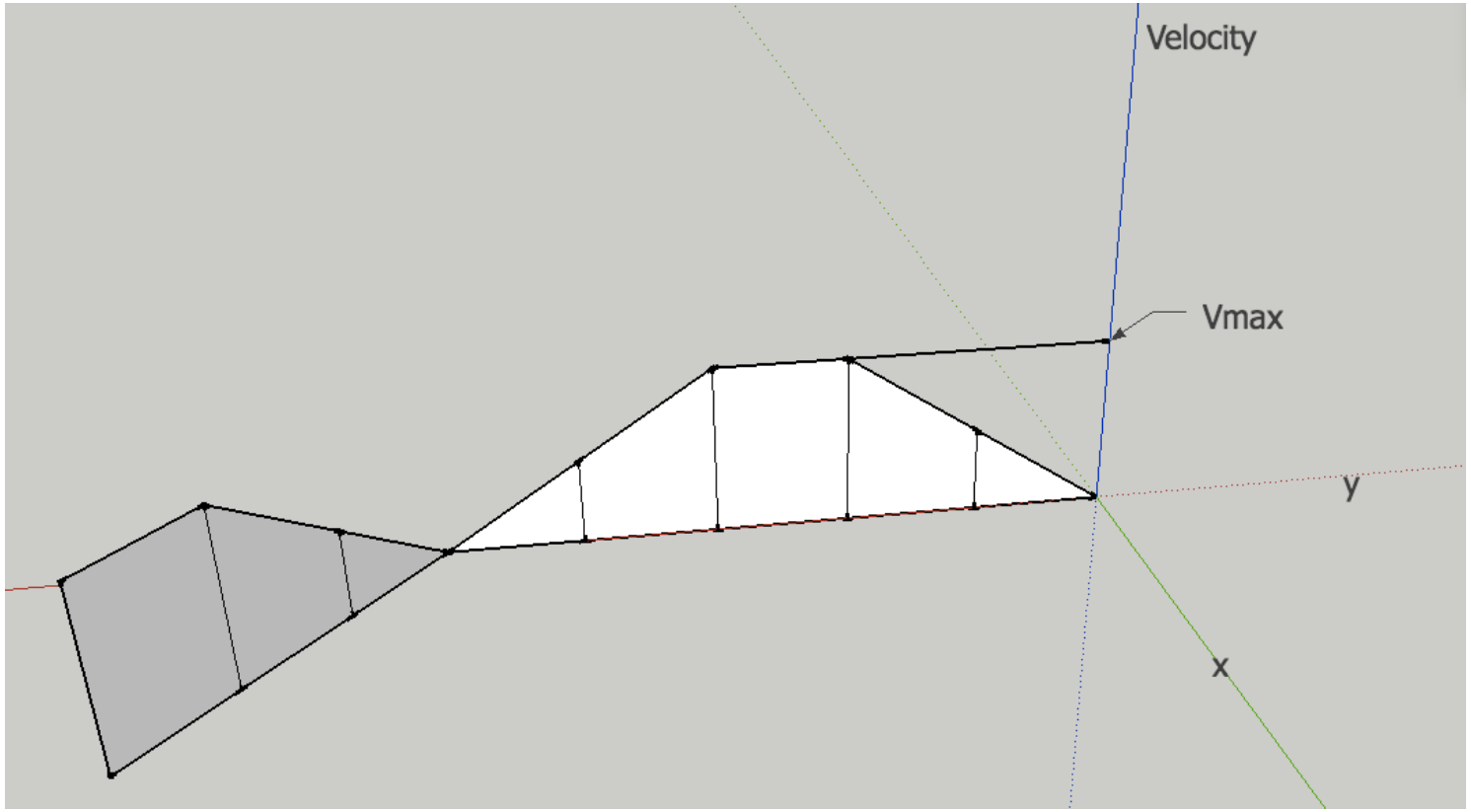


CAM

- 常用CAM软件

  UG、Pro/Engineer、MasterCam

  CAXA ME、CATIA、Cimatron、PowerMill 、 Tebis，Delcam，Edgecam
- 模拟：VERICUT，OpenRAVE
- CAM开发: 接口，OpenCascade, AnyCAD

- CNC term：

http://www.hsmworks.com/docs/cncbook/en/

https://www.cnccookbook.com/cnc-dictionary/

机器操作

Jiefeng雕刻机注意事项：

1,不要轻易按“返回原点”

2,用平底刀粗加工，球形到半精和精加工；

3,加工铝一定要用水冷；

4,机器上面的金属部件要导出静电，尤其是电机本身的静电

5,球形刀不能垂直加工

6,加工铝主轴转速>18000rpm/min; 代木>15000rmp/min;

7,分中操作后才能用AC轴；

8,机床机动轴要保持有油感；

9,切削材料之前一定要让主轴转动起来

10，注意换刀是的符号问题

11，加工完一个零件后要及时清理粉尘

12，带口罩

13，如果NC文件过长，jiefeng的机器会有剧烈的震动；

14，不能直接把g03替换为g01；

15, jiefeng是认圆弧路径的

16，Jiefeng的每个轴的最高限速不能太高，1500-2000比较合适，不然会发漂；

17，用刀具水冷要把机器太高

18，限位电机的螺丝一定要拧紧，先拧定位，再拧轴向的螺丝，才不会漂移和震动

19，加工前期削平不用很多，1mm足够

20，定位方法，定中心

Connected Fermat Spirals for Layered Fabrication

ACM SIGGRAPH 2016

Haisen Zhao[1], Fanglin Gu[1], Qi-Xing Huang[2], Jorge Garcia[3], Yong Chen[4], Changhe Tu[1], Bedrich Benes[3], Hao (Richard) Zhang[5], Daniel Cohen-Or[6], Baoquan Chen[1]

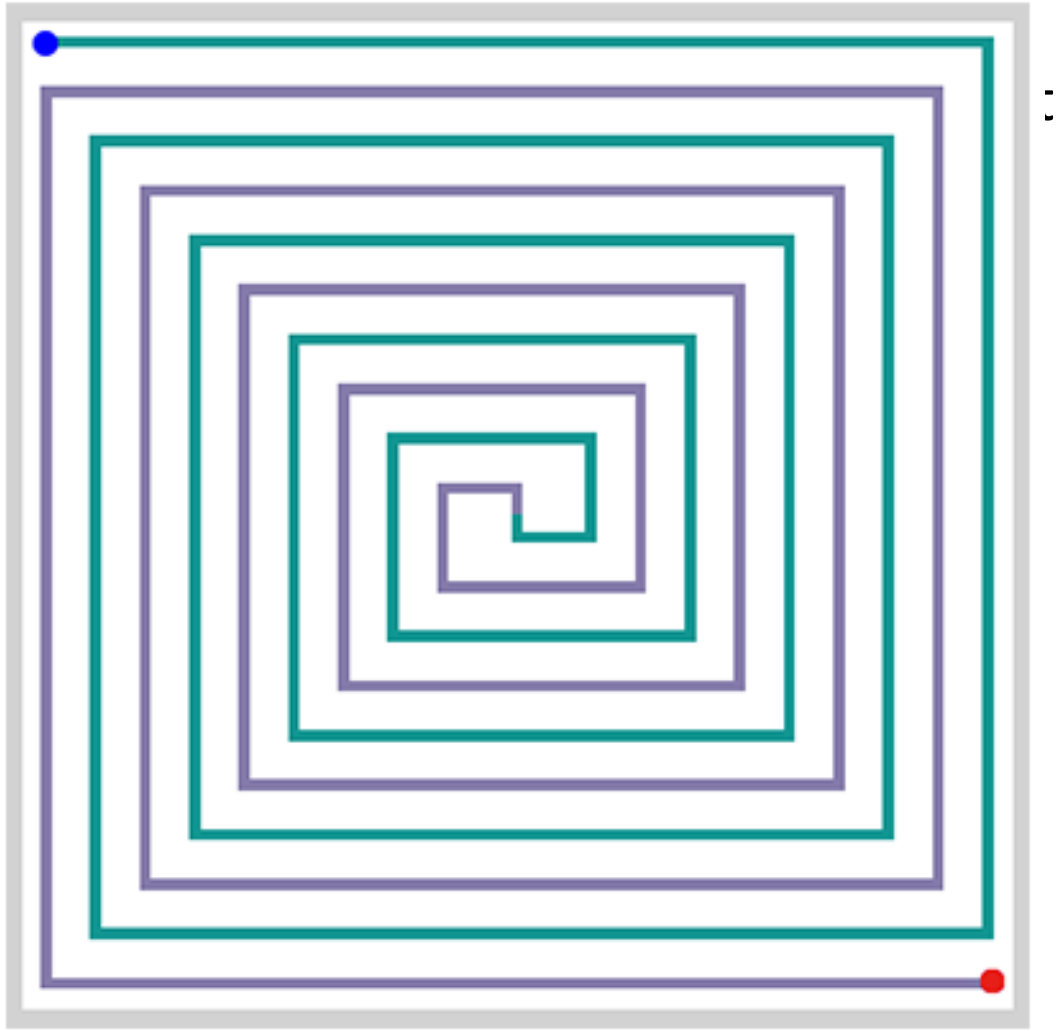
[1]Shandong University [2]TTI Chicago [3]Purdue University [4]USC

[5]Simon Fraser University [6]Tel-Aviv University

Key idea: Fermat spirals!

Pierre de Fermat (1636)

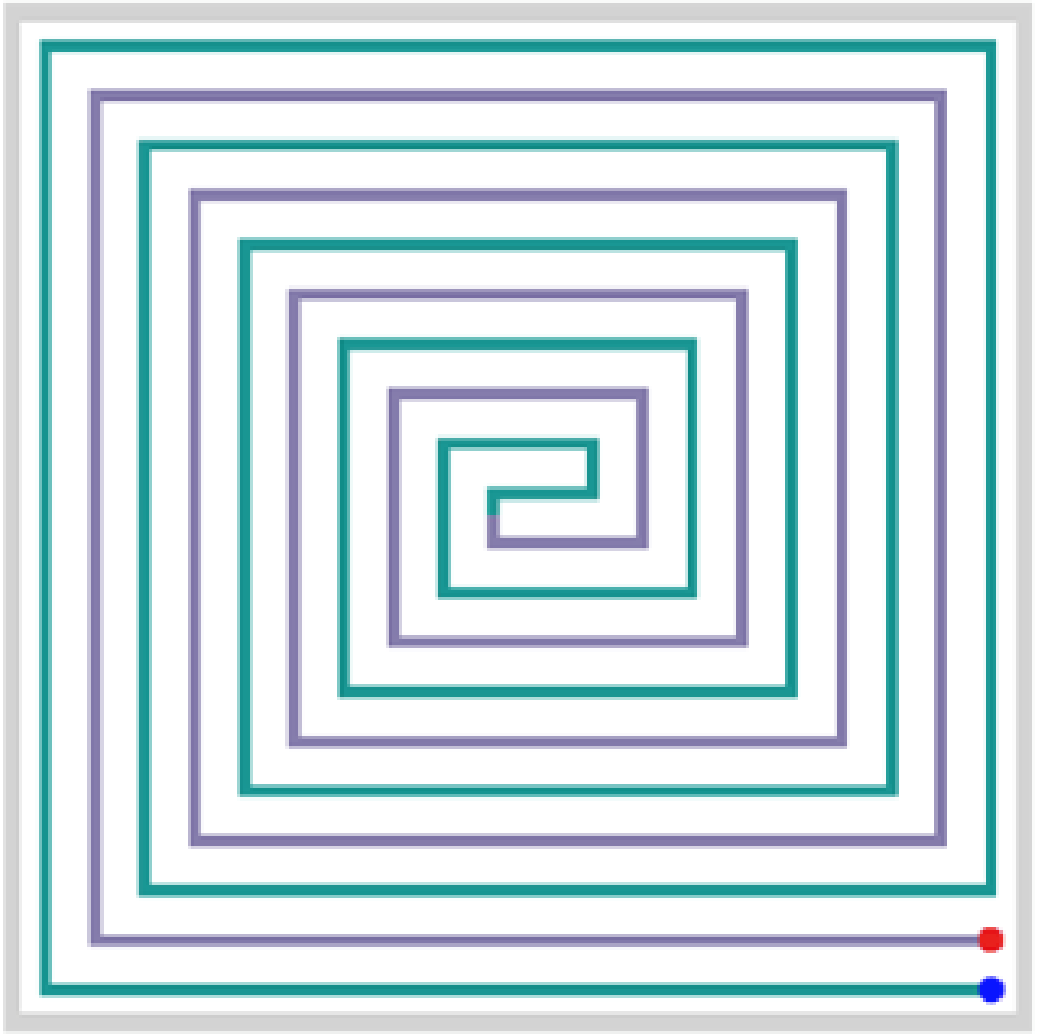
Fermat spiral: compelling properties



start point end point

- Similarities to spiral and CPPs
  - Conform to surface boundaries
  - Less sharp turns than zigzag
  - Continuity for simple shapes
- New: start & end on boundary
- Key observation: can place start & end points freely along boundary
- Allows connection of all Fermat spirals to achieve global continuity

Fermat spiral: compelling properties



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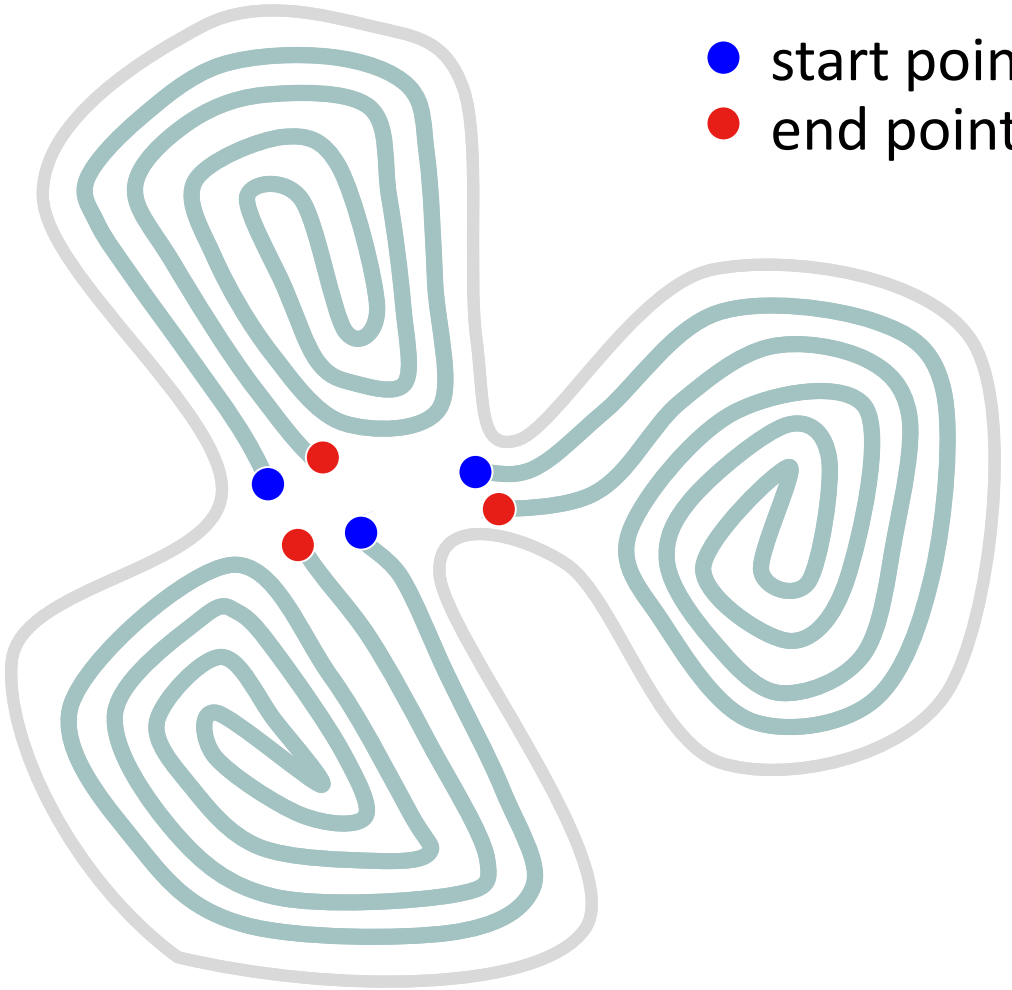

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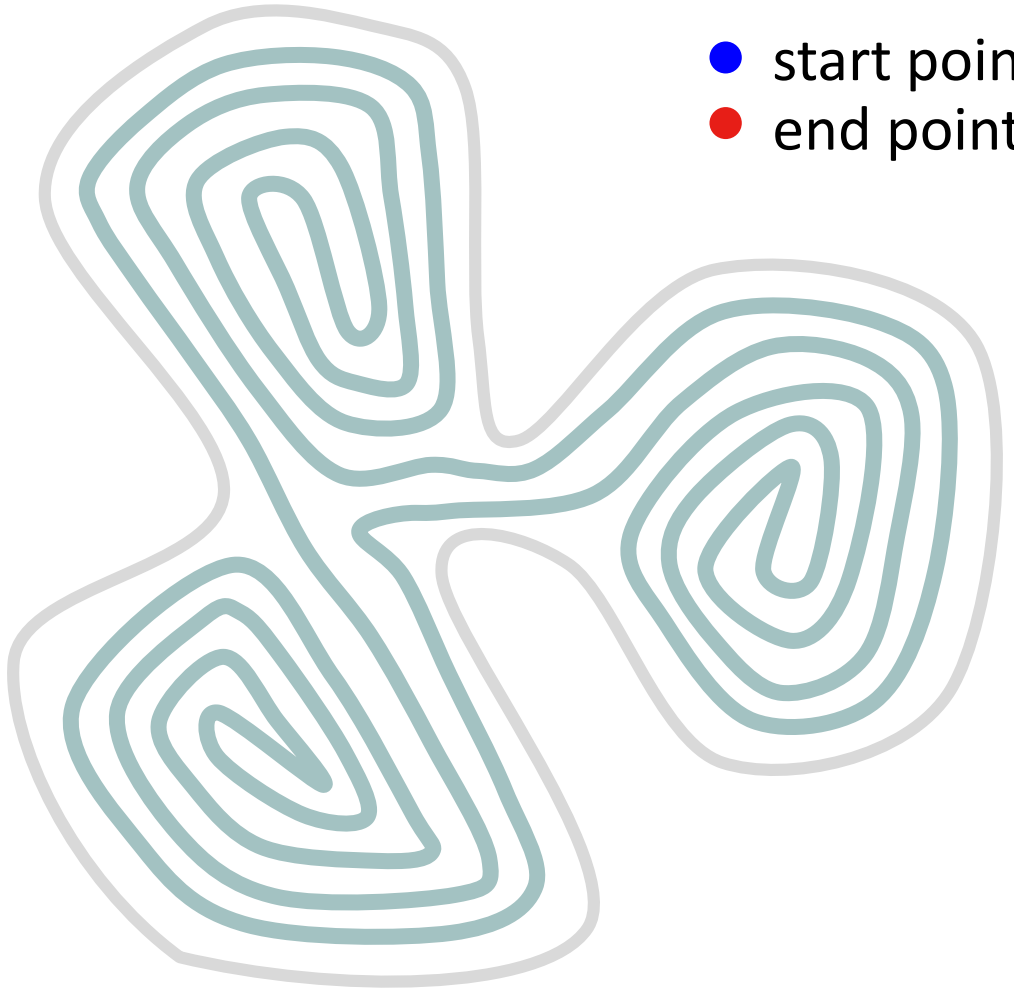

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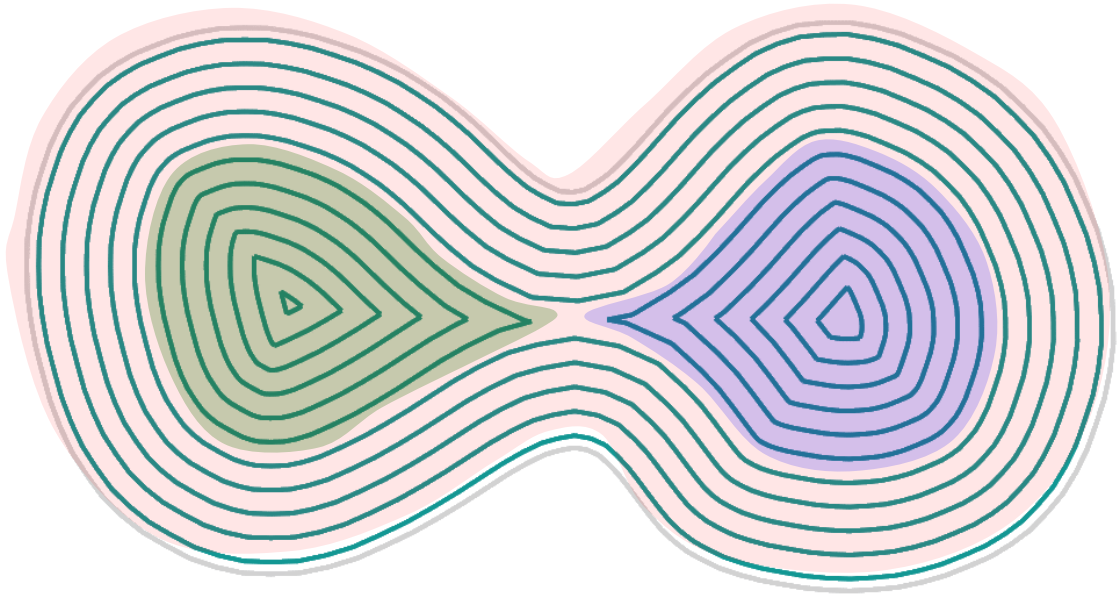
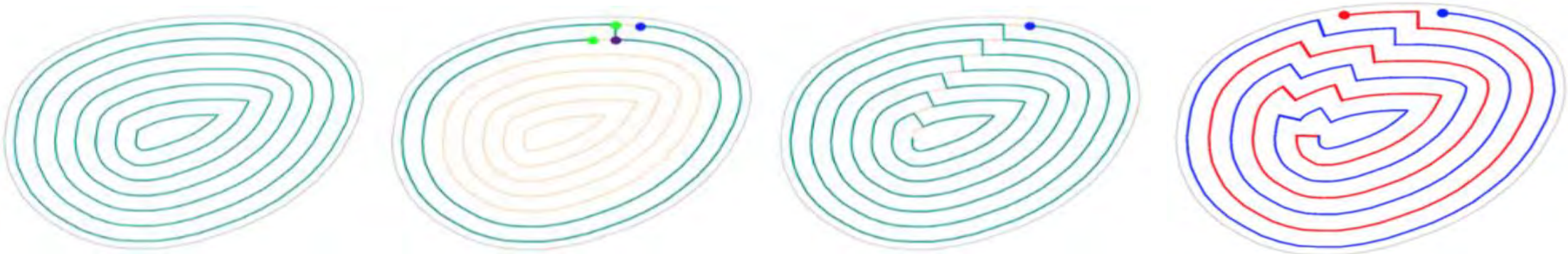
Key steps

1. Apply Euclidean distance transform to the input 2D layer to obtain iso-contours and a set of pockets



Key steps

1. Apply Euclidean distance transform to the input 2D layer to obtain iso-contours and a set of pockets
2. For each pocket, convert contour parallel paths into a Fermat spiral with start and end points next to each other



Parallel contours | One re-routing | To a spiral | Re-route to a Fermat spiral

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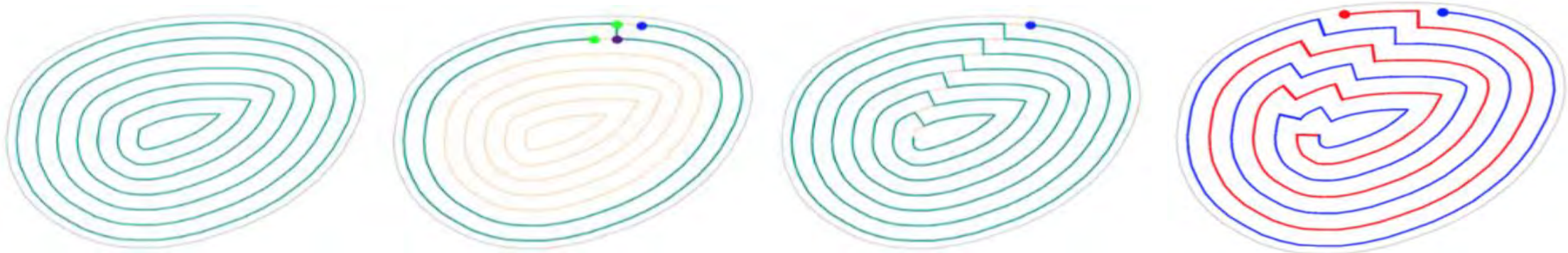


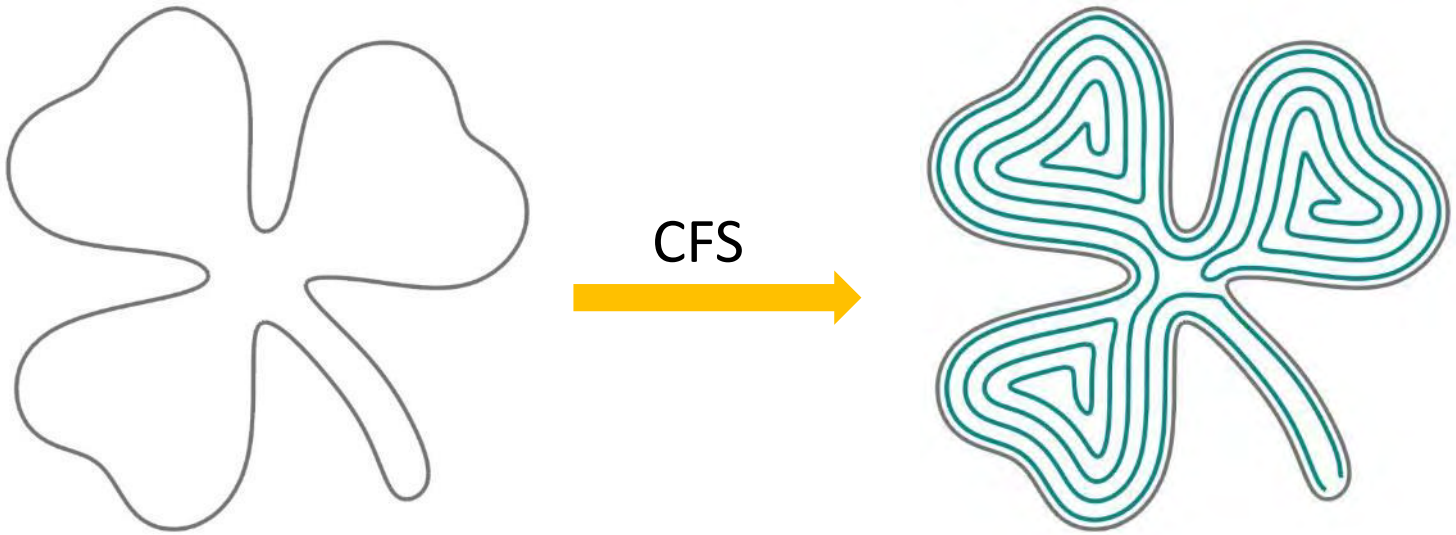
Parallel contours | One re-routing | To a spiral | Re-route to a Fermat spiral

3. Connect all Fermat spirals via a traversal and local re-routing

Contributions

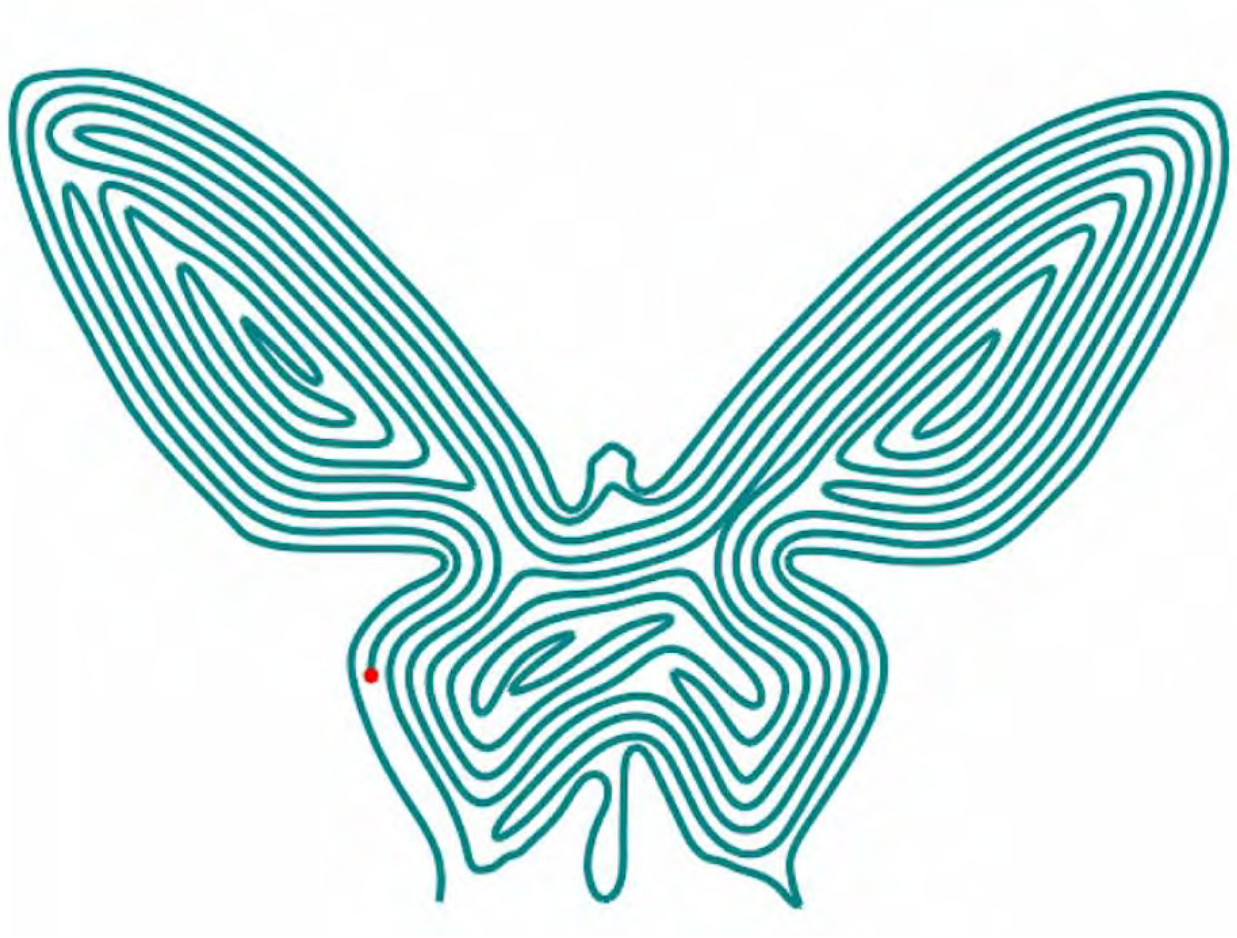
- Introducing Fermat spirals as a new kind of 2D fill pattern

- A tool path planning algorithm based on connected Fermat spirals (CFS) to continuously fill a connected 2D region

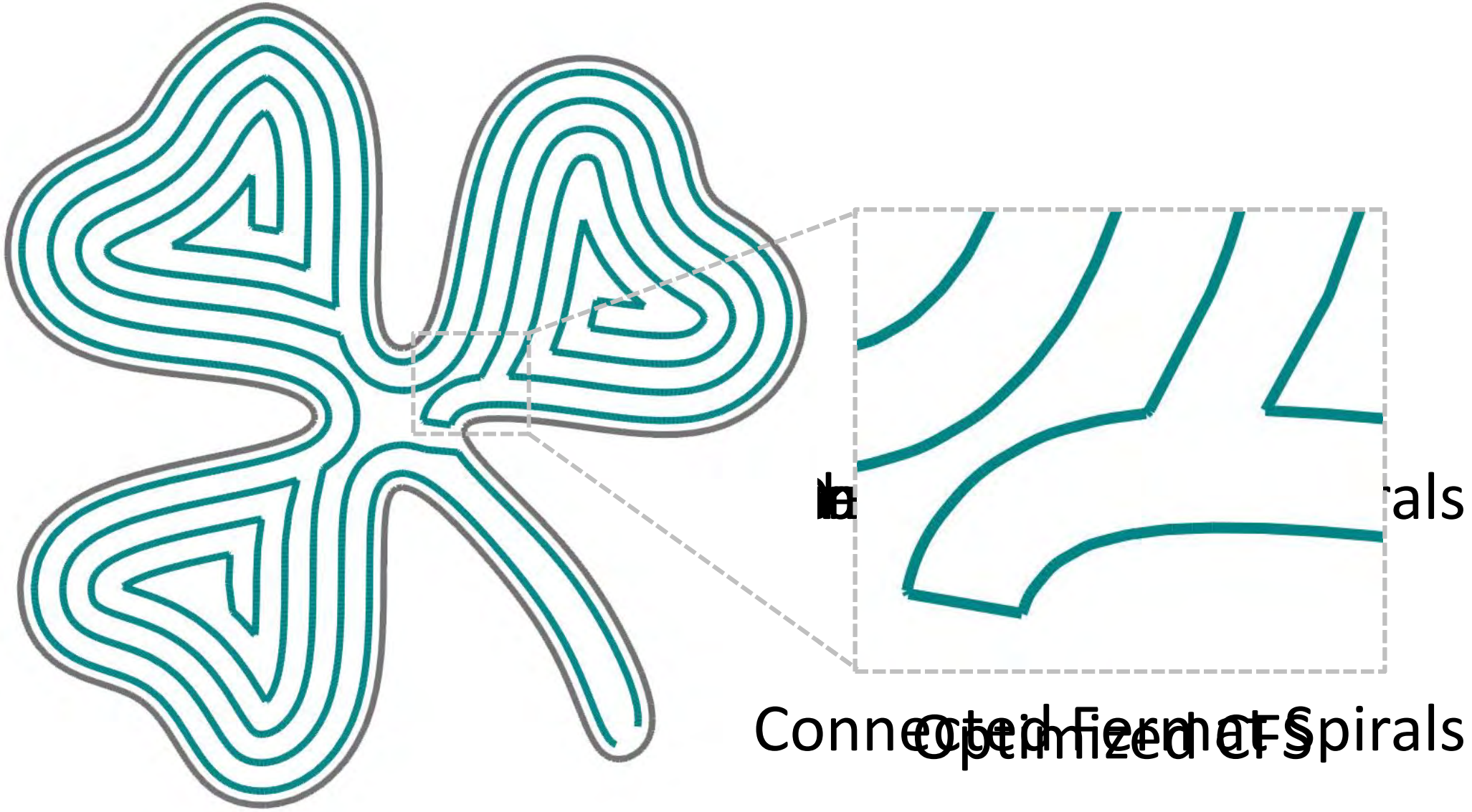


Connected Fermat spirals

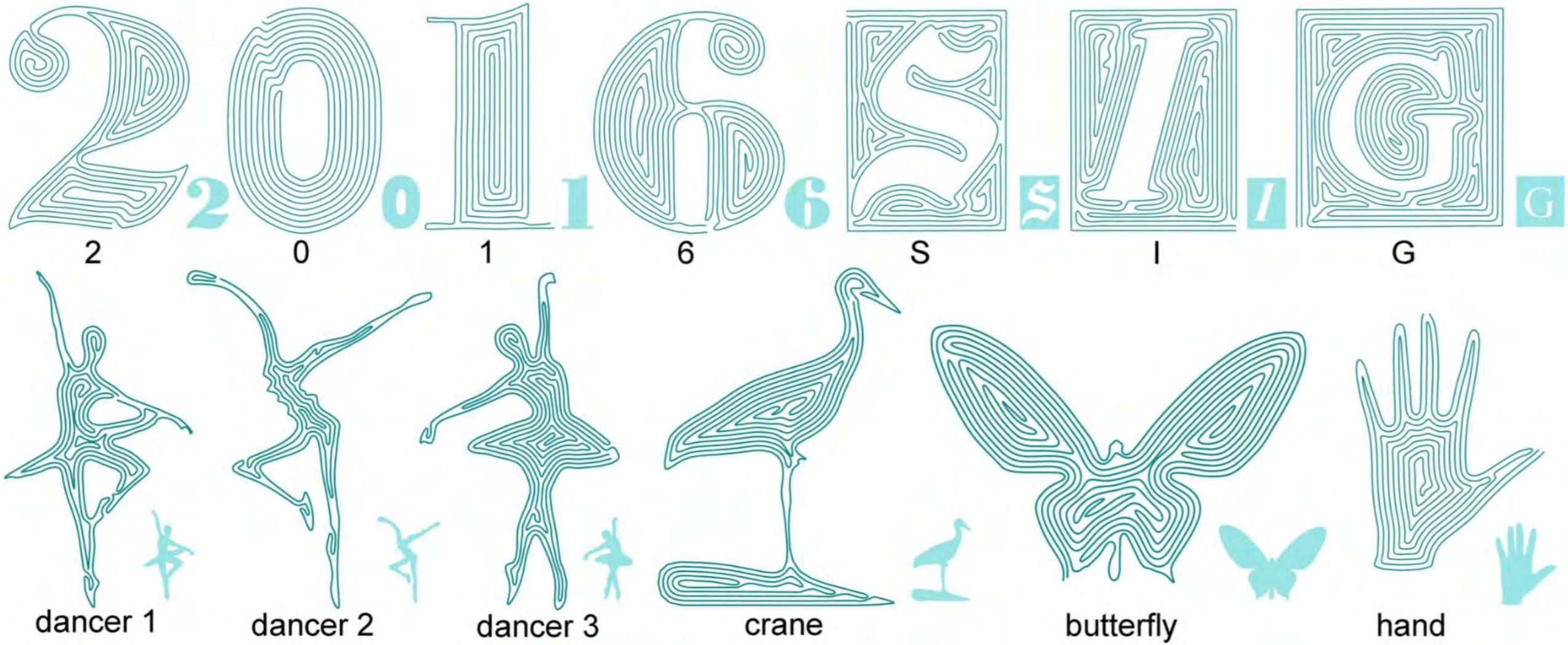
- Global continuity
- Long and low-curvature paths



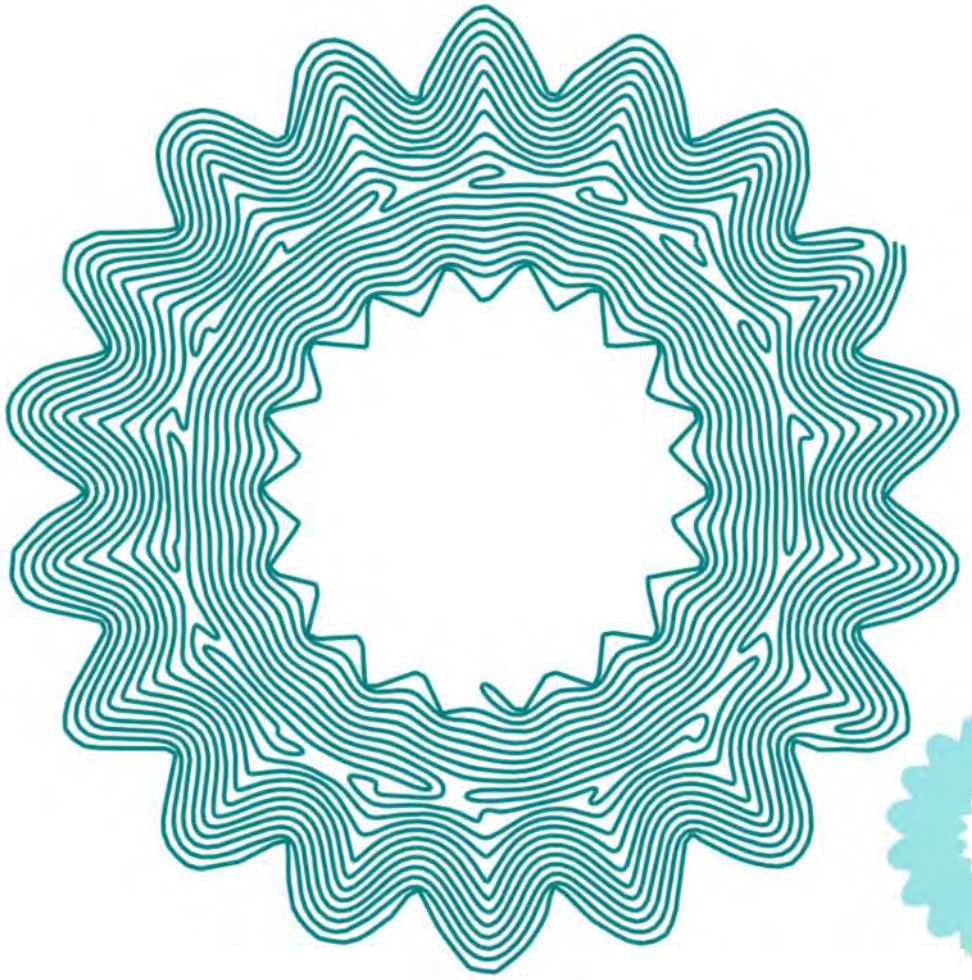
Overview



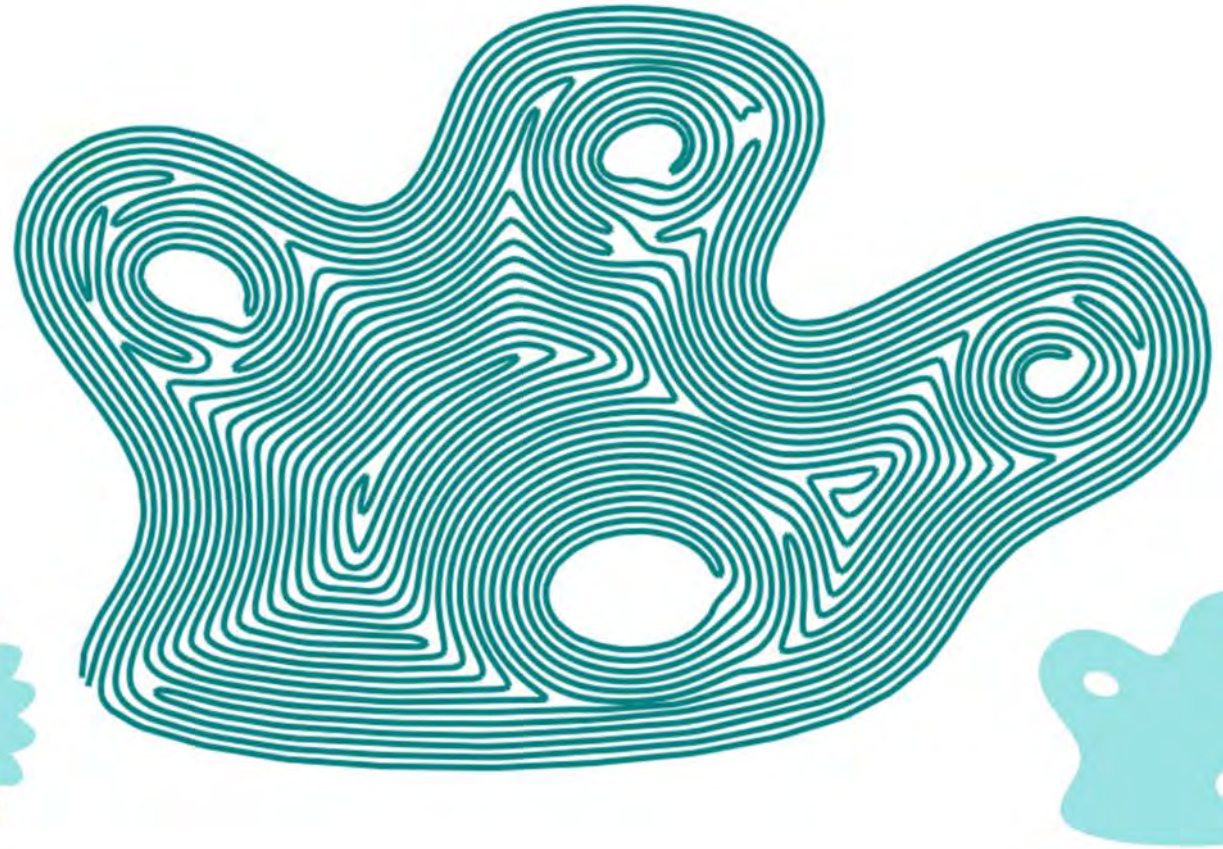
Results



Results



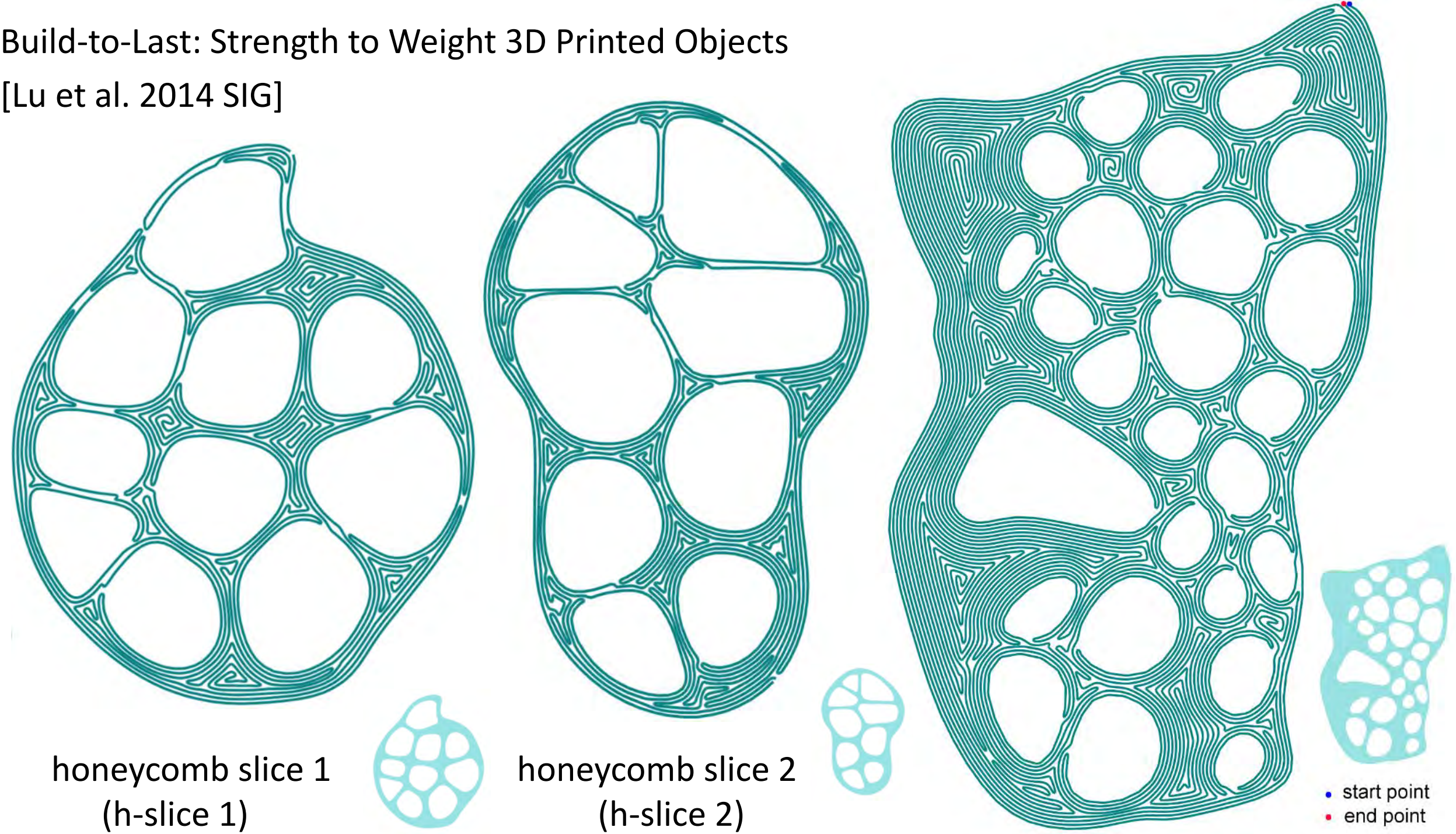
Gear



Paw

Build-to-Last: Strength to Weight 3D Printed Objects

[Lu et al. 2014 SIG]



honeycomb slice 1
(h-slice 1)

honeycomb slice 2
(h-slice 2)

Results

Z: zigzag paths
C: contour-parallel paths
F: connected Fermat spiral paths

- Number of disconnected tool path segments

Input	#segZ	#segC
dancer 1	22	14
dancer 2	19	10
dancer 3	21	13
crane	8	17
butterfly	16	24
hand	9	11
gear	51	105
paw	20	55
h-slice1	53	58
h-slice2	47	56

Slic3r

Results

Z: zigzag paths
C: contour-parallel paths
F: connected Fermat spiral paths

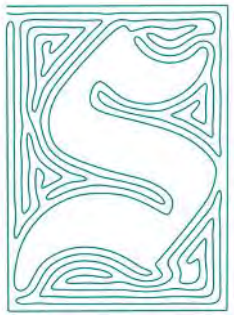
- Percentage of sharp turns for the three fill patterns

Input	%stZ	%stC	%stF
dancer 1	5.87%	1.40%	**1.38%**
dancer 2	6.58%	1.55%	**1.08%**
dancer 3	4.11%	1.19%	**0.81%**
crane	4.86%	**0.46%**	0.93%
butterfly	1.81%	0.83%	**0.52%**
hand	4.84%	1.07%	**0.56%**
gear	1.18%	2.11%	**0.23%**
paw	1.25%	0.51%	**0.31%**
h-slice1	4.35%	1.08%	**0.81%**
h-slice2	5.12%	0.88%	**0.70%**

Visual quality

Z: zigzag paths
C: contour-parallel paths
F: connected Fermat spiral paths

Z

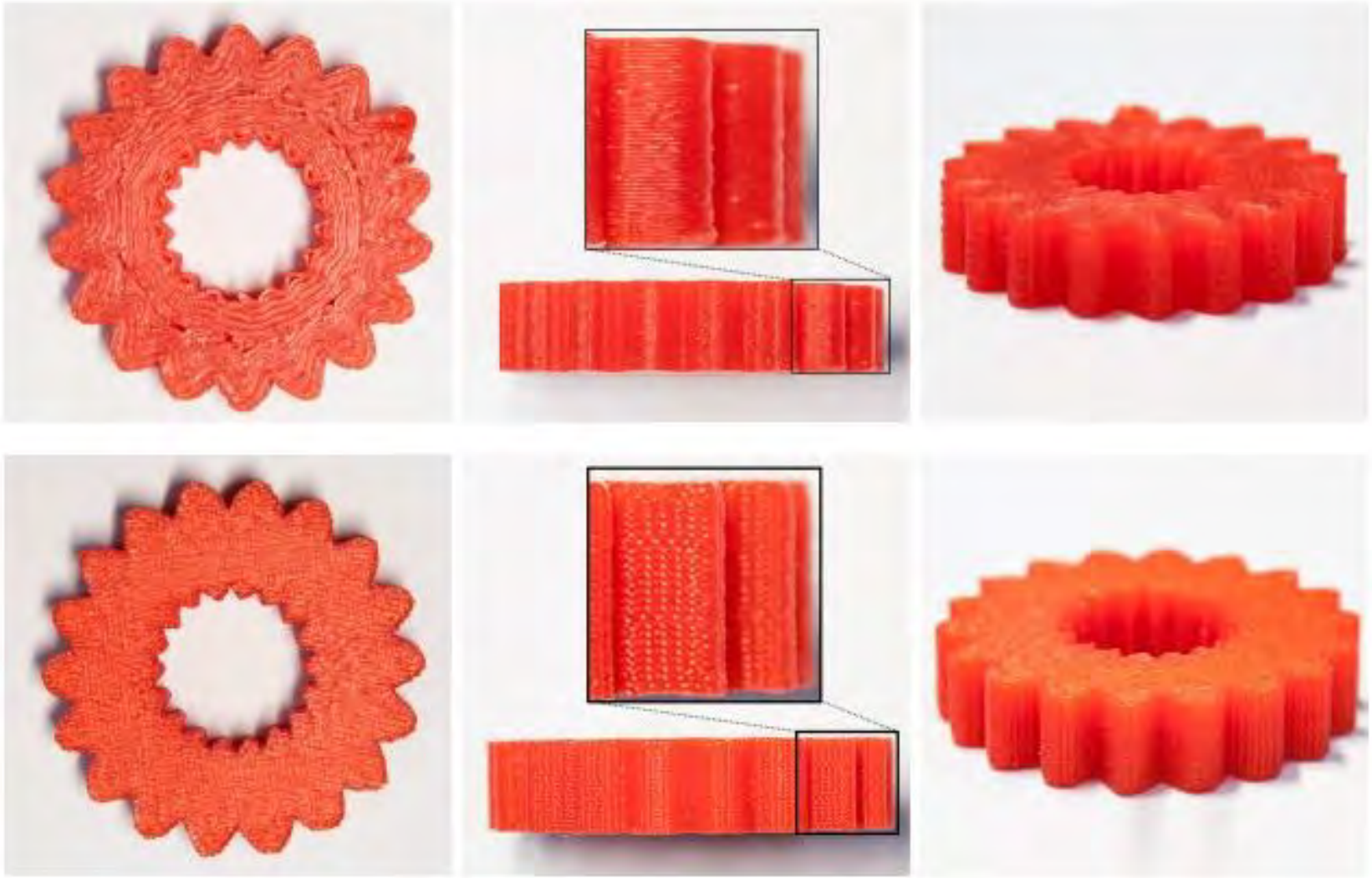


CFS

Visual quality

Connected Fermat spiral (CFS)

Zigzag



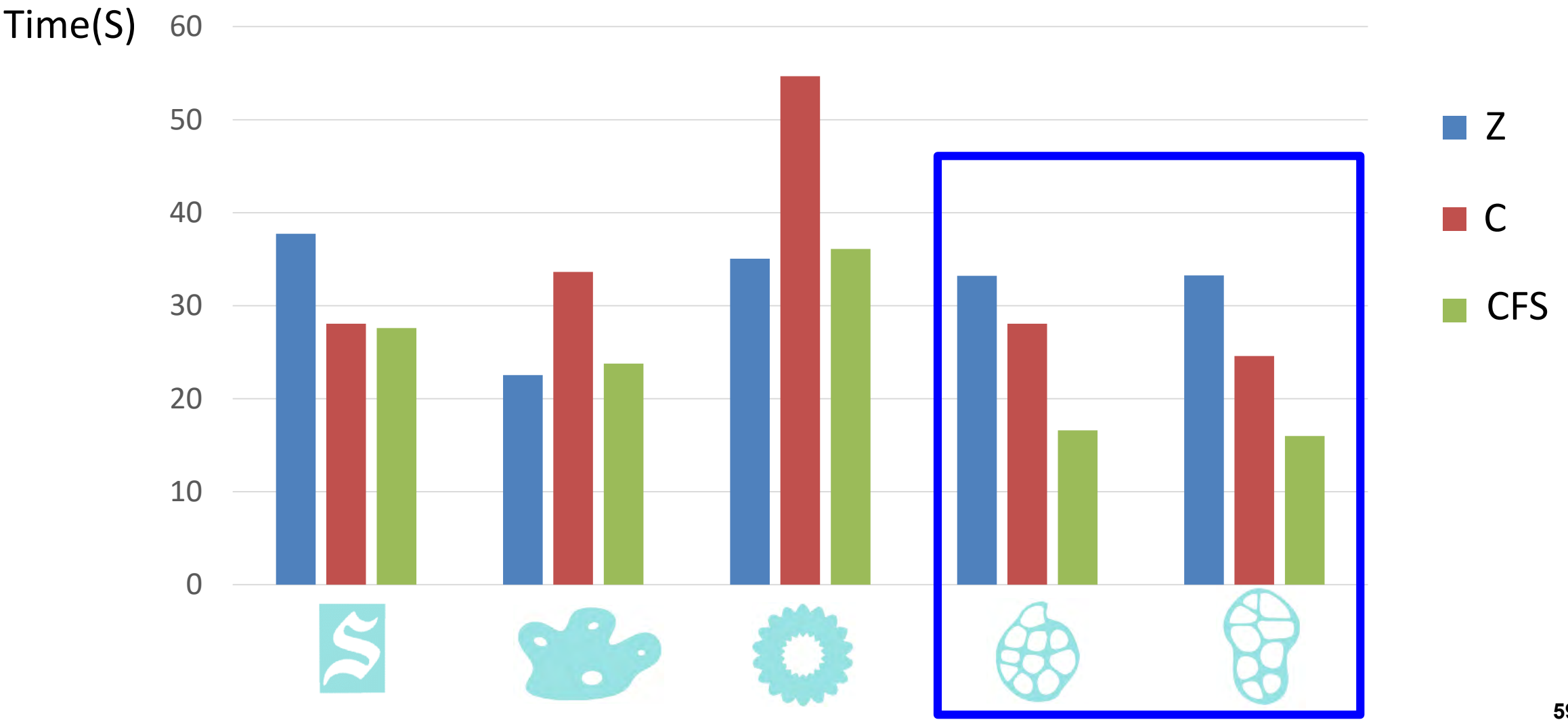
50 layers

1cm

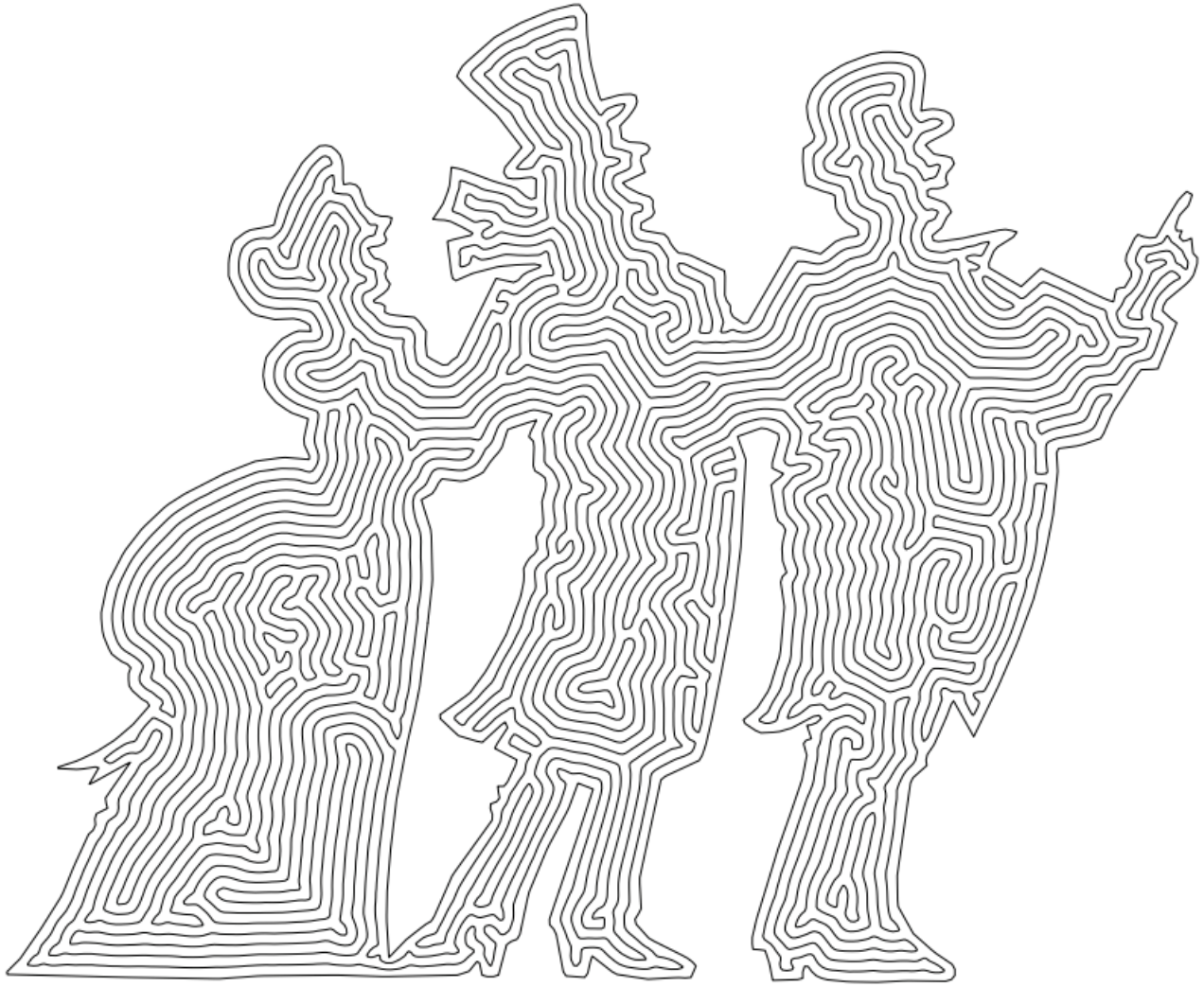
Photographs of 3D fabrications using FDM

Fabrication times

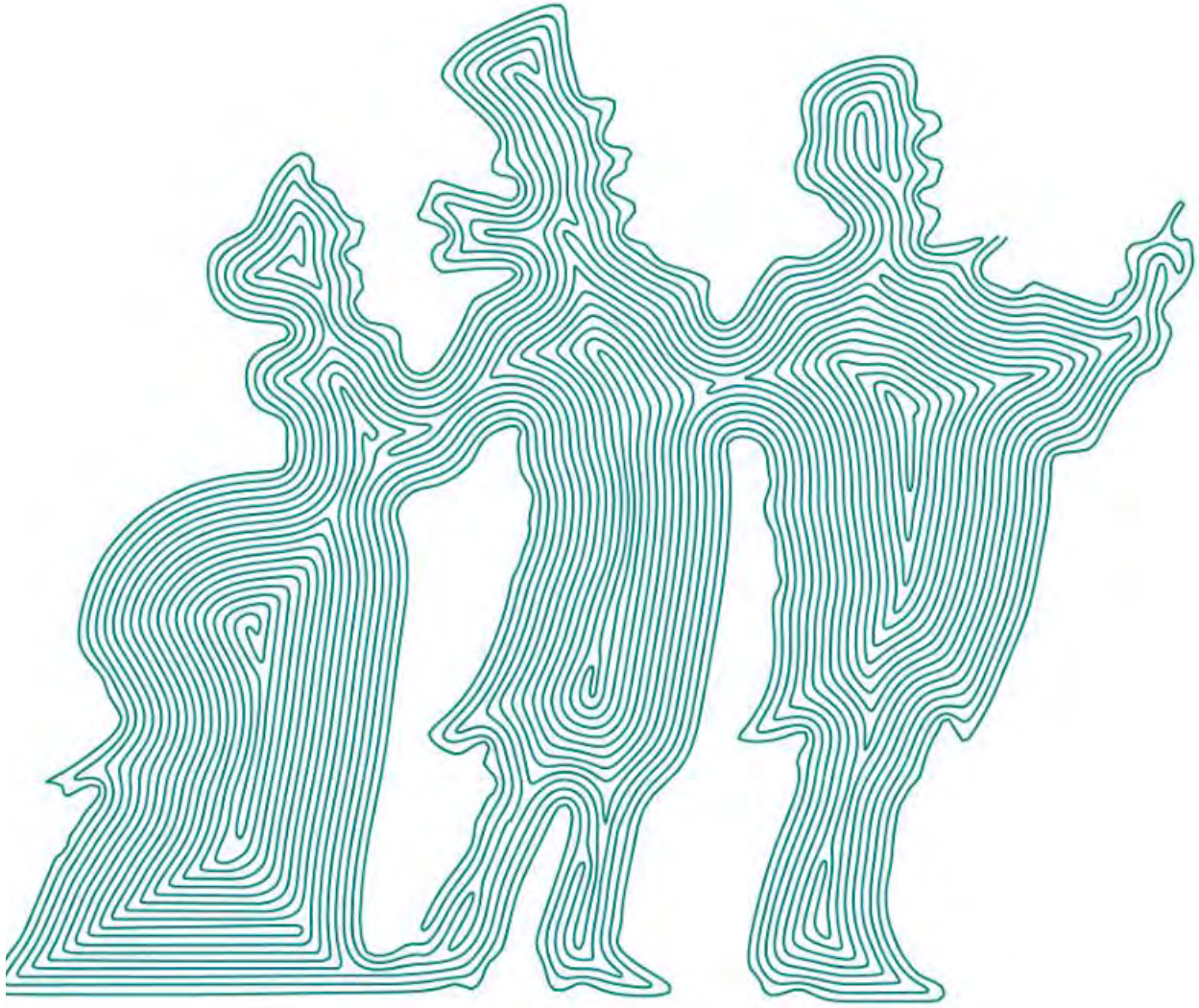
Z: zigzag paths
C: contour-parallel paths
F: connected Fermat spiral paths



Beyond tool path planning



A maze [Pedersen and Singh 2006]



Our result

Beyond tool path planning

Patch work

Irrigation paths in Israel

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

ACM SIGGRAPH 2018

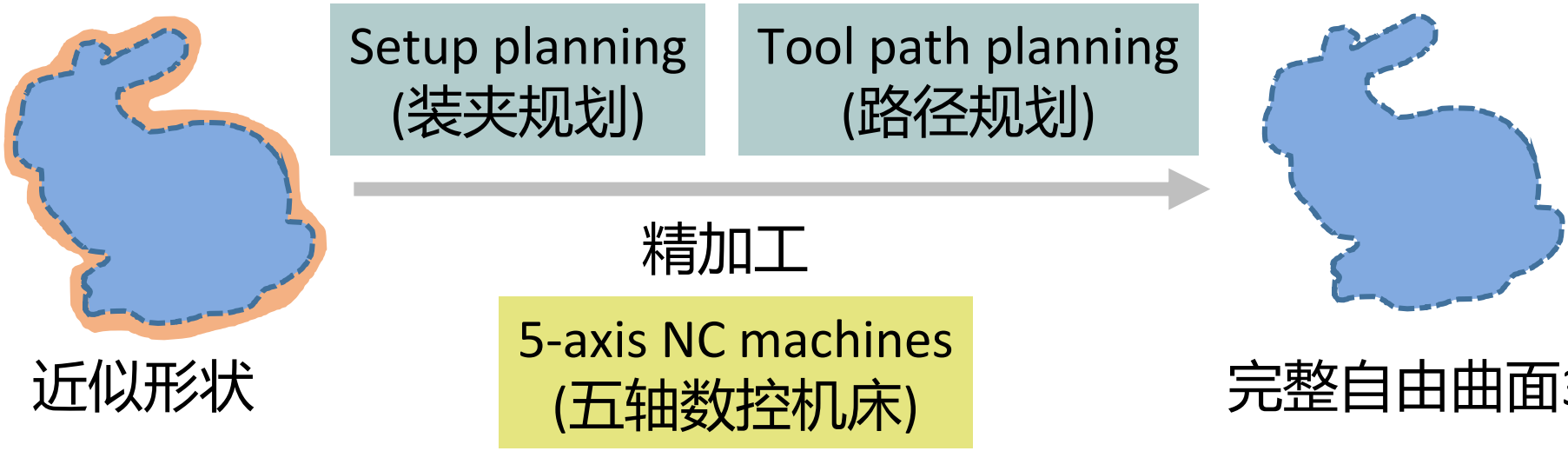
Haisen Zhao[1], Hao (Richard) Zhang[2], Shiqing Xin[1], Yuanmin Deng[1], Changhe Tu[1], Wenping Wang[3], Daniel Cohen-Or[4], Baoquan Chen[1,5]

[1]Shandong University [2]Simon Fraser University [3]Hong Kong University

[4]Tel-Aviv University [5]Peking University

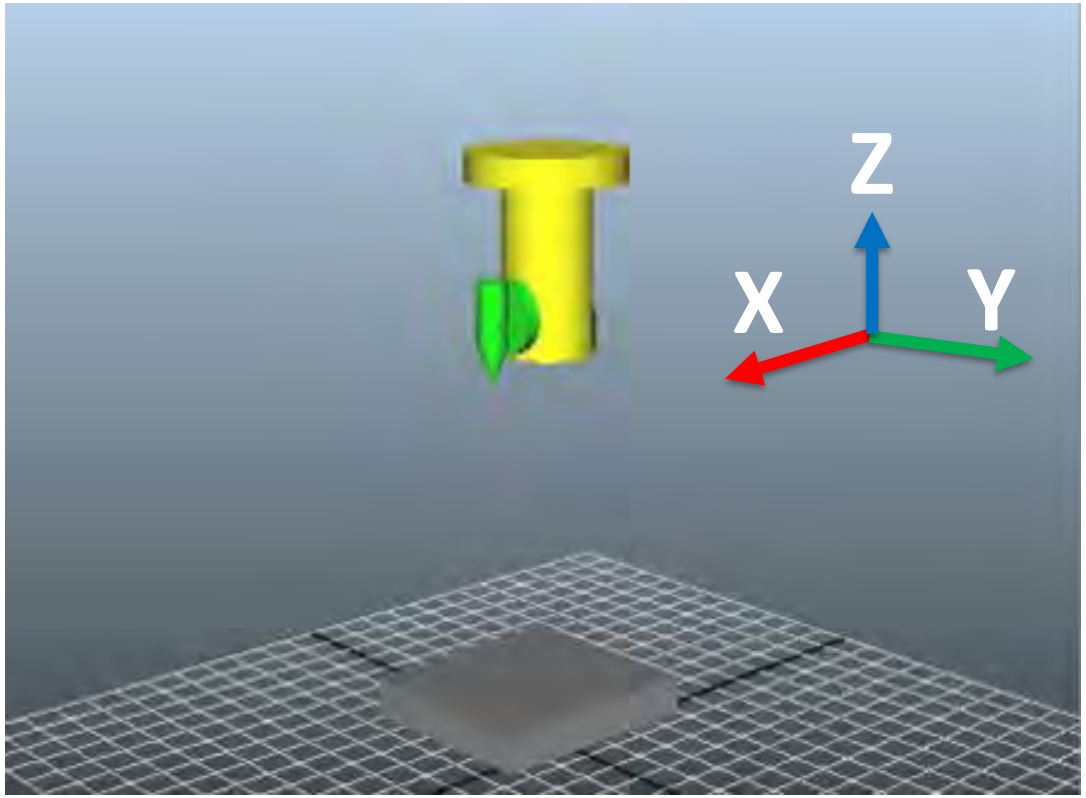
Our goal

- Automatic optimization of **setup** and **tool path planning** for **finish-stage machining** of **full free-form 3D objects**/sculpted surfaces using **5-axis NC** machining.

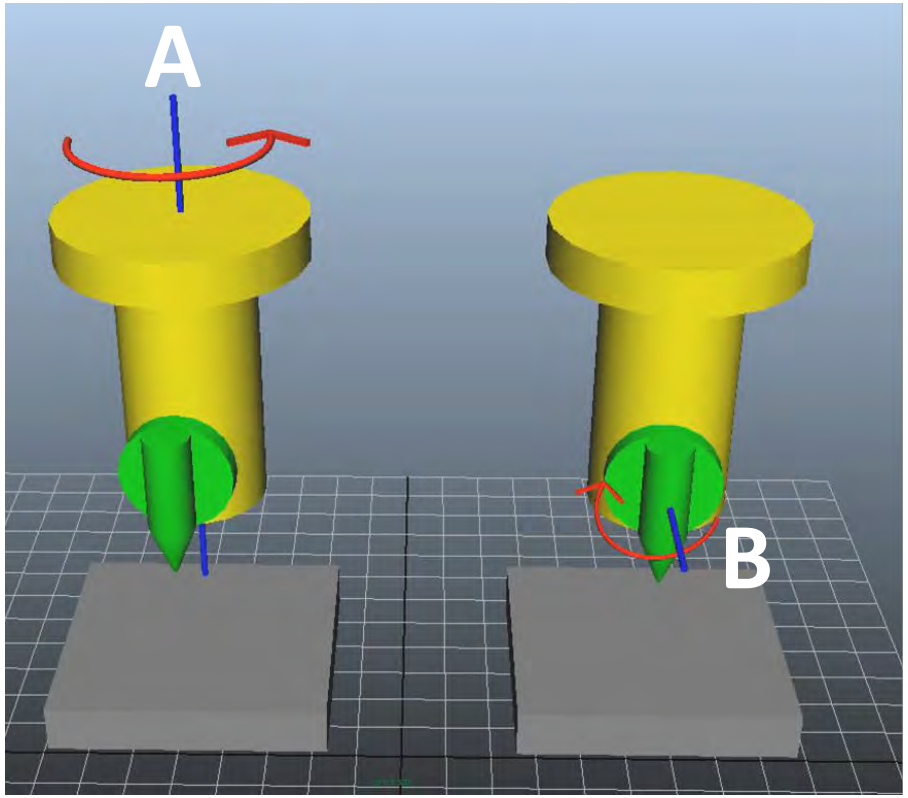


5-axis CNC machines

- **Free-form surfaces** are typically carved by **5-axis CNC machines**.
- 5-axis CNC machine: X,Y,Z translation axes + A,B rotation axes

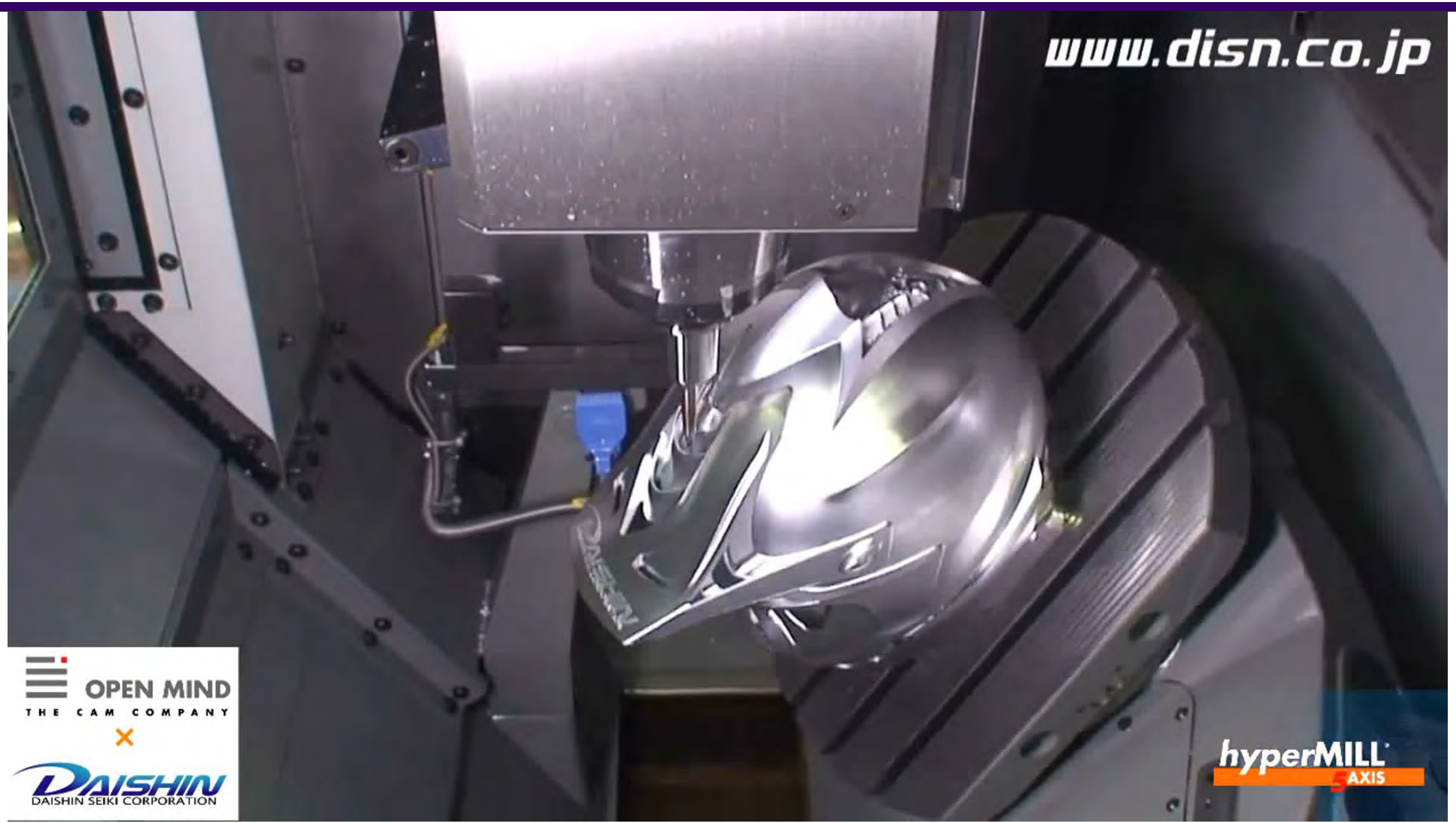


三个移动轴 (XYZ)

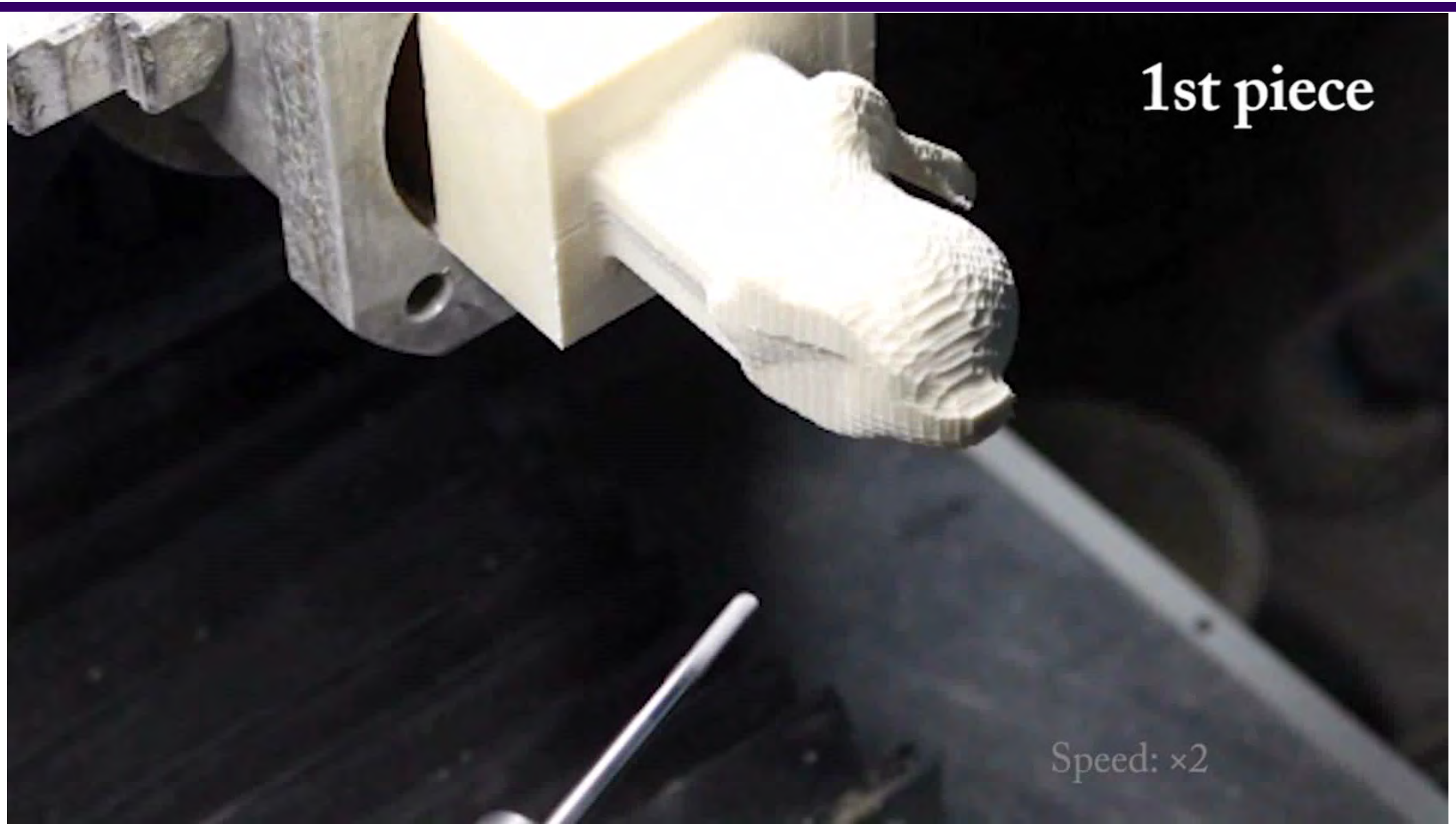


两个转动轴 (AB)

5-axis machining 五轴联动



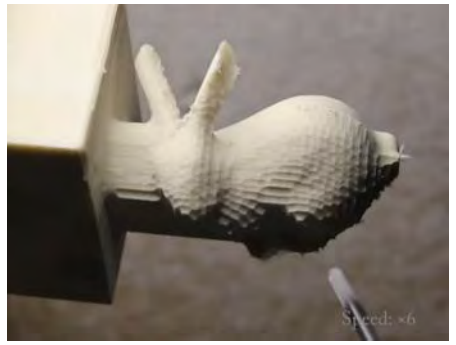
3+2 machining 定轴加工



3+2 machining vs 5-axis machining

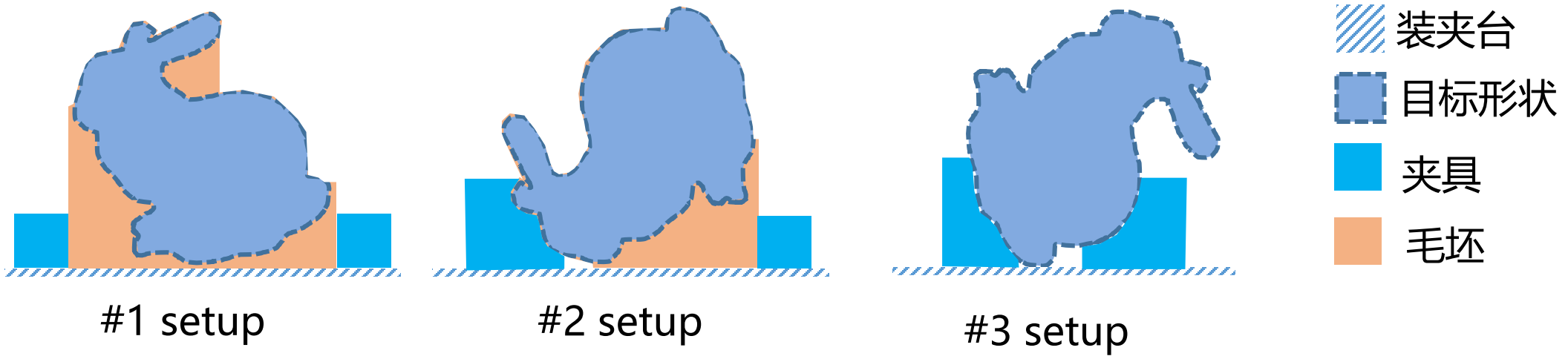
- 3+2 machining：common used

- Less programming work (路径易于编程)
- Greater stiffness (轴体刚度更好)
- Longer tool life (刀具寿命更长)
- Higher surface quality (切削表面质量好)
- Higher machining efficient (加工效率高)

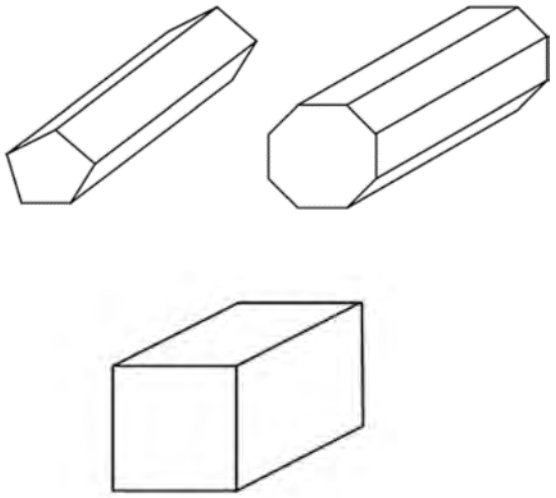


Setup planning 装夹规划

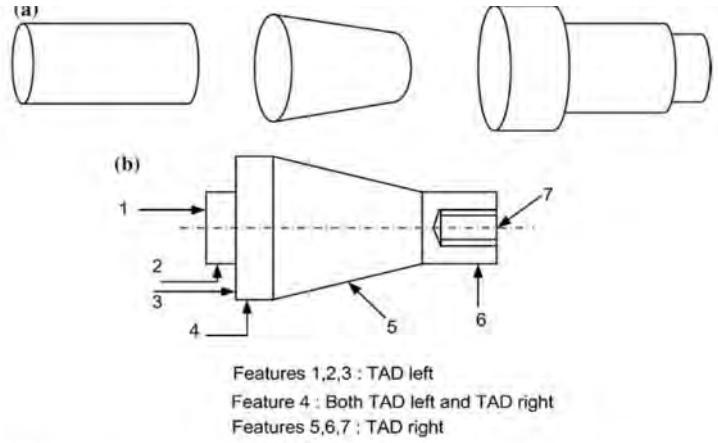
- Orient and stabilize the shape stock with fixtures for carving.
  - Highly critical to minimize the number of setups



Setup planning—Related works



Prismatic parts
(箱体工件)



Rotational parts
（回转体工件）

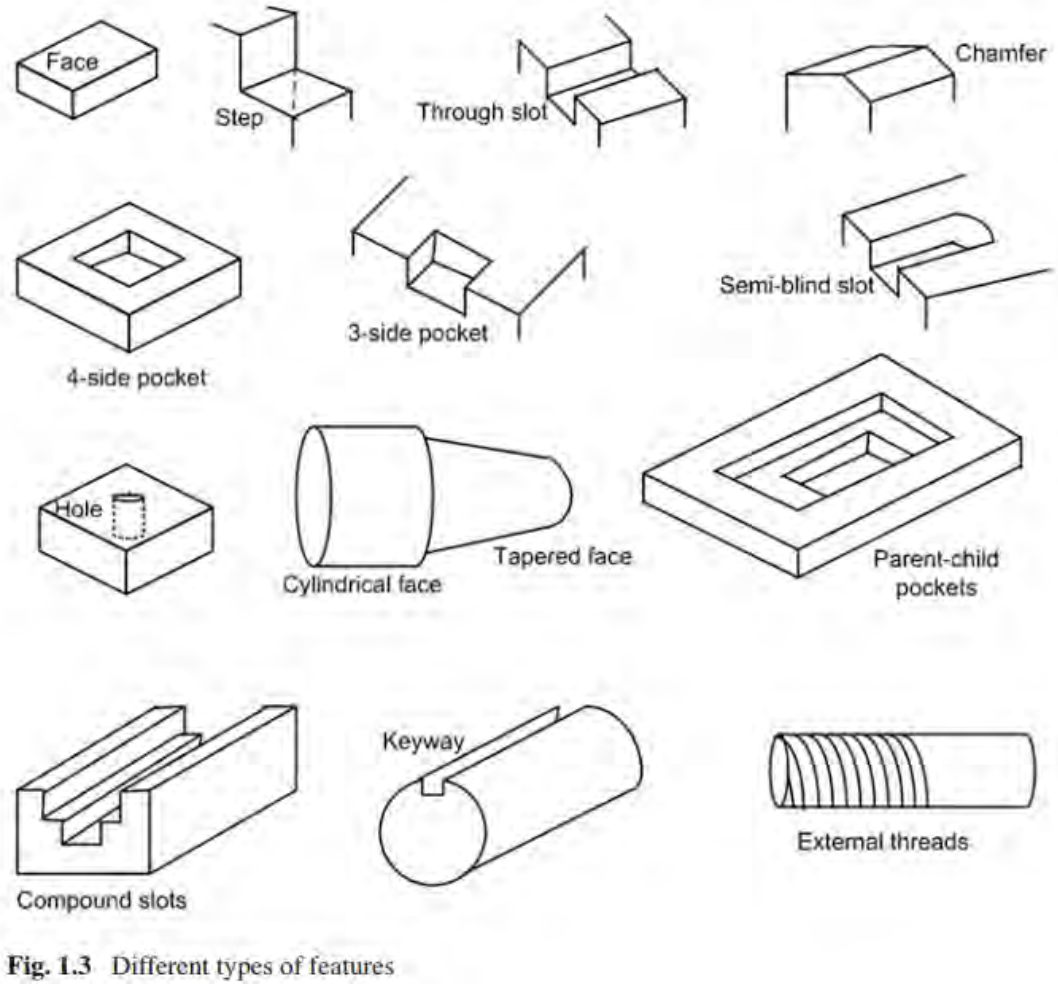
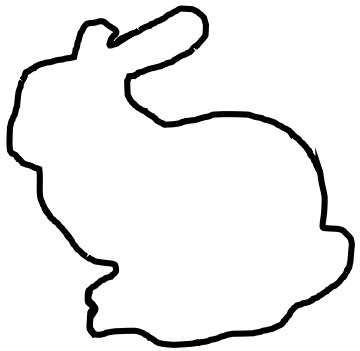


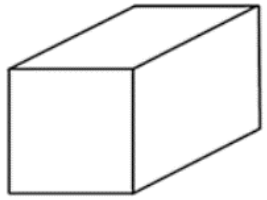
Fig. 1.3 Different types of features

Setup planning—Industry area

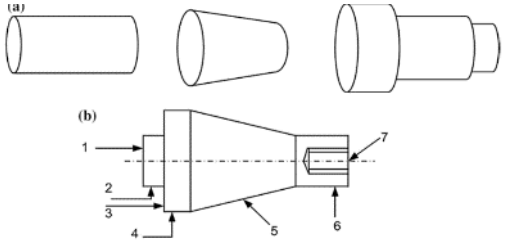
- In practice, a **manual** process
  - Heavily rely on experts' domain knowledge and experience;



自由曲面3D工件



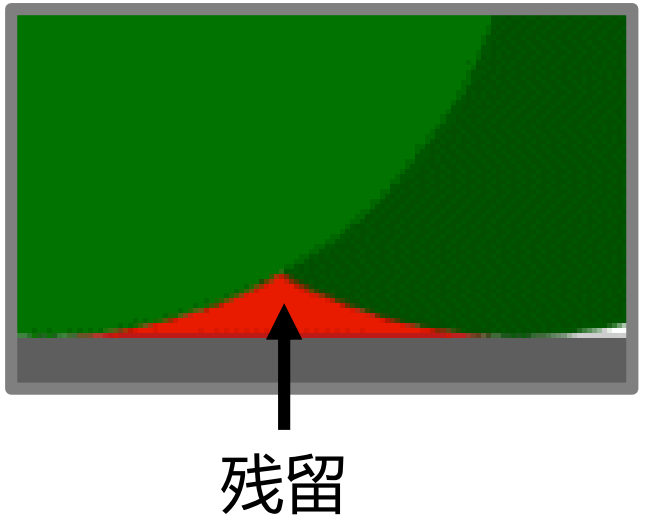
箱体工件



回转体工件

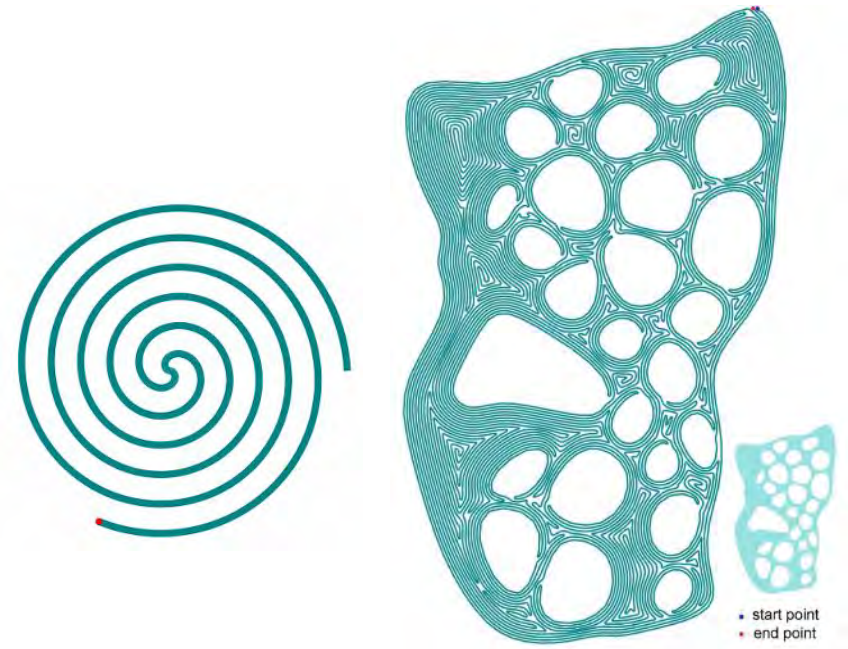
Tool path planning 路径规划

- Desirable properties of tool paths
  - Fairness (平滑性)
  - Continuity (连续性)
    - less on/off switching or tool retractions
  - **Scallop distribution** (残留分布)
    - Residual material after carving.
    - **Maximize uniformity** of the scallop within maximal scallop height (最大残留高度)



Fermat spiral to CNC

- Global continuity
- Long and low-curvature paths



Connected Fermat spirals
[Zhao et al. SIG 2016]

2D – 3D

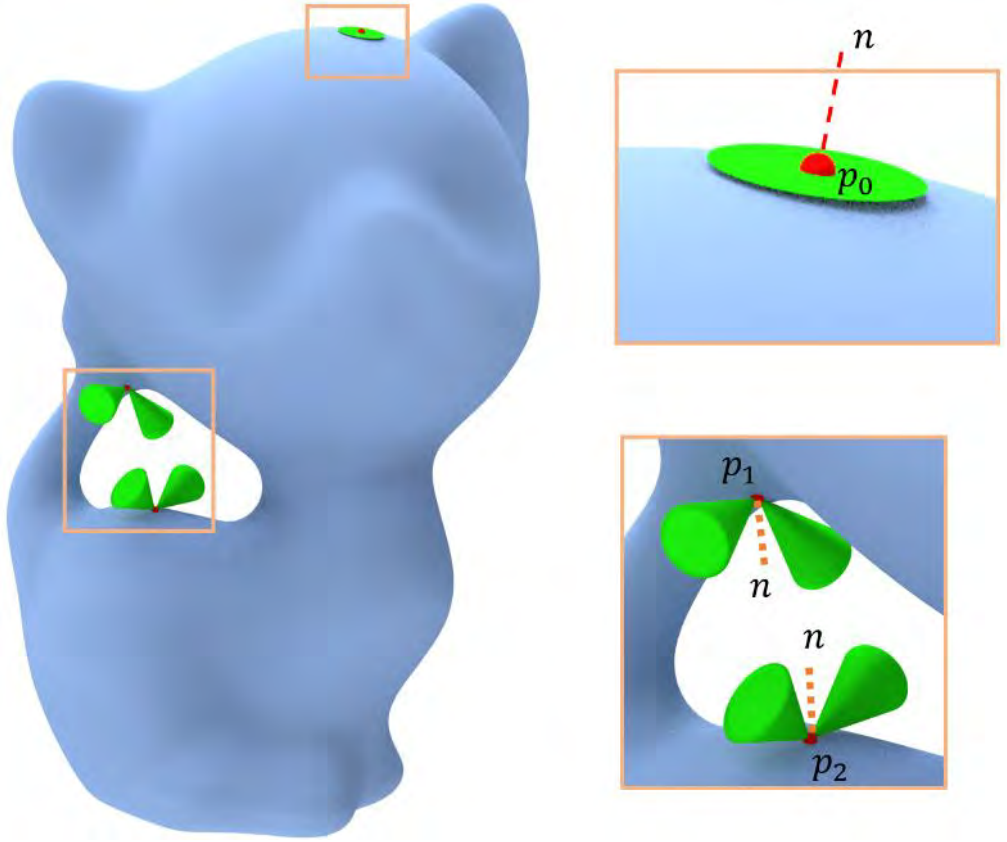
Scallop distribution

Connected ISO-scallop Fermat spirals

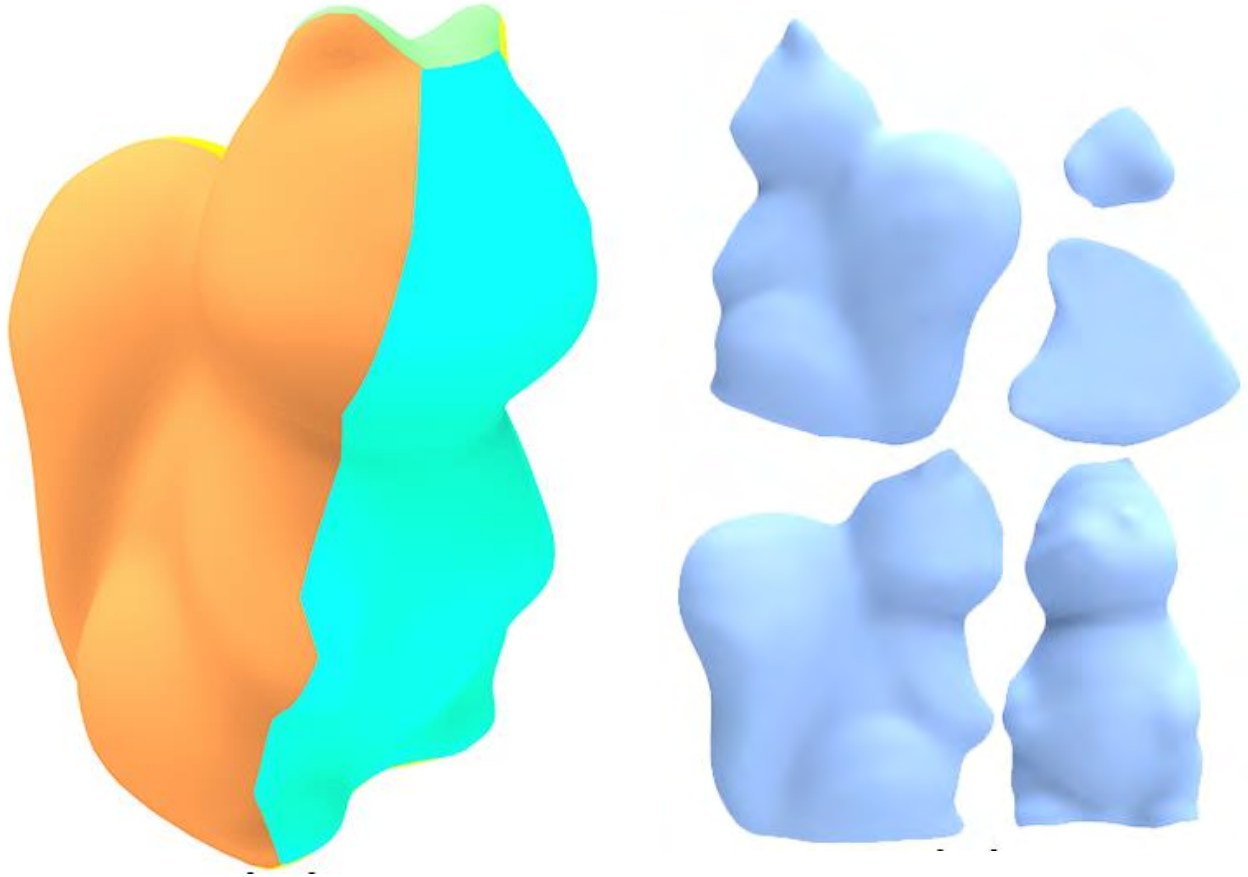
Setup planning

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.

- Height field decomposition (3+2 machining)



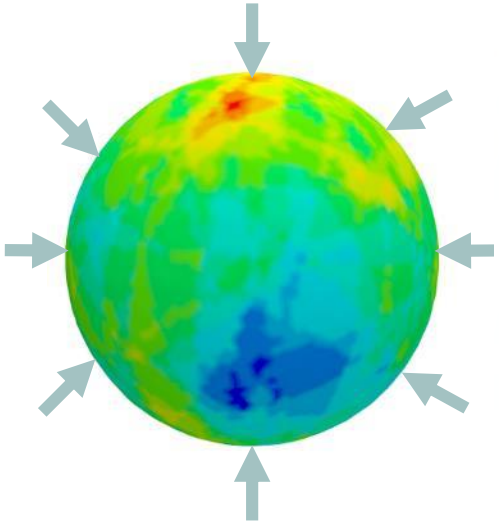
Accessible cone



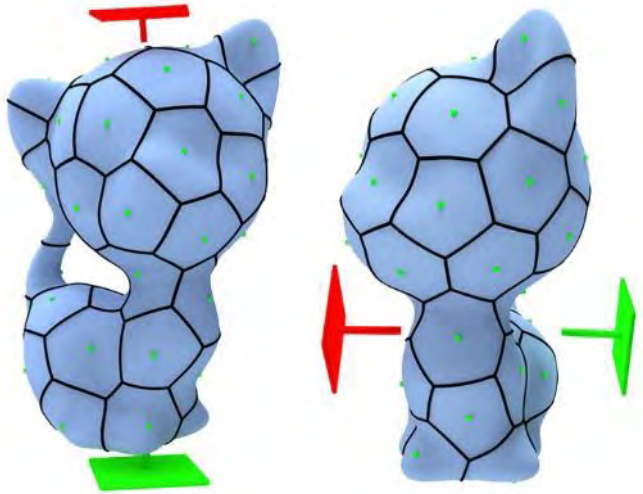
pre-segmentation to a few height fields based on [Herholz et al. 2015]

Setup planning

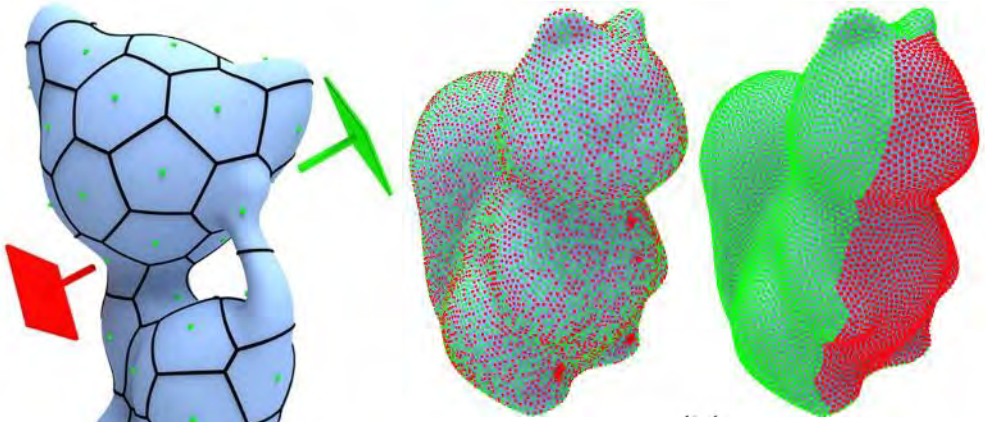
- Sampling setup directions
- Minimum number of accessible regions by Set cover problem(SCP)
- Integrate the resulting regions with the height field parts.
- Form a final decomposition



Sampling setup directions

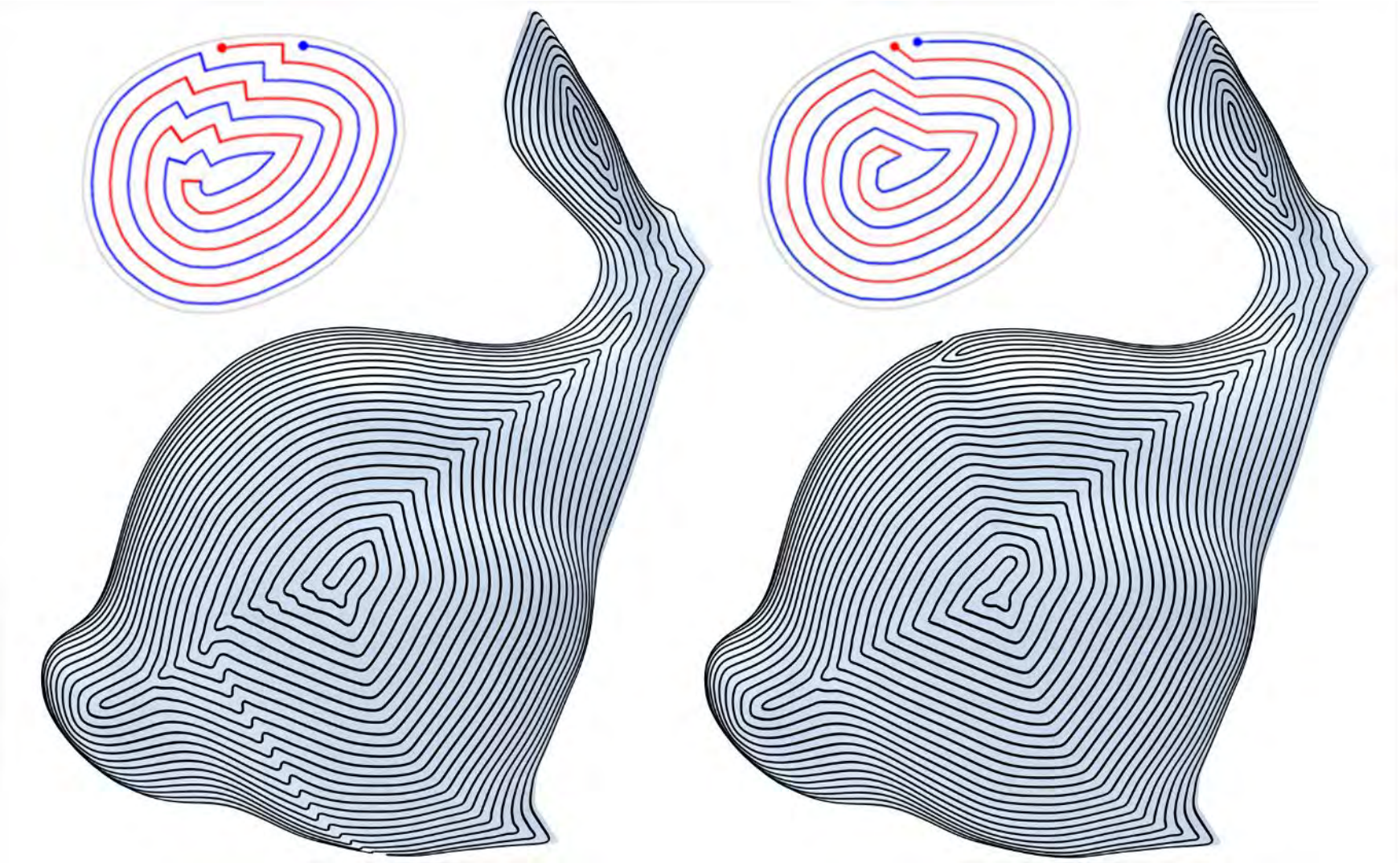


MINORIs

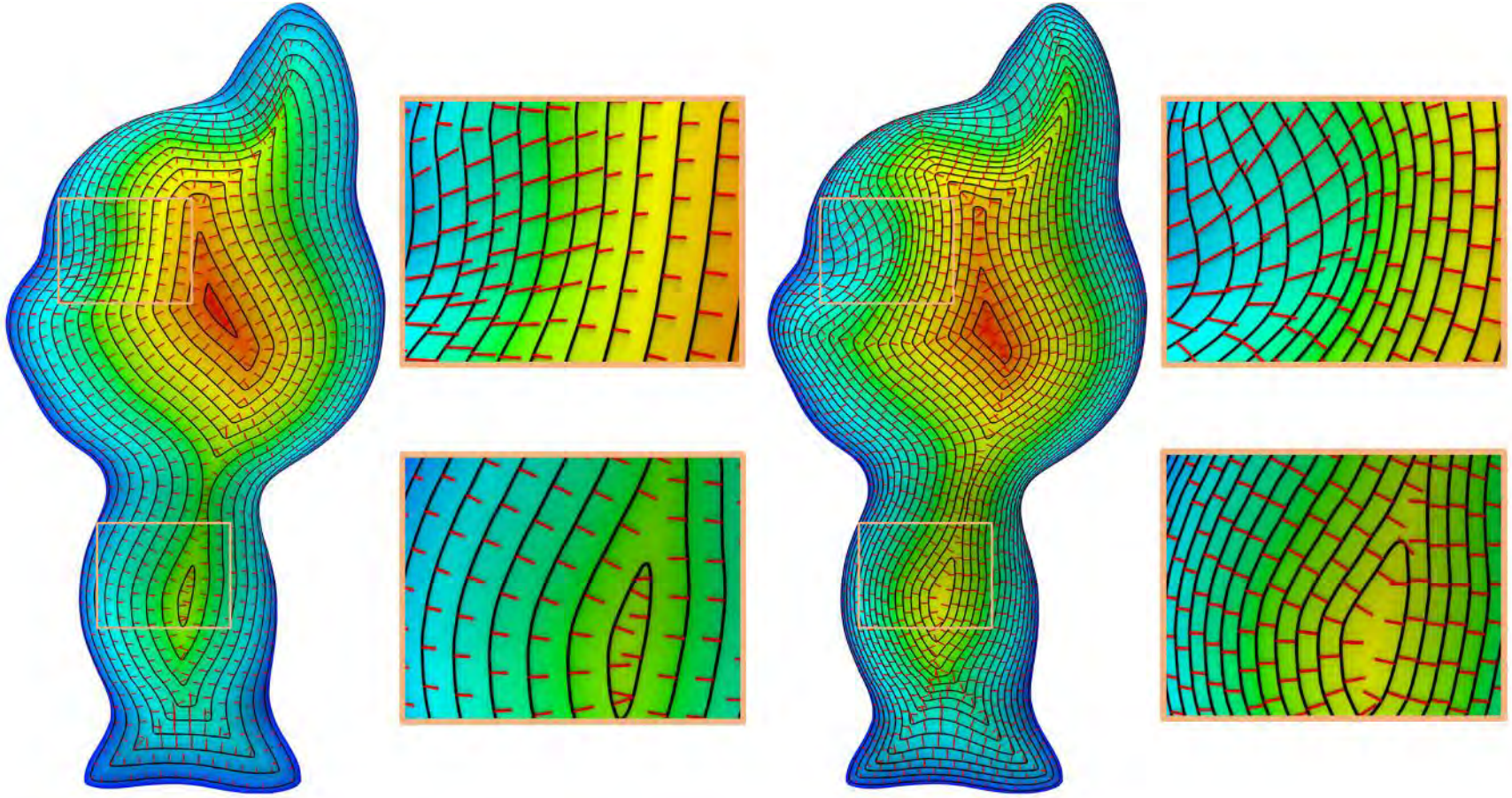


Integration with pre-segmentation

Fermat spirals



ISO-scallop field generation



An nonhomogeneous version of the heat method [Crane et al. 2013a] for geodesic computations

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.

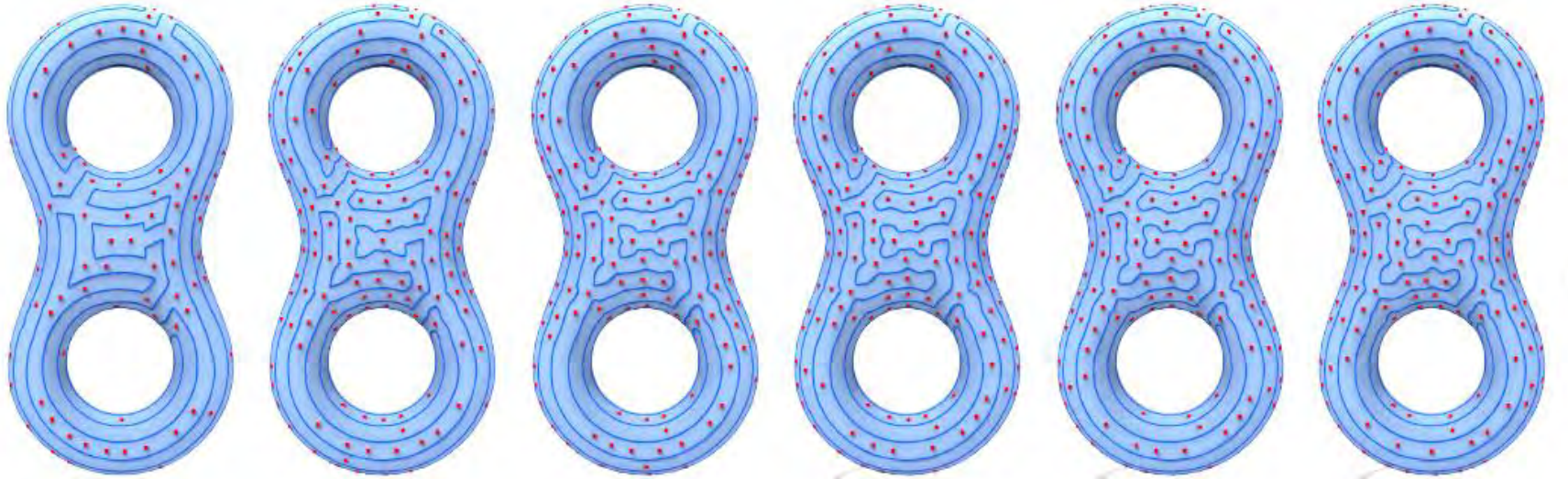
Tool path refinement

- Connected ISO-scallop Fermat spirals:

  C_0 continuous and non-uniform scallop-ware spacing

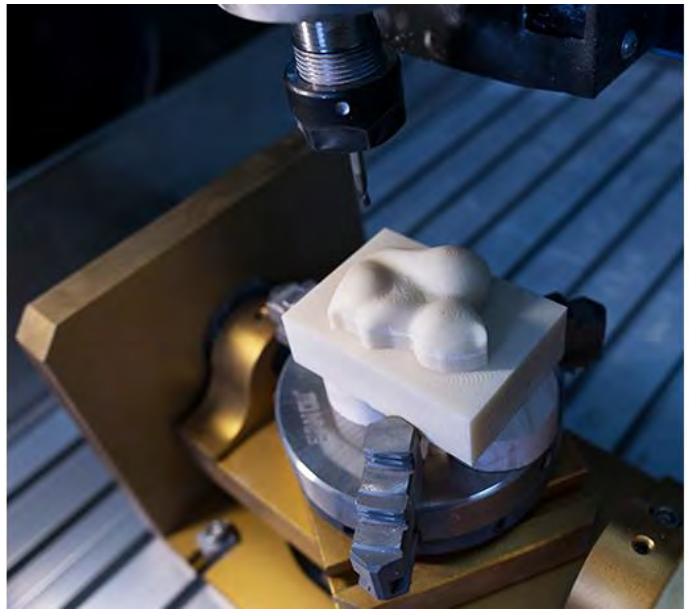
- Locally optimize continuous path considering

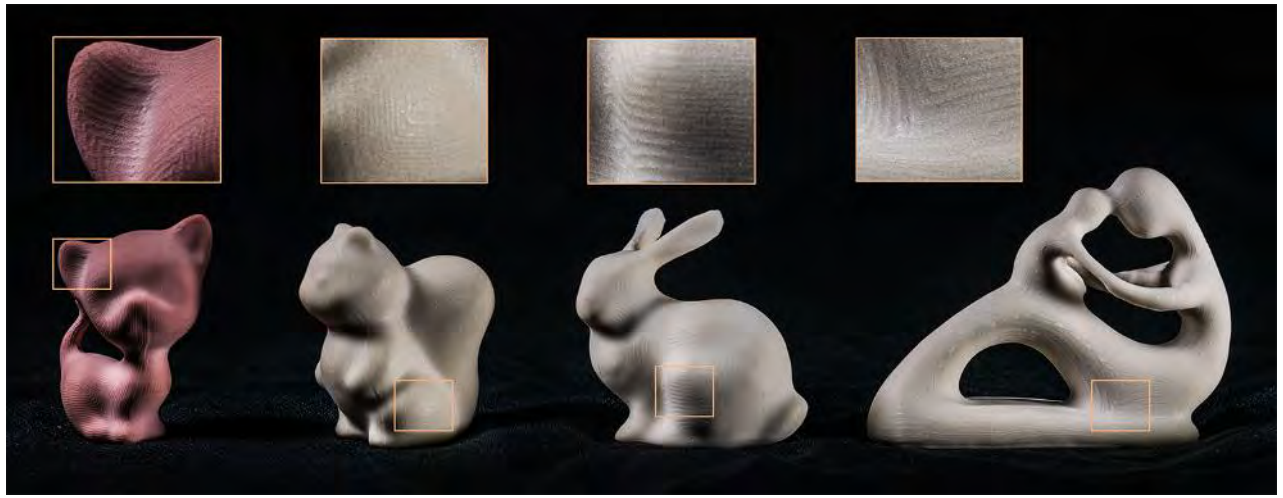
  fairness and scallop distribution



(a) Initial (b) #20 (c) #40 (d) #60 (e) #80 (f) #100

Experiments environment



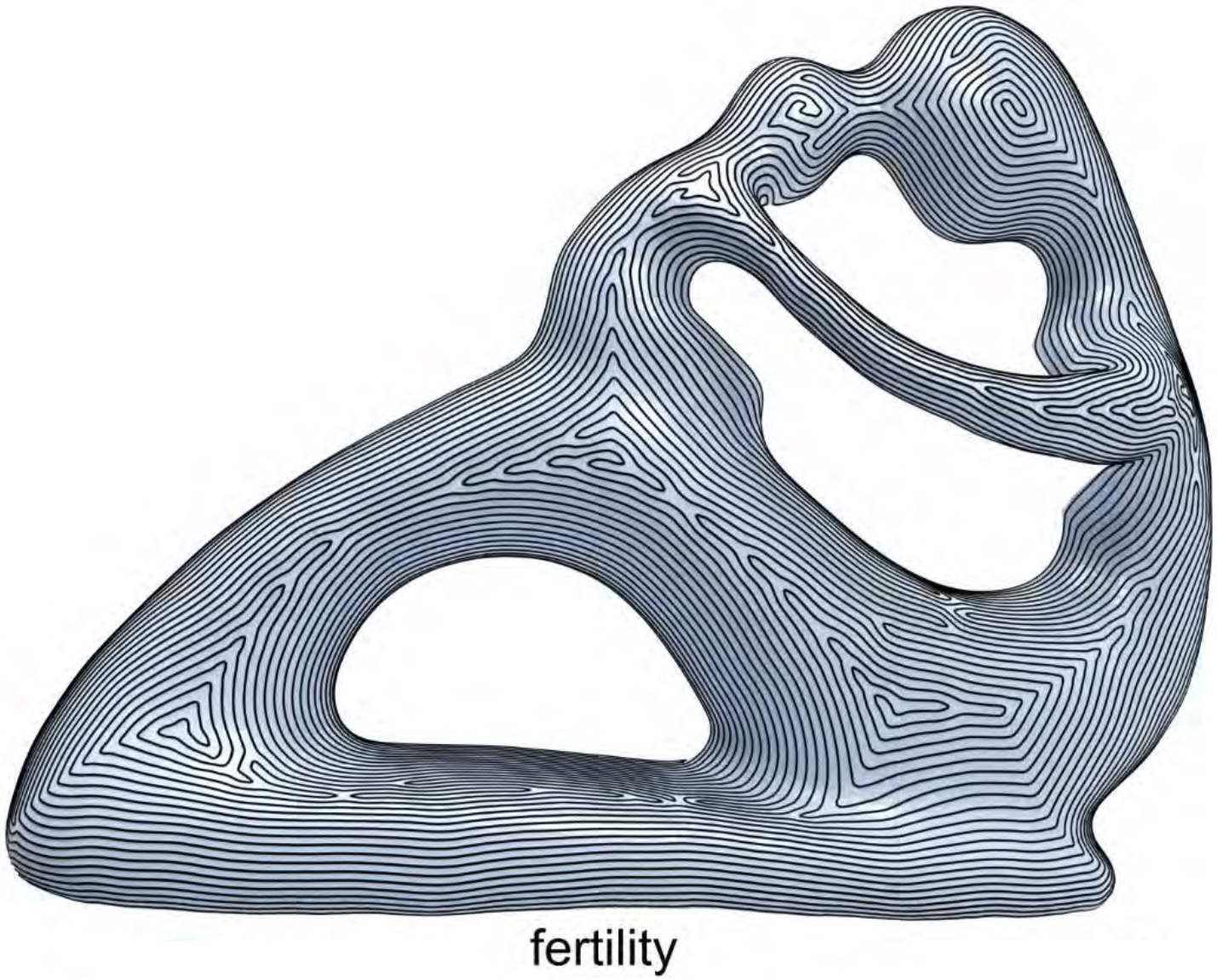


CNC 6040 2200W 5-axis machine

- 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 board(代木) as testing material.

Results

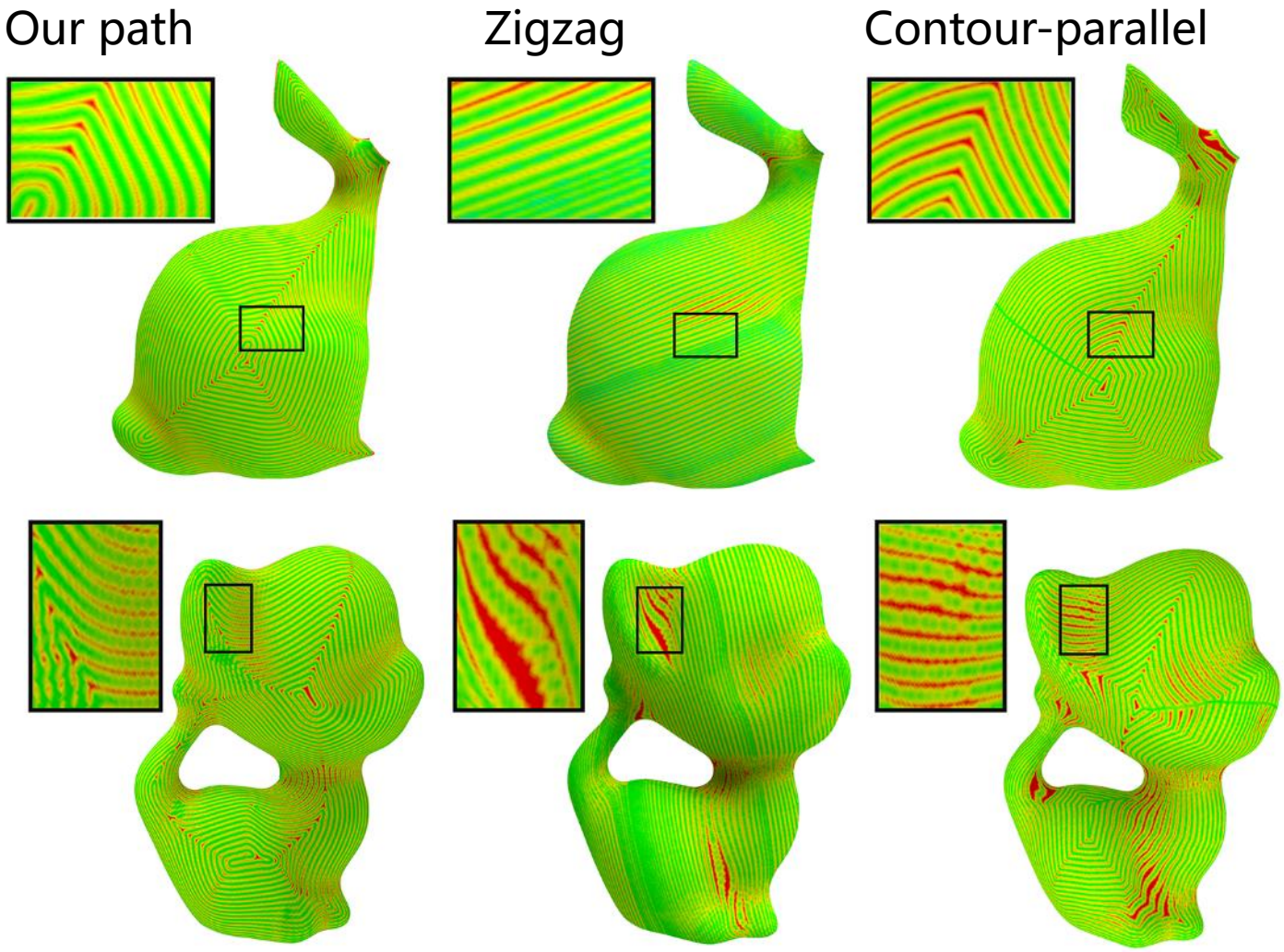


Results

Table 2. Comparing zigzag (Z) and contour-parallel (C) tool paths generated by commericial software packages to iso-scallop Fermat spirals (F) generated by our method. We report results on patches shown in Figure 15 using the following statistics: number of tool path segments (#sgZ, #sgC, and #sgF); percentage of sharp turn points (%tnZ, %tnC, and %tnF), and real machining time in seconds (t_Z, t_C, and t_F), using the CNC 6040 2200W machine.

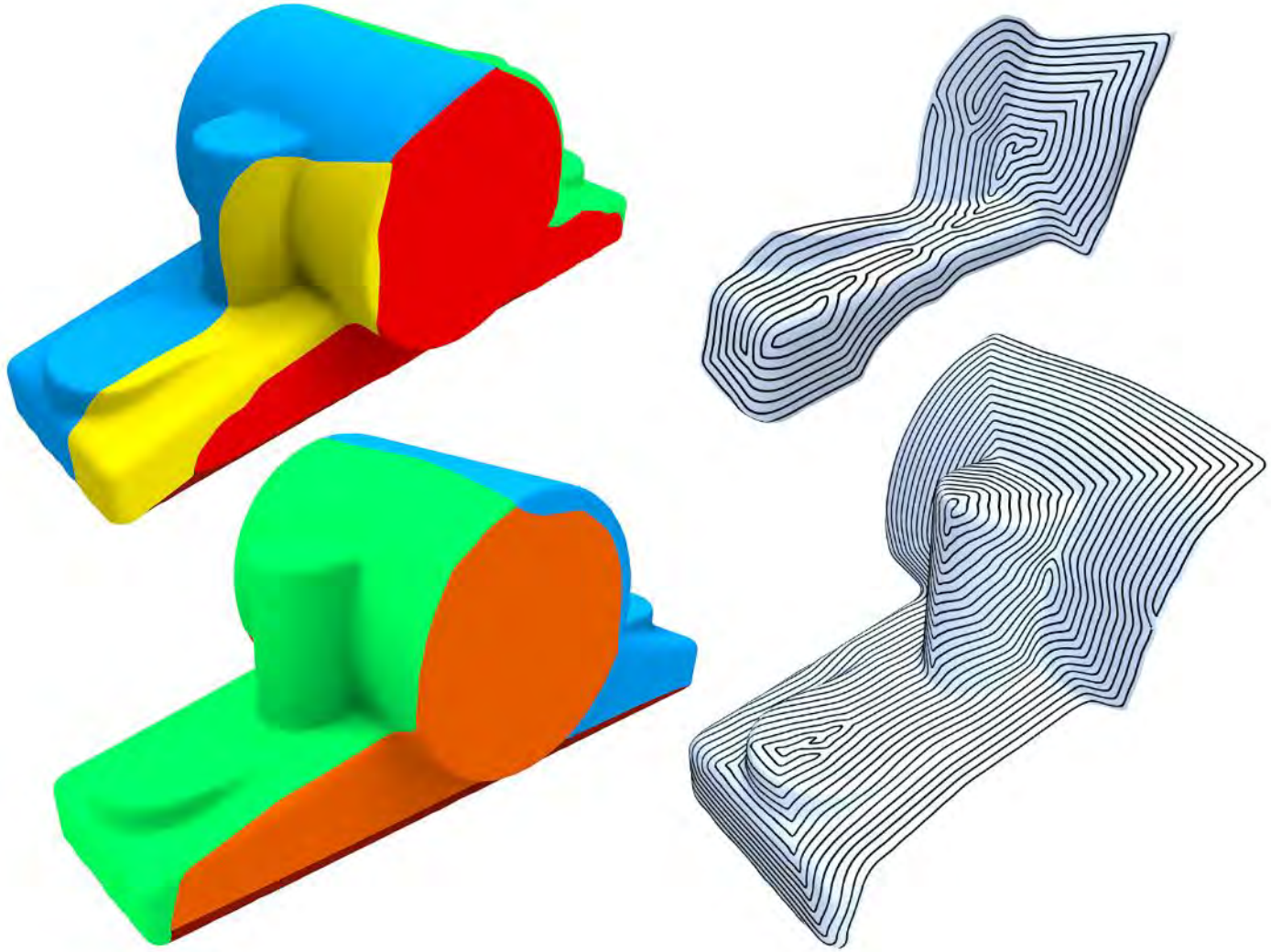
Patch	#sgZ	#sC	#sgF	%tnZ	%tnC	%tnF	t_Z	t_C	t_F
#1 (BUNNY)	9	4	**1**	7.1%	4.7%	**1.5%**	450	368	**342**
#2 (FERTILITY)	18	6	**1**	6.6%	4.0%	**3.8%**	1908	1054	**1034**
#3 (MAXPLANK)	5	**1**	**1**	7.6%	6.0%	**2.5%**	245	232	**205**
#4 (SQUIRREL)	6	**1**	**1**	6.0%	2.8%	**1.9%**	539	428	**416**
#5 (KITTEN)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

Results



Scallop heights visualization

Results



CAD/Engineering parts

Limitation and future works

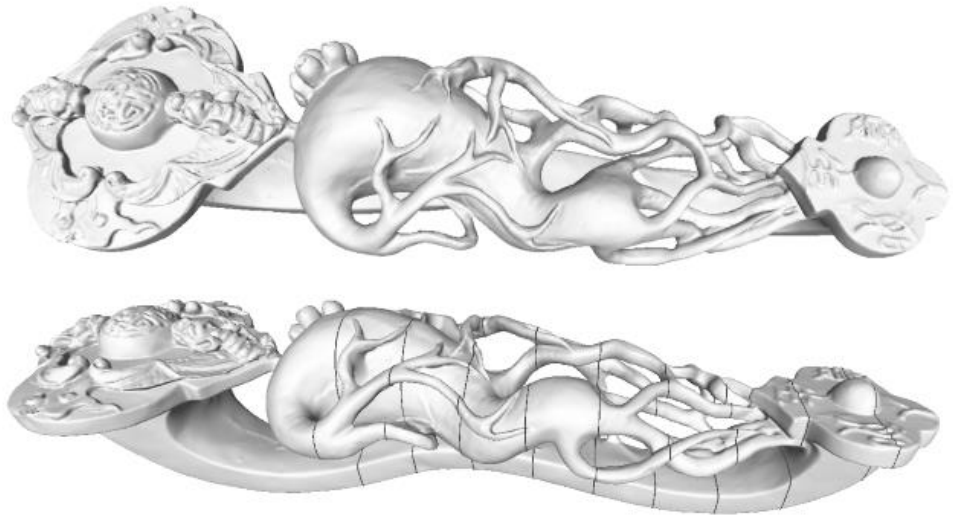
- Practical CNC machining issues
  - Fixture design, cutter switching
  - Overlook rough machining
  - Do not address **inaccessibility** from tunnels or hollow parts

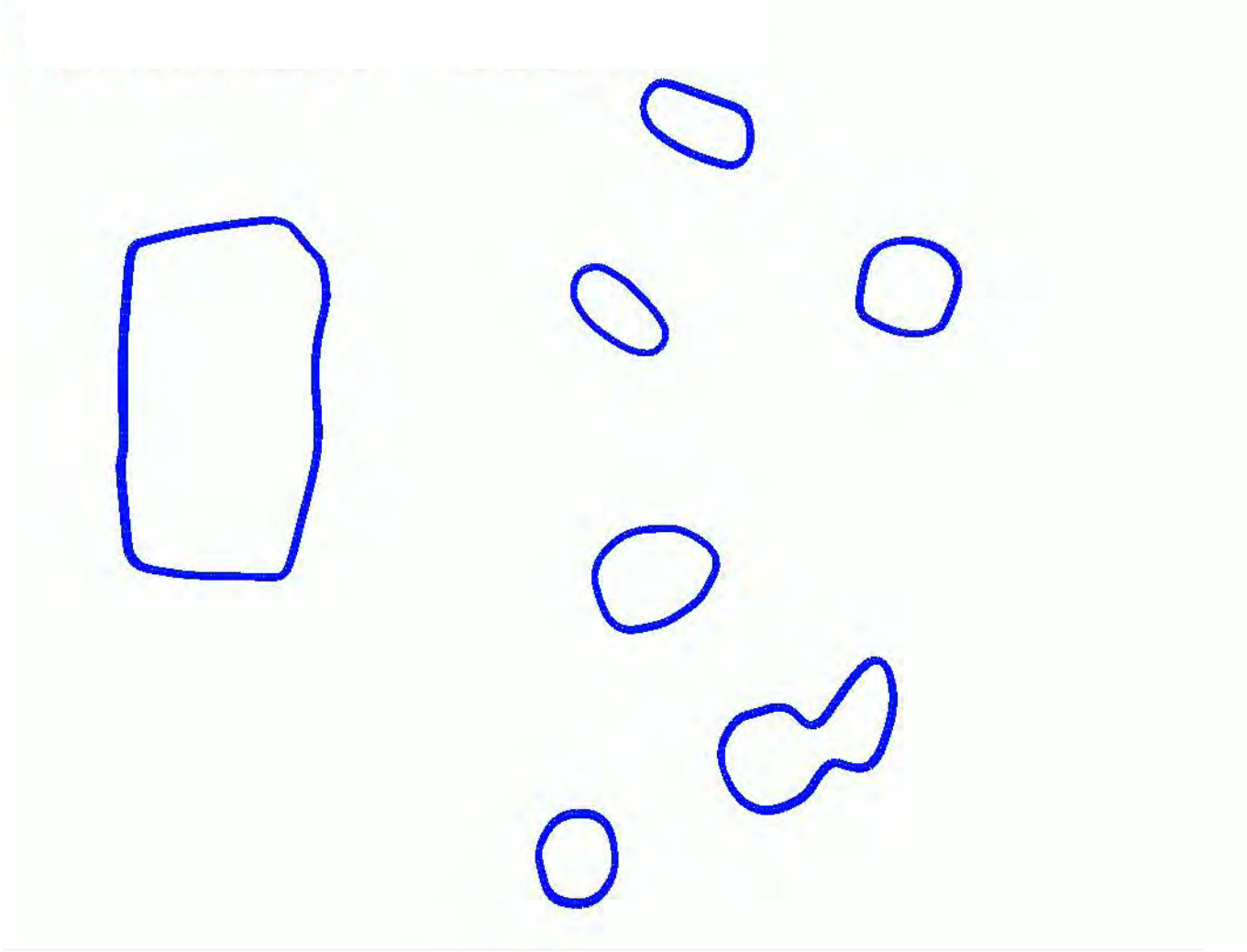
- Did not produce a globally continuous carving path for one setup

新的研究问题

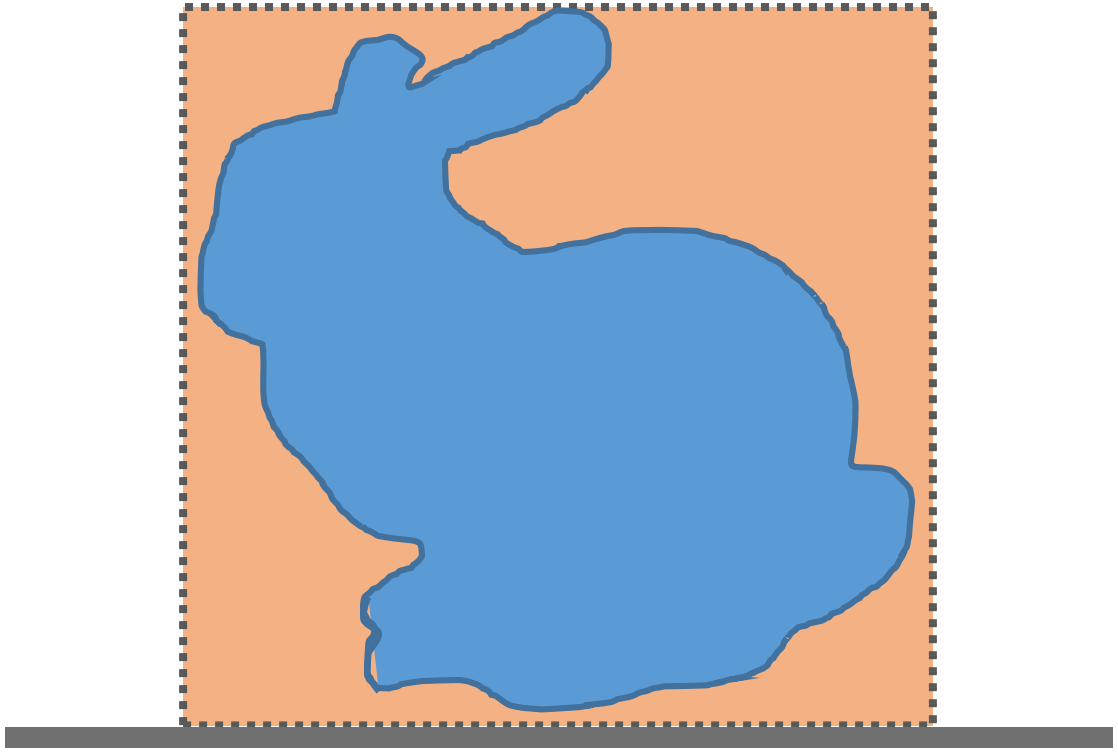
- 4 axis machining
- Rough machining
- Fixture design
- 机器人路径机械最短路径
- 机器人喷漆
- 石材切割问题（特种刀具）
- 冷却水路设计

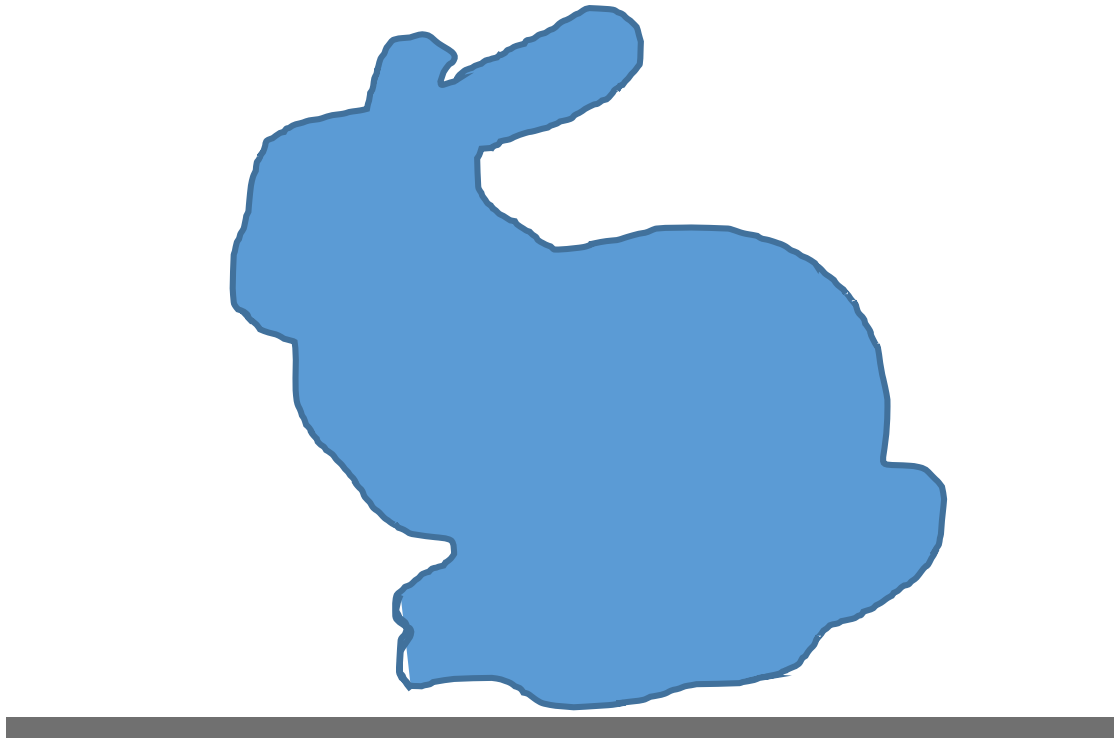
4 axis machining



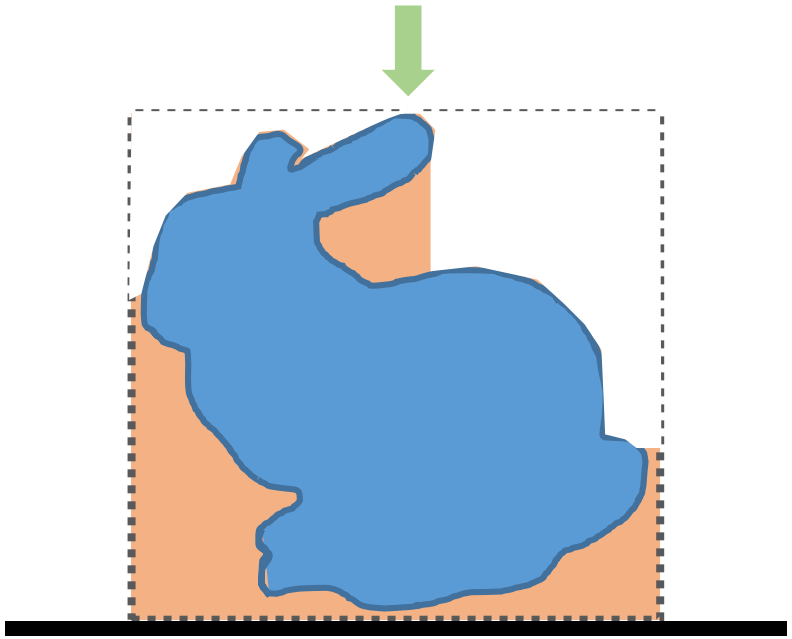


Rough machining

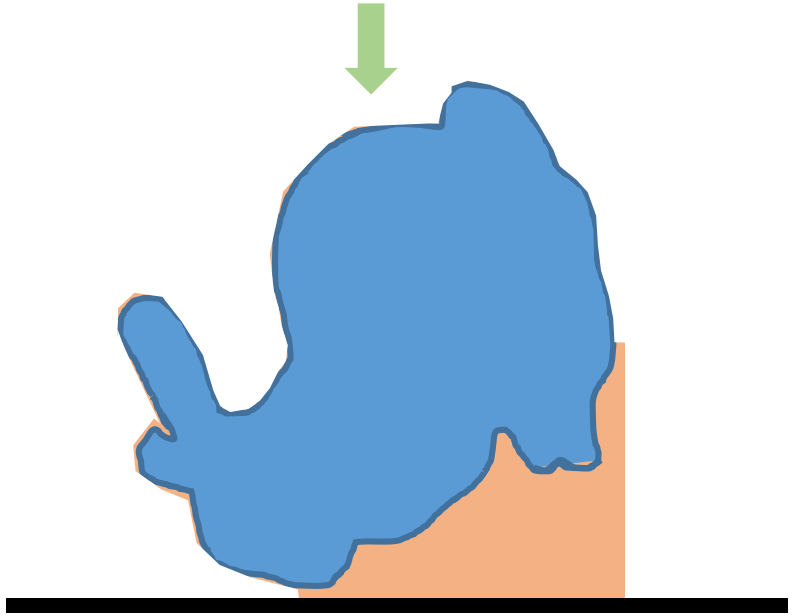




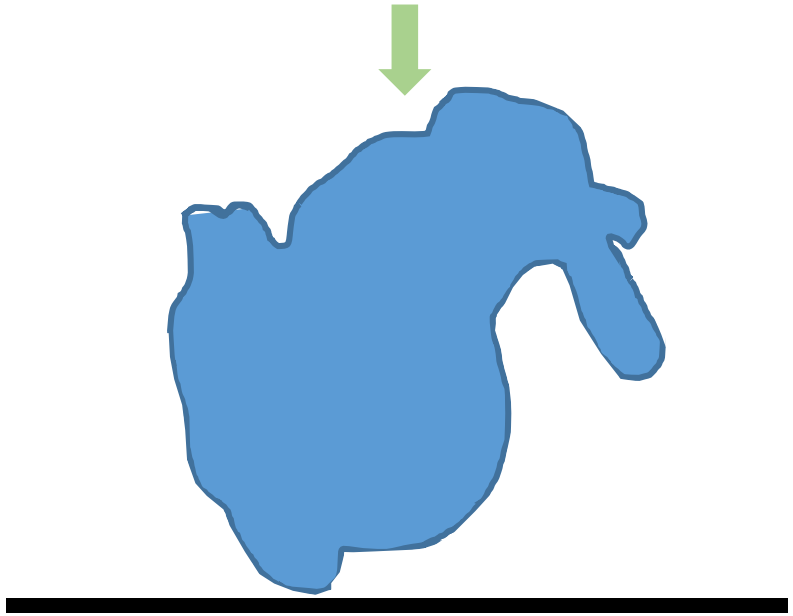
Rough machining



#1 setup

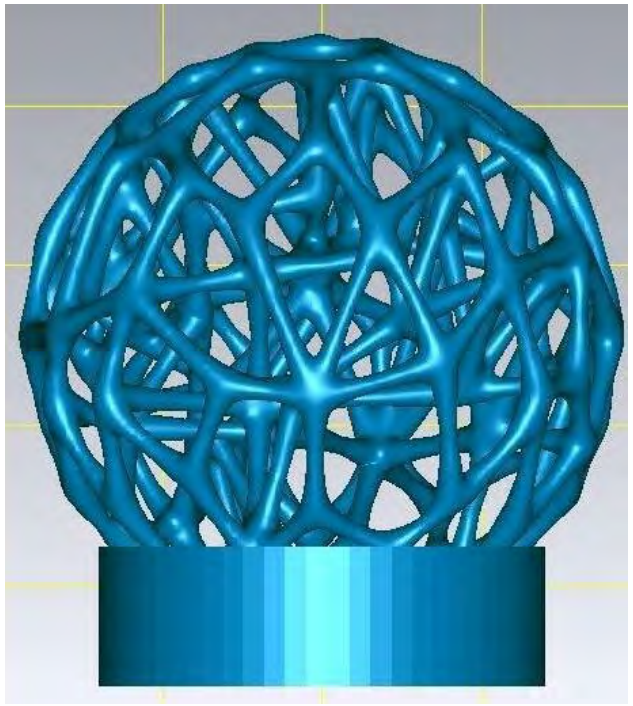


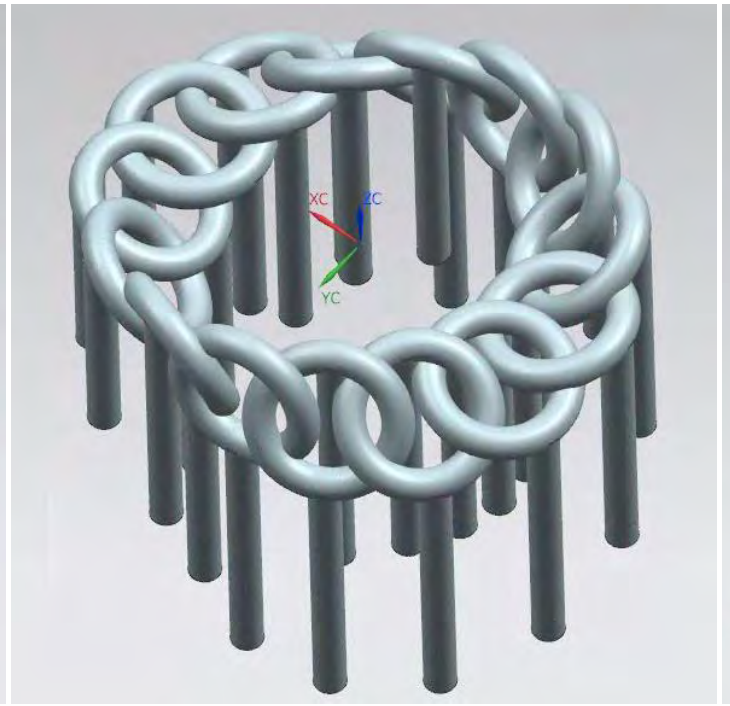
#2 setup



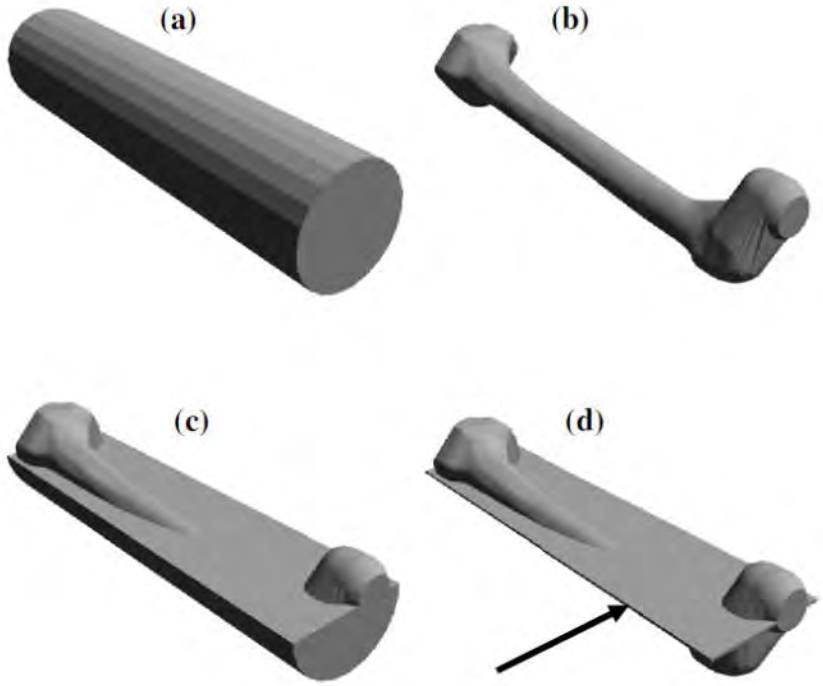
#3 setup

Rough machining

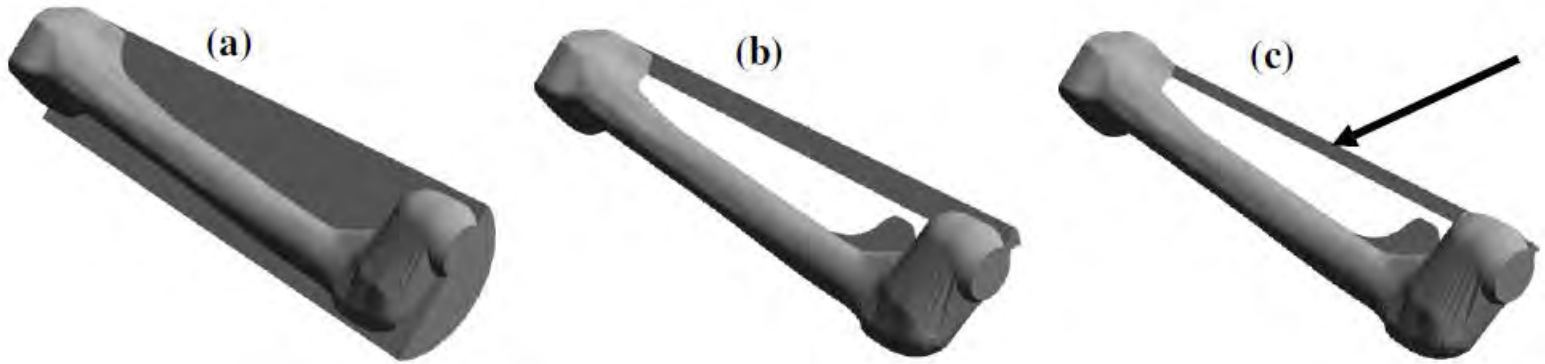




Rough machining



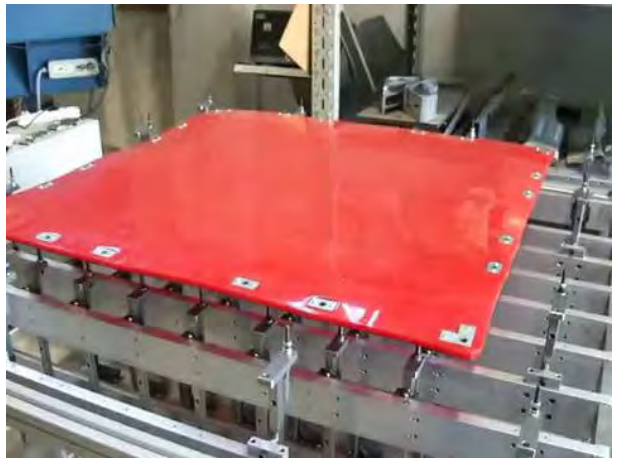
Webs Structures

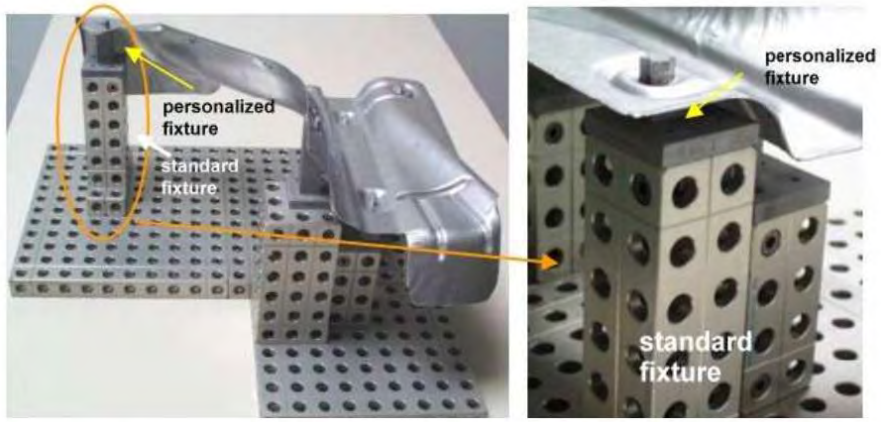


Strings Structures

Fixture design

- **Fixture:** a mechanism used in manufacturing to **hold** a workpiece, **position it correctly** with respect to a machine tool, and **support it** during machining.





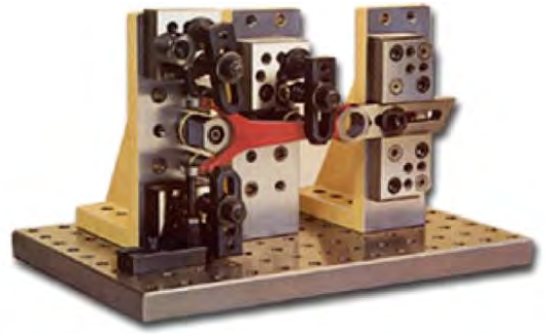
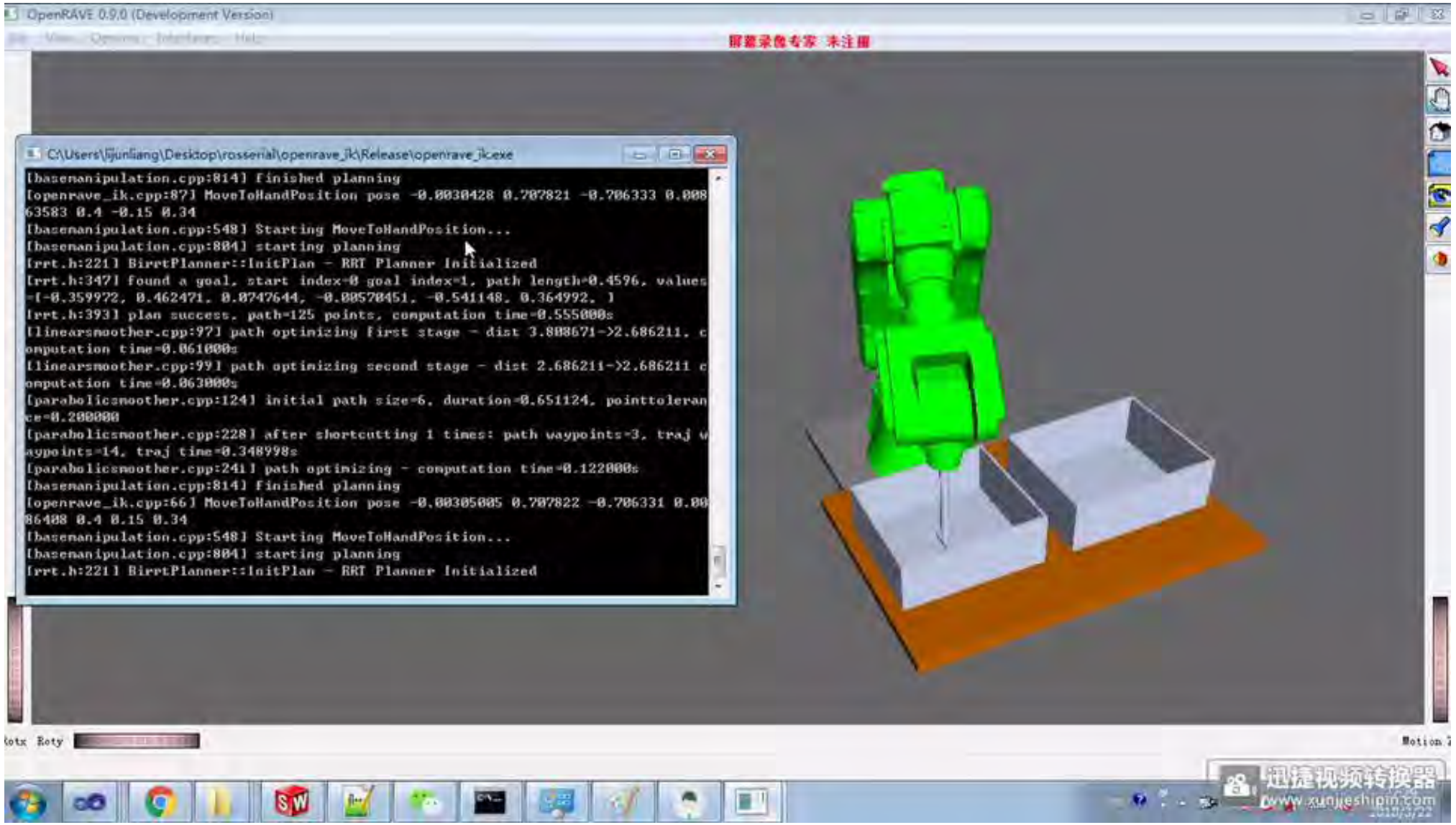


Fig. 8. Modular fixture for a part for the construction machinery (*BLUCO corp.*) [30].

机器人路径机械最短路径

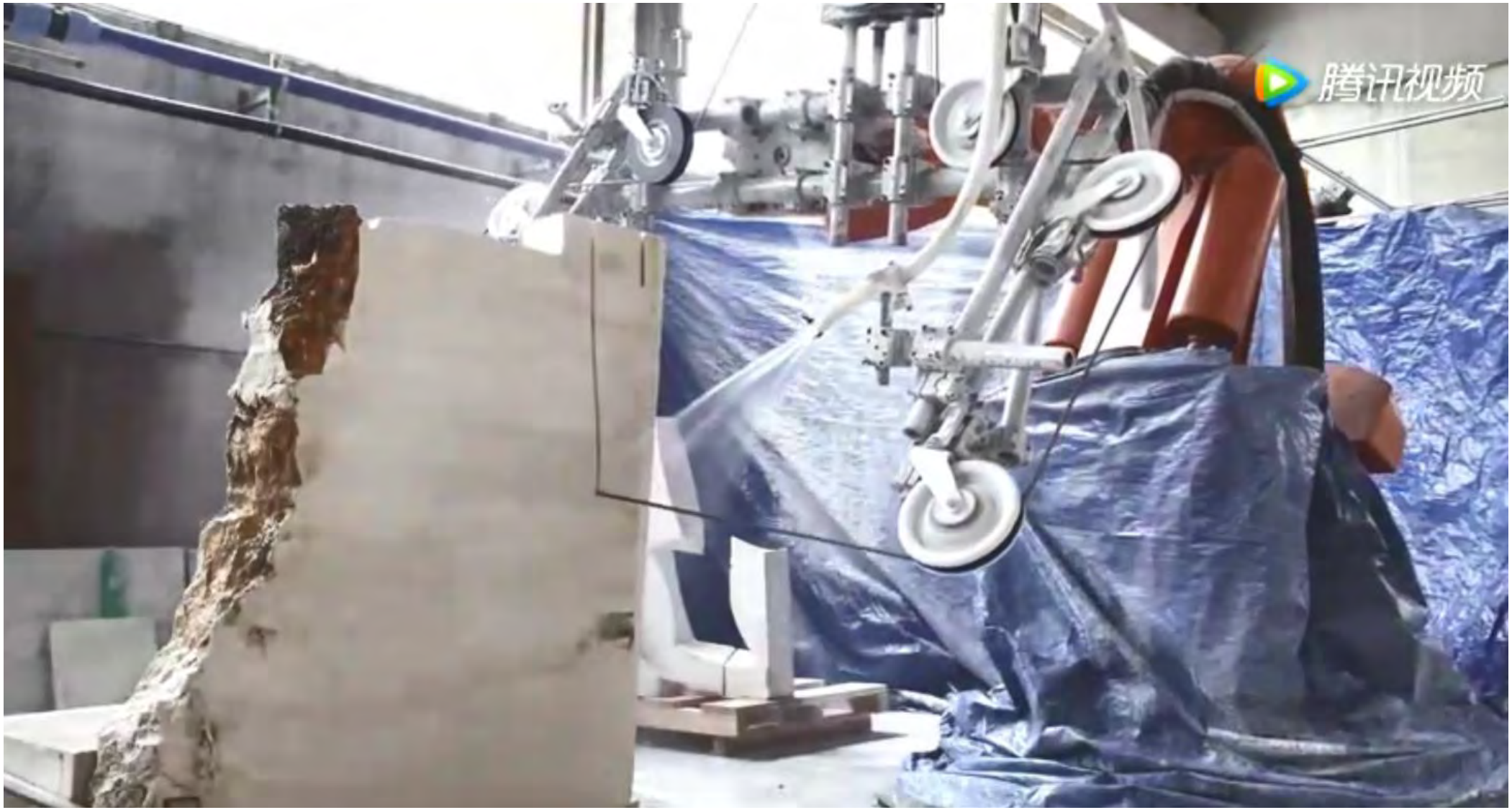
机器人路径机械最短路径



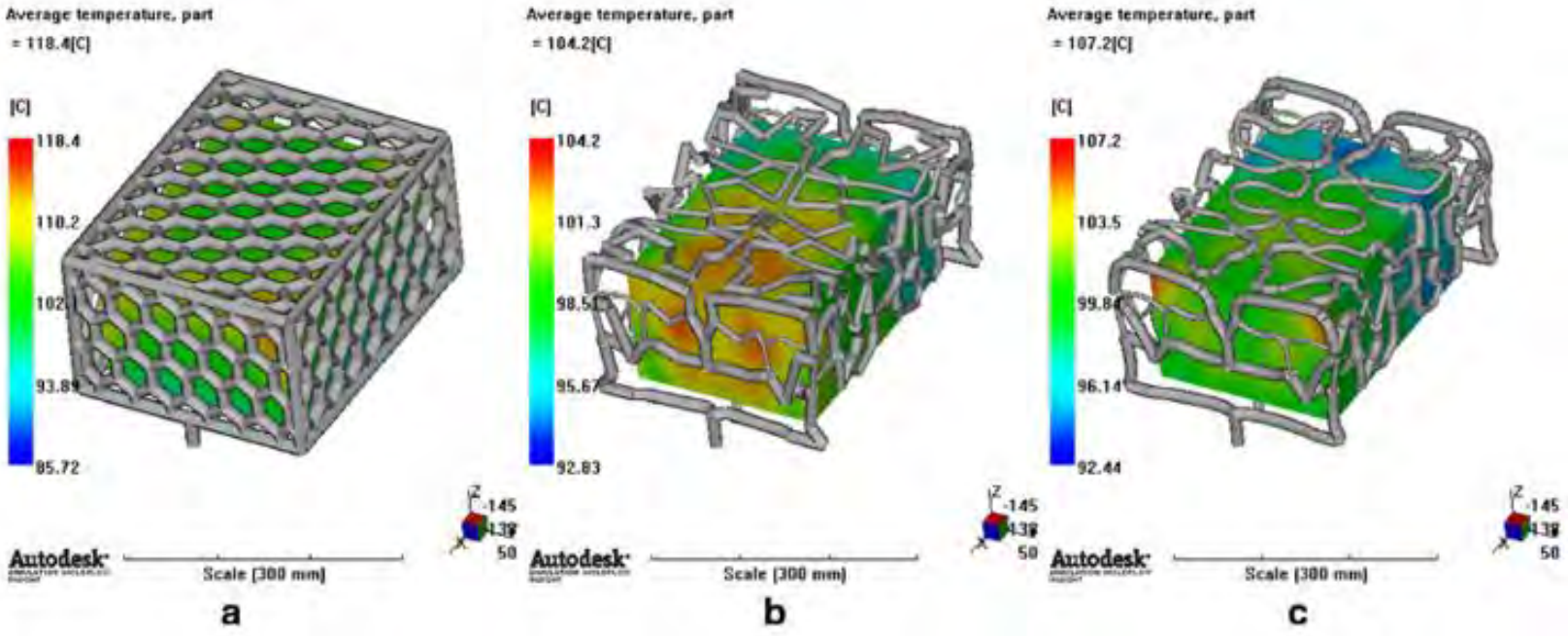
机器人喷漆

石块切割问题

石块切割问题

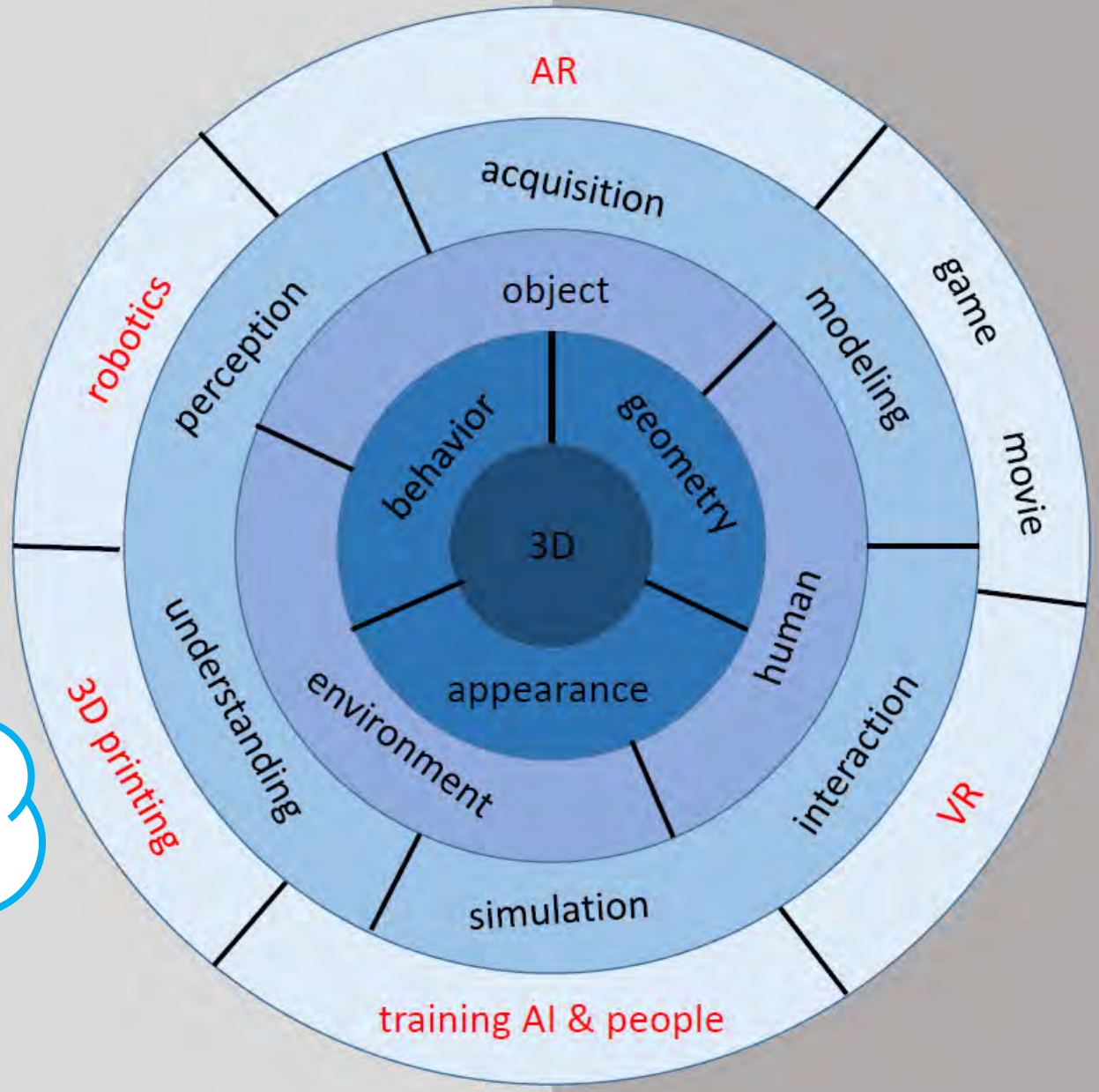


冷却水路设计问题


Average temperature, part
= 118.4[C]
[C]
118.4
110.2
102
93.89
85.72
Autodesk
Scale (300 mm)
a
Average temperature, part
= 104.2[C]
[C]
104.2
101.3
98.5
95.67
92.83
Autodesk
Scale (300 mm)
b
Average temperature, part
= 107.2[C]
[C]
107.2
103.5
99.84
96.14
92.44
Autodesk
Scale (300 mm)
c

Real World

Virtual World



Subtractive Manufacturing

Thank you!
Questions?

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Website: http://www.cs.sdu.edu.cn/irc/~zhaohaisen/