Direct Geometry Processing for Tele-Fabrication

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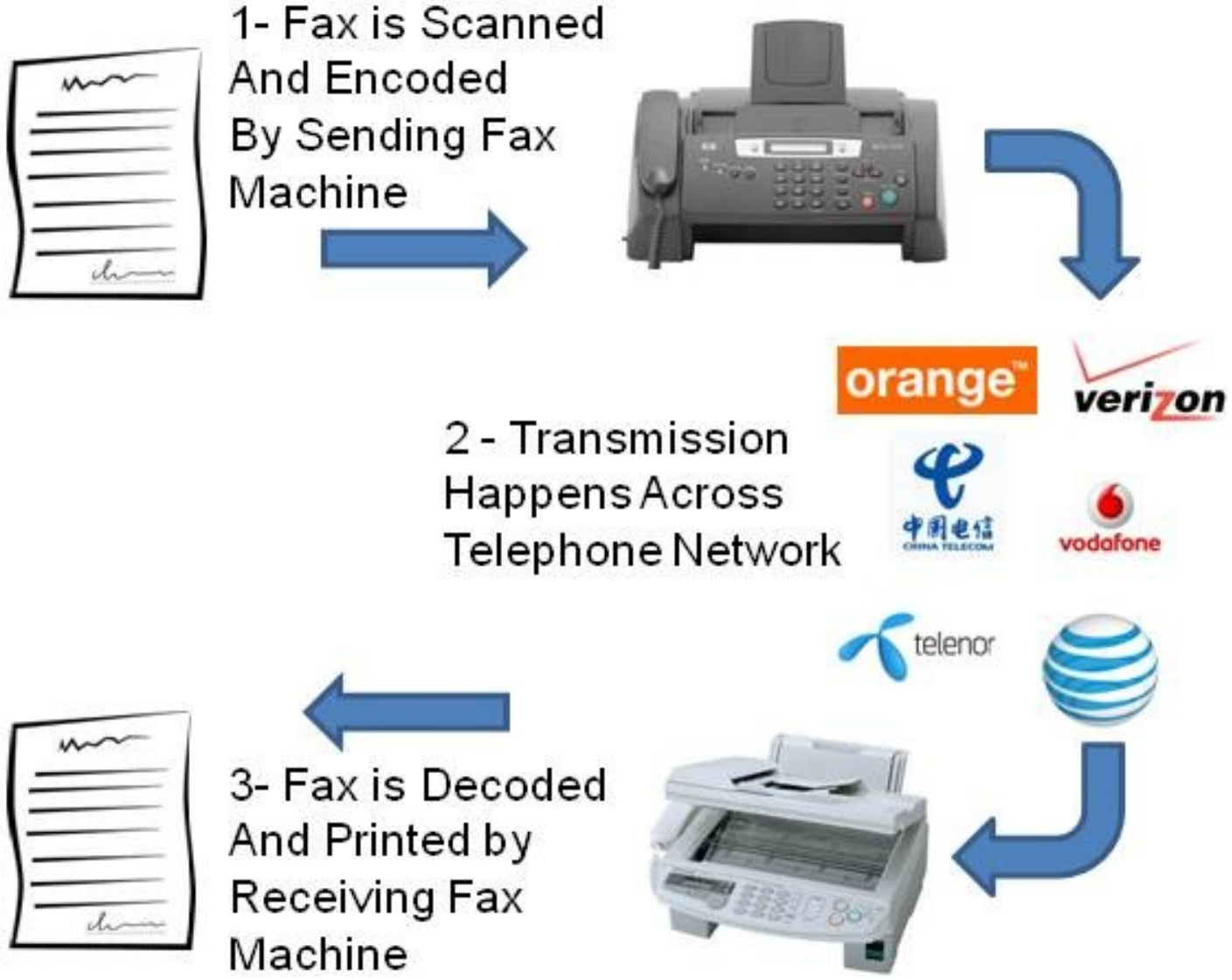
- Introduction of 3D tele-fabrication
- 3D data acquisition
- Geometry processing
  - Point cloud slicing
  - Support generation
  - Mask image planning
- Fabrication results and discussion
- Summary

2D Faxing

2D Scanning (Chicago)

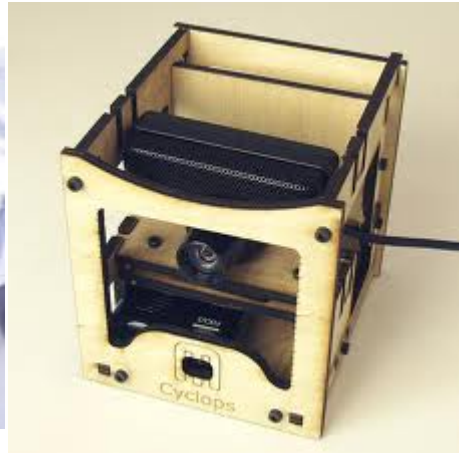
Printing (Los Angeles)

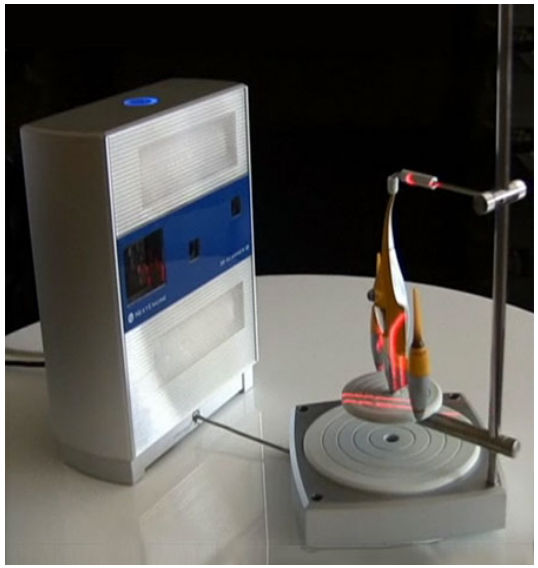
2D Faxing Processing



3D Scanners

- Zcorp
- Makebot 3D replicator
- NextEngine
- 3Shape
- HDI 3D Scanner
- etc.

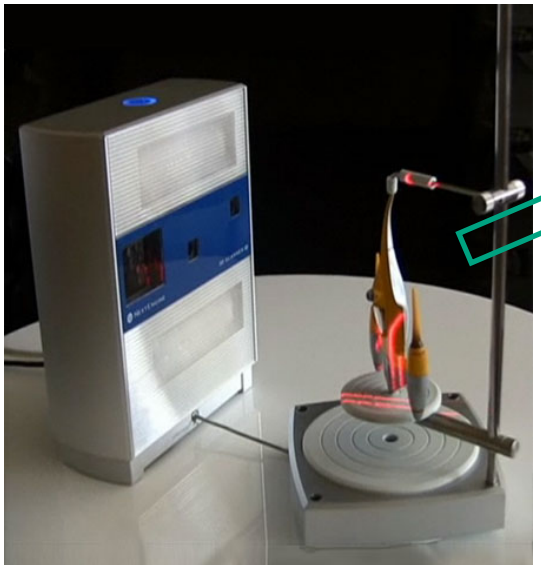




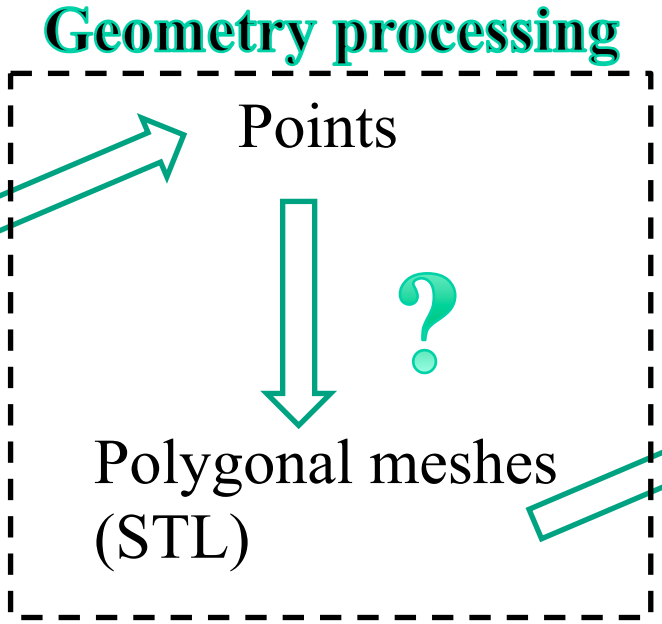
3D Printers

- Cubify
- VFlash
- Perfactory
- ZCorp
- Objet
- Projet
- uPrint
- etc.

3D Faxing



3D Scanners



3D Printers

- ***An open question: how would geometry be processed in future 3D faxing systems?***

3D Tele-fabrication overview

3D Scanning
(Chicago)

Point cloud slicing

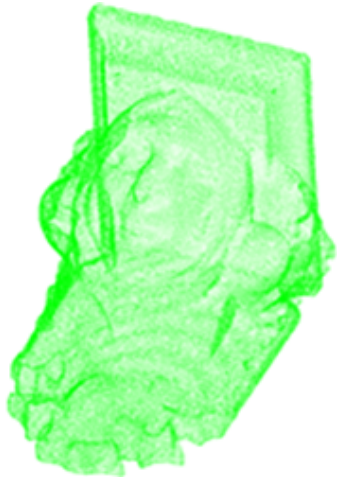
Support generation

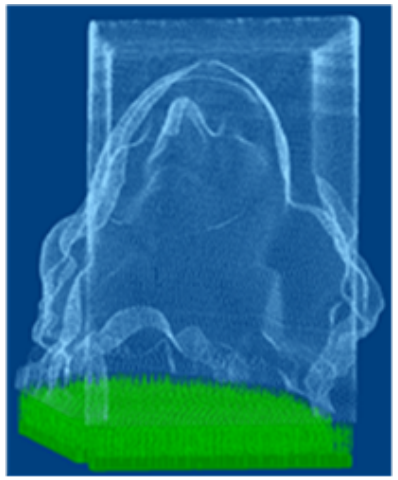
Mask image planning

Geometry processing

Manufacturing
(Los Angeles)

Geometry processing flowchart

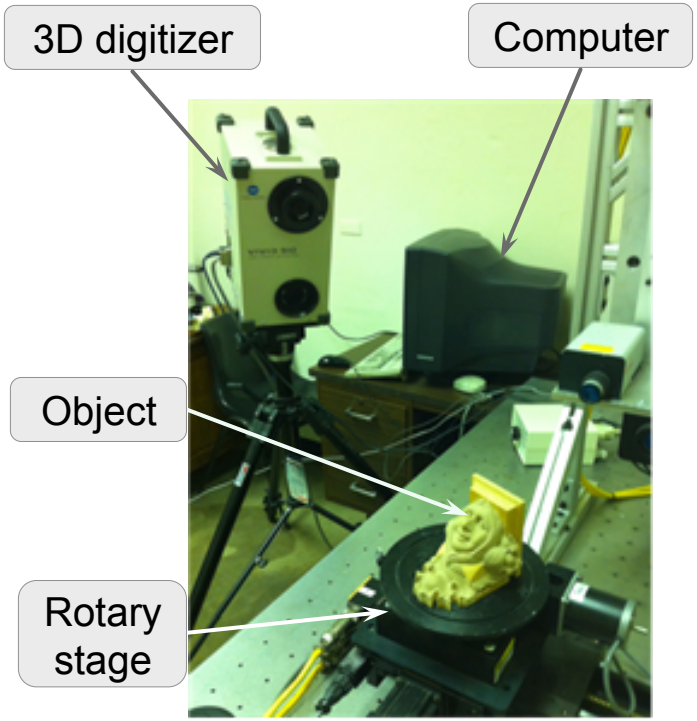



Physical object → Scanned point data → Sliced contours → Support structure → Manufactured model

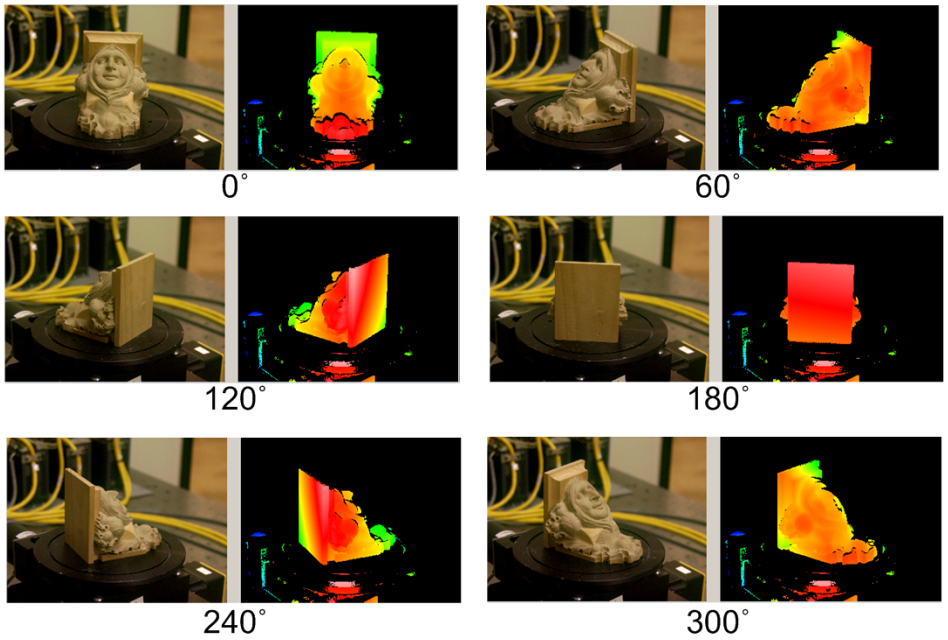
Chicago

Los Angeles

Data acquisition

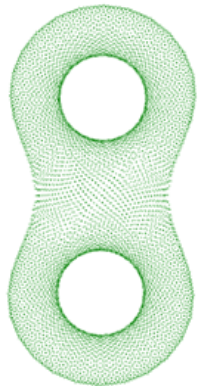


Digitizing system

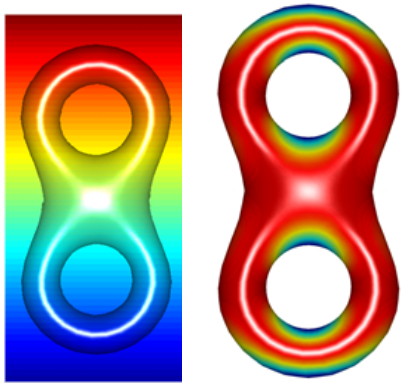


6-step range image scanning

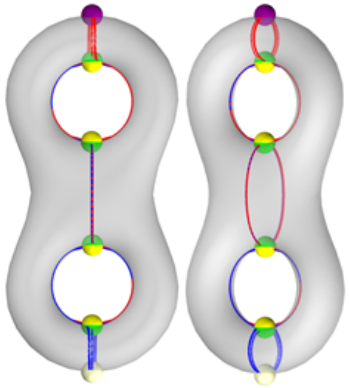
Point cloud slicing overview



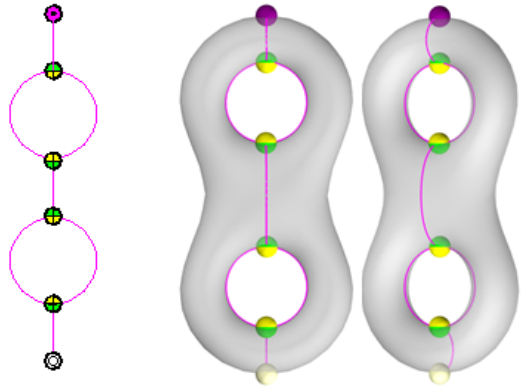
Point cloud



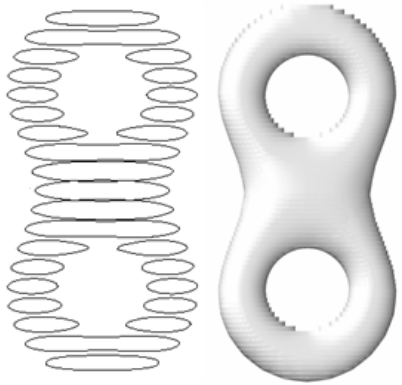
Morse function and MLS surface



Critical points and Morse-Smale complex



Enhanced Reeb graph



Sliced model

Moving Least Square (MLS) surface

Implicit definition stationary set of a projection operator

$$S = \{\boldsymbol{x} \in R^3 \mid \boldsymbol{\psi}_p(\boldsymbol{x}) = \boldsymbol{x}\}$$

Energy function

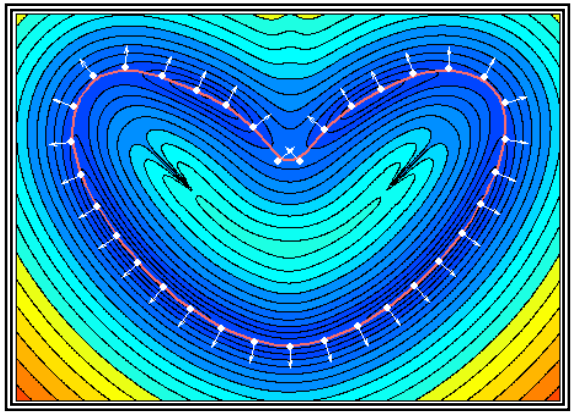
$$e(\mathbf{y}, \mathbf{n}(\mathbf{x}_i)) = \sum_{\mathbf{q}_i \in \mathbf{Q}} \left((\mathbf{y} - \mathbf{q}_i)^T \mathbf{n}(\mathbf{x}_i)\right)^2 \theta_N(\mathbf{y}, \mathbf{q}_i)$$

Normal vector field

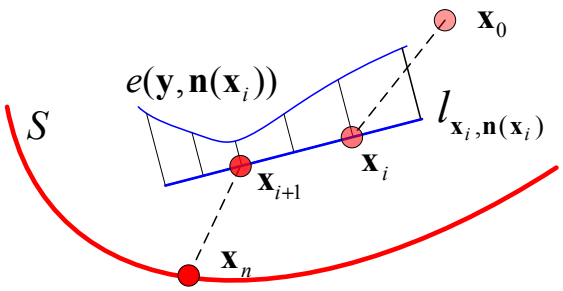
$$\mathbf{n}(\mathbf{x}) = \frac{\sum_{\mathbf{q}_i \in \mathbf{Q}} \mathbf{v}_i \theta_N(\mathbf{x}, \mathbf{q}_i)}{\left\| \sum_{\mathbf{q}_i \in \mathbf{Q}} \mathbf{v}_i \theta_N(\mathbf{x}, \mathbf{q}_i) \right\|} \qquad \theta_N(\mathbf{x}, \mathbf{q}_i) = \frac{e^{-\|\mathbf{x}-\mathbf{q}_i\|/h^2}}{\sum_{\mathbf{q}_i \in \mathbf{Q}} e^{-\|\mathbf{x}-\mathbf{q}_j\|/h^2}}$$

MLS explicit definition

$$g(\mathbf{x}) \equiv \mathbf{n}(\mathbf{x})^T \left(\frac{\partial e(\mathbf{y}, \mathbf{n}(\mathbf{x}))}{\partial \mathbf{y}} \bigg|_{\mathbf{y}=\mathbf{x}} \right) = 0$$



Energy function and normal vector field

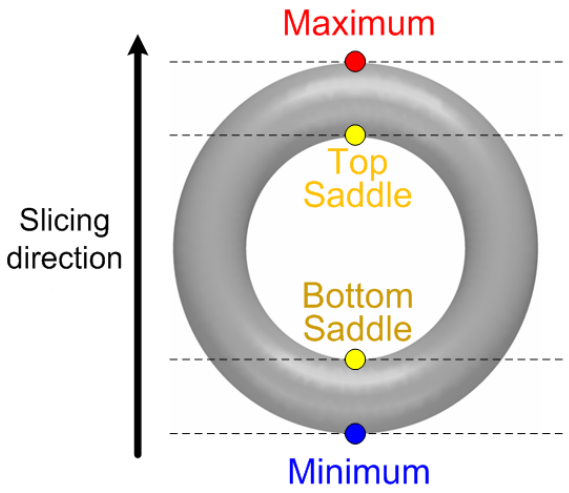


MLS surface point with local minimum energy

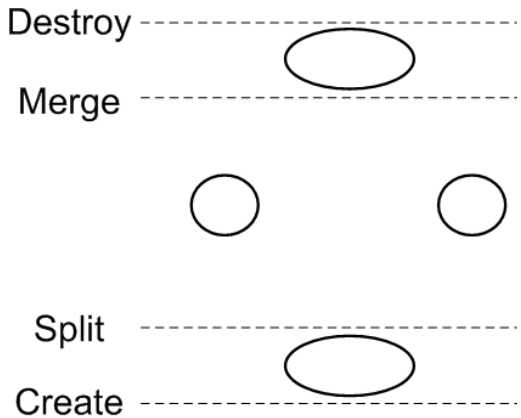
Critical points

Morse function
f: height value

φ on MLS



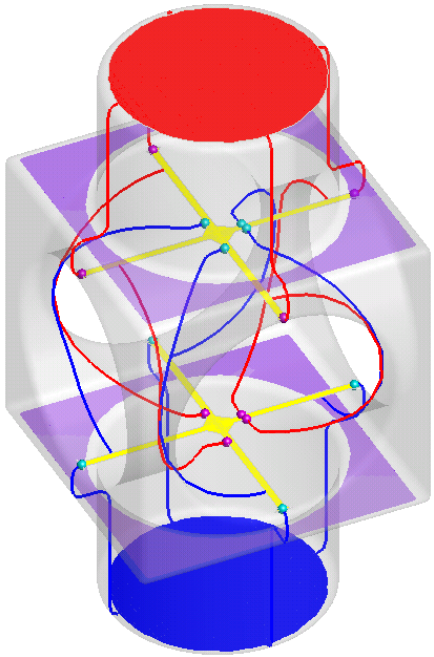
4 types of critical points



Contour topology

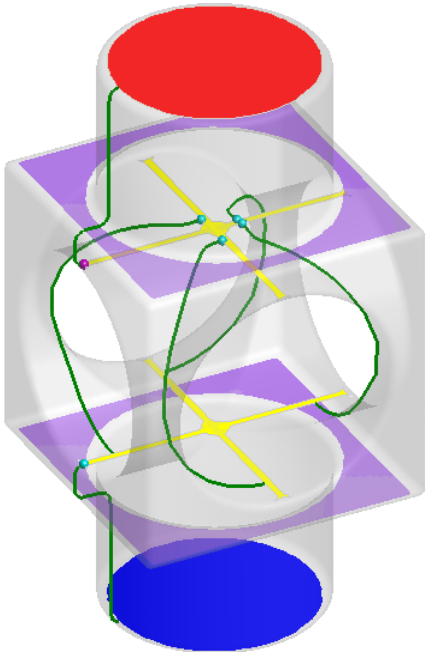
- Critical points identified by: $\varphi(\mathbf{x}) \equiv 1 - \left(\frac{\nabla f(\mathbf{x})}{\|\nabla f(\mathbf{x})\|} \cdot \frac{\nabla g(\mathbf{x})}{\|\nabla g(\mathbf{x})\|} \right)^2 = 0$
- Slicing contour topology controlled by critical points

Morse-Smale complex and enhanced Reeb graph



MS complex:
integral lines tracing

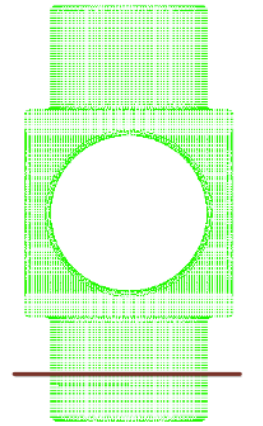
Grouping / Pruning

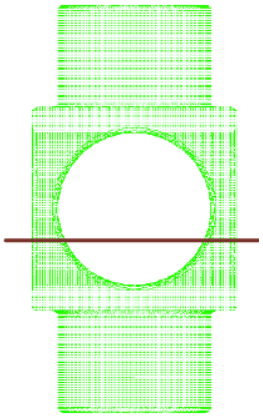


Enhanced Reeb graph:
MS complex re-organizing

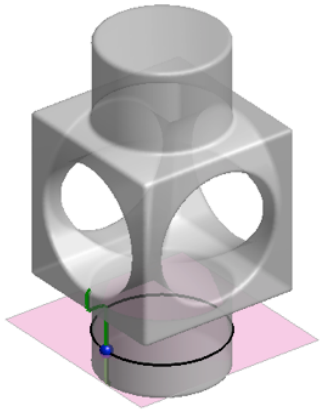
- Morse-Smale (MS) complex: tracing integral lines from saddles to maximum/minimum
- Enhanced Reeb graph: graph processing of MS complex

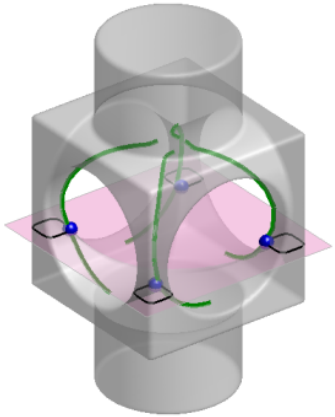
Enhanced Reeb graph as contour marching start



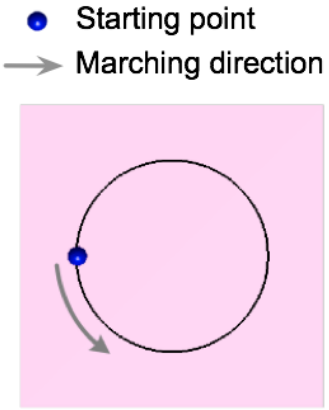


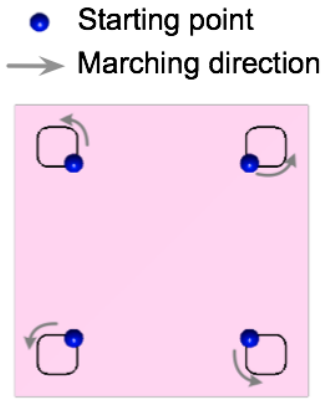
Slicing plane



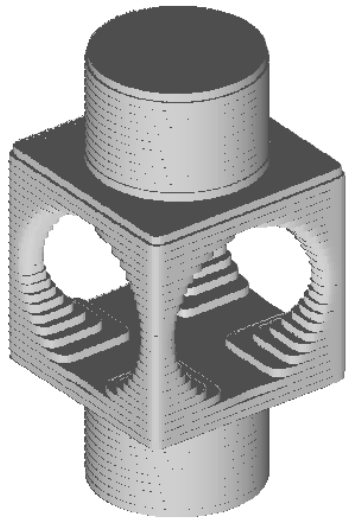


Intersection with enhanced Reeb graph



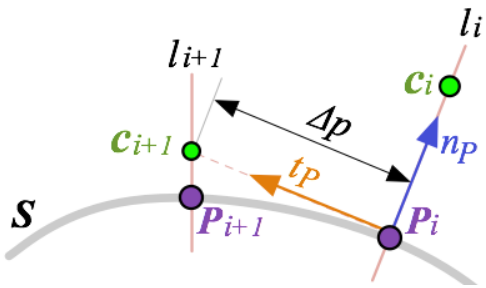


Contour marching from intersected point

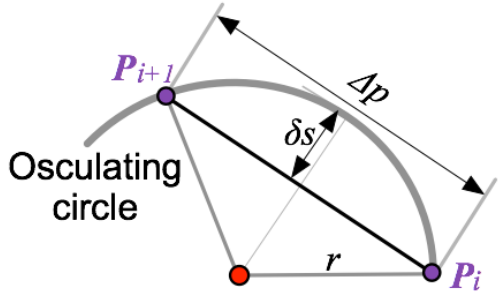


Sliced model: all raised contours stacked

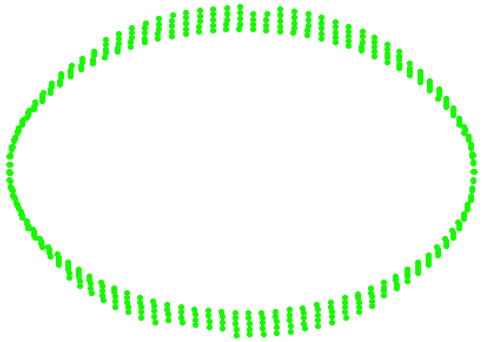
Curvature-adaptive contour marching



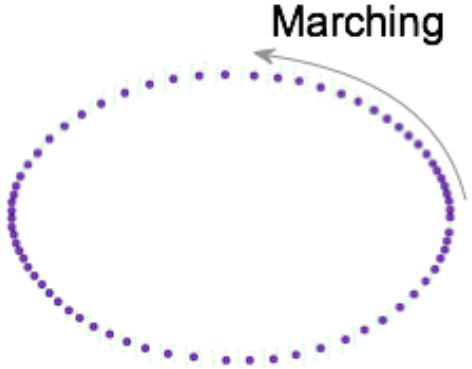
Contour marching by intersection



Curvature-adaptive step size



Point subset near the slicing plane

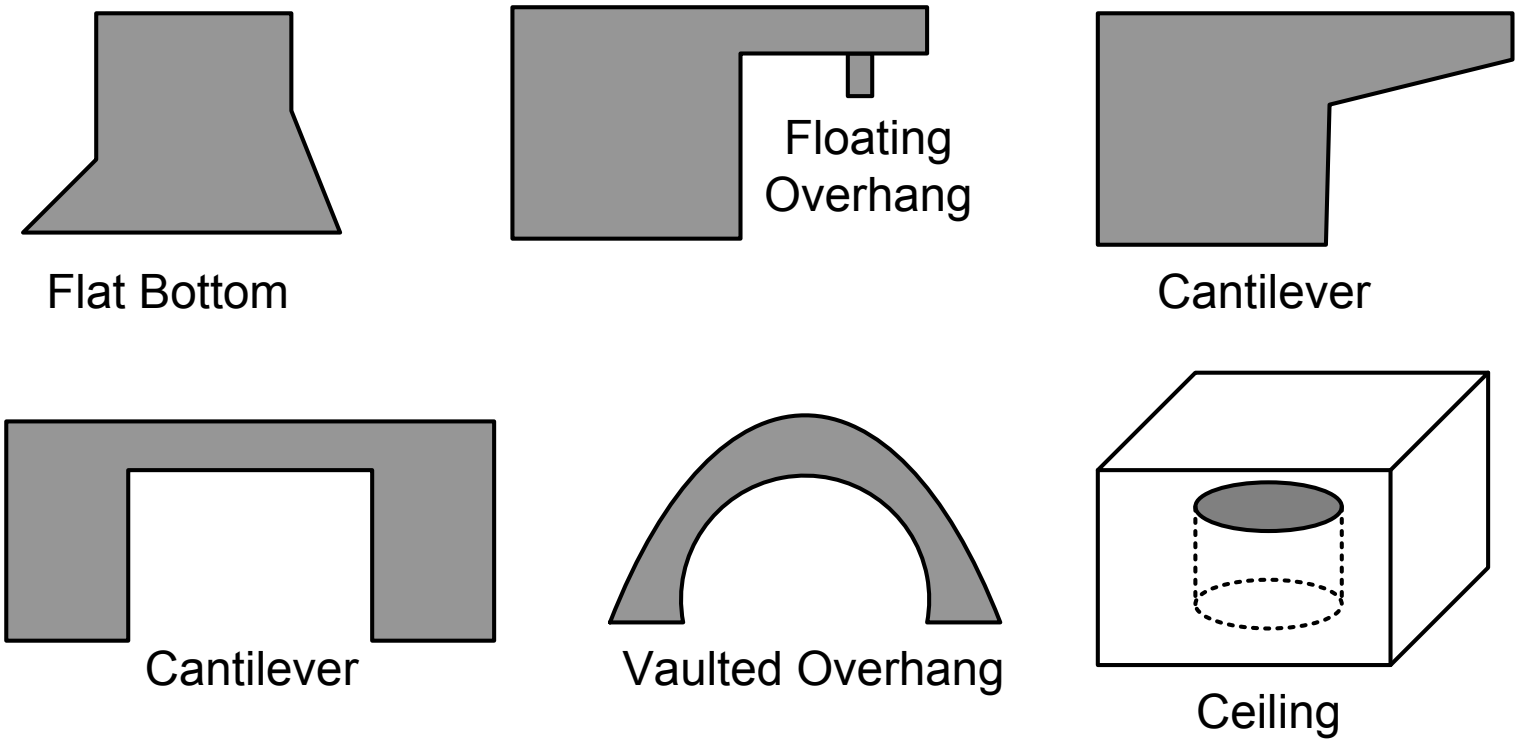


Adaptive contour points generation

- Step size determined by osculating radius

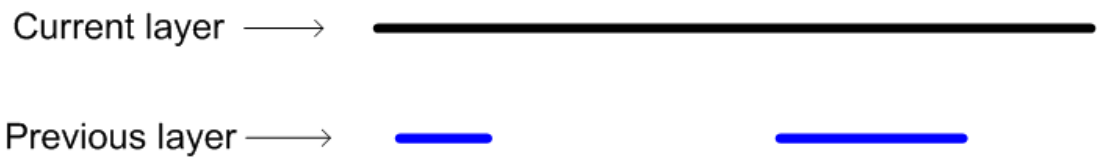
$$\Delta p = 2\sqrt{r^2 - (r - \delta_s)^2} = 2\sqrt{2r\delta_s - \delta_s^2}$$

Support generation based on contours

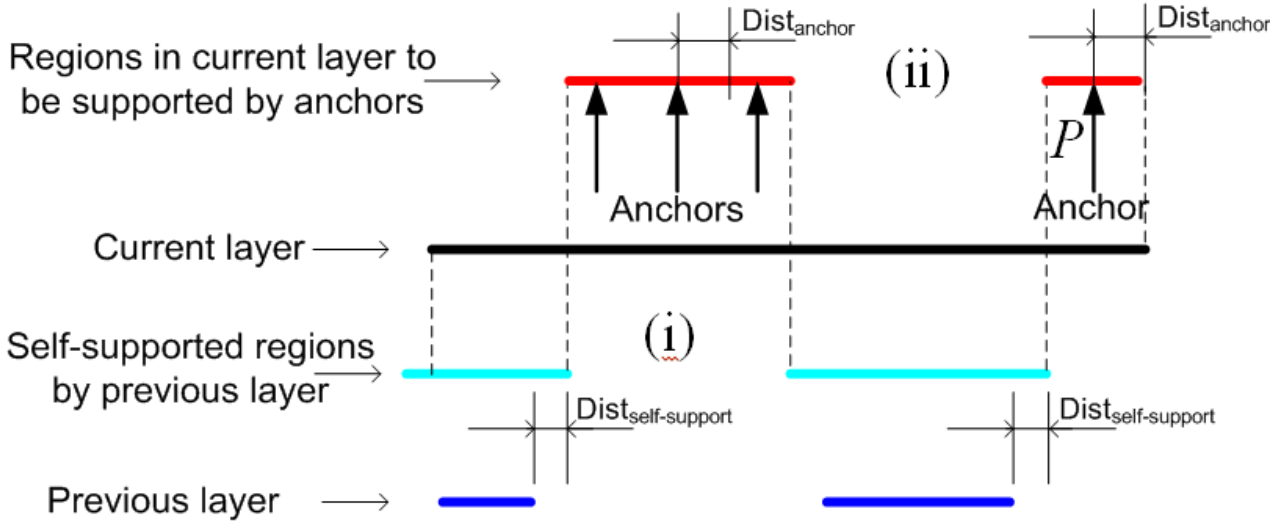


- Supports are required to ensure the success of the 3D printing process
  - No drifting/floating away;
  - Reduce deformation due to shrinkage.

Contour-based support generation principle

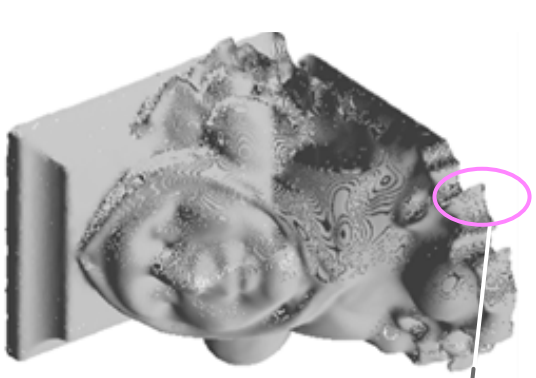


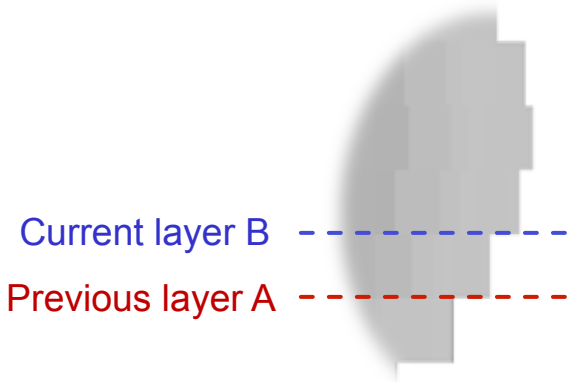
Two consecutive layer contours

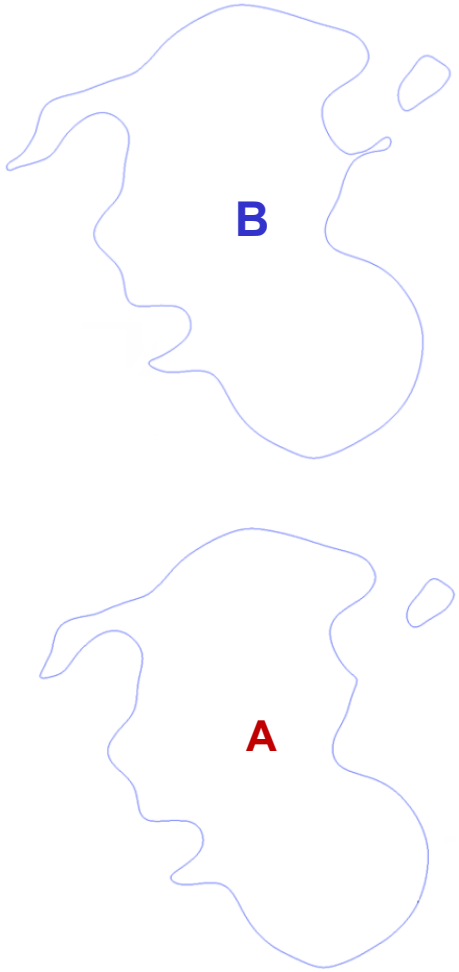


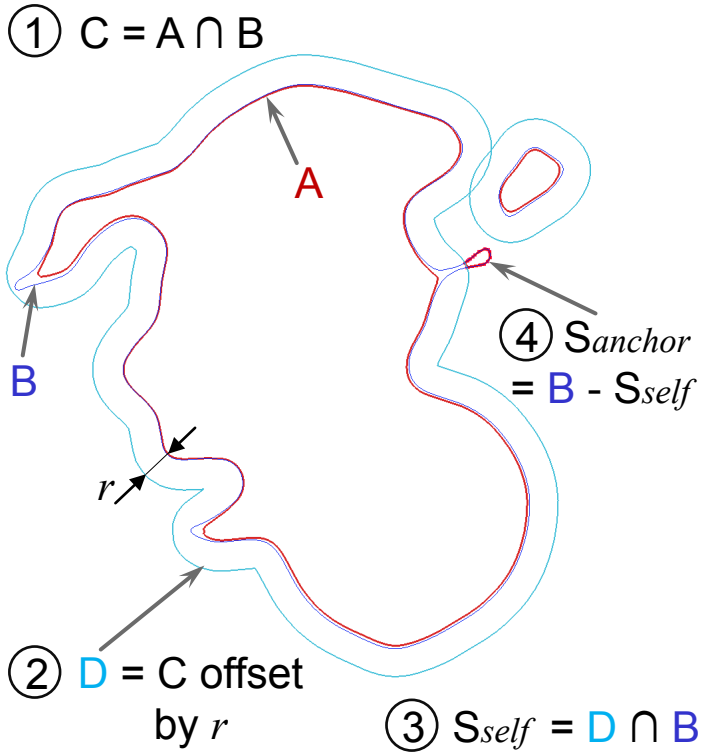
Support structure analysis

Support generation algorithms





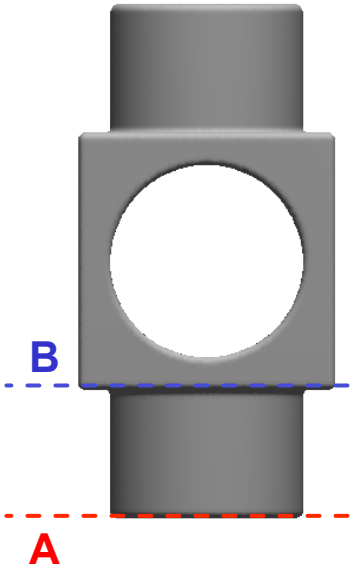




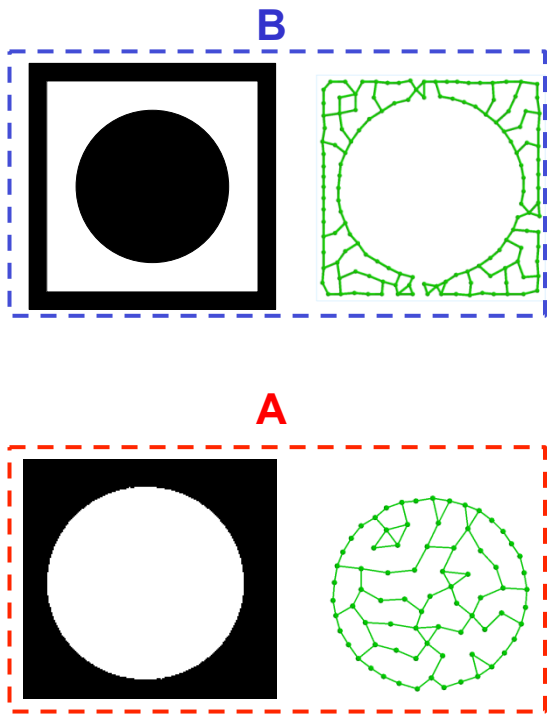
S_{anchor} : anchor-support region

S_{self} : self-support region

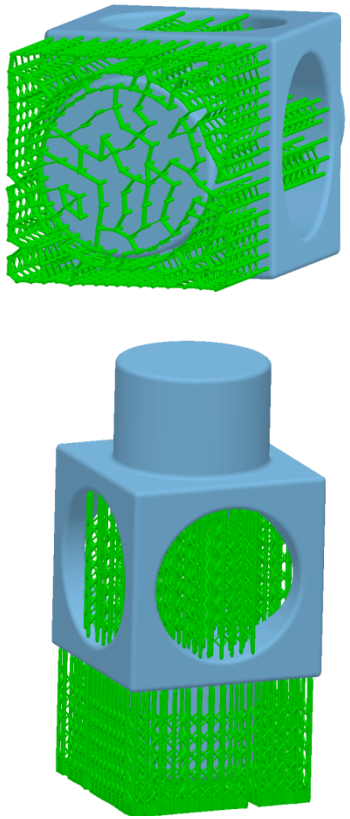
Anchor-support region covering



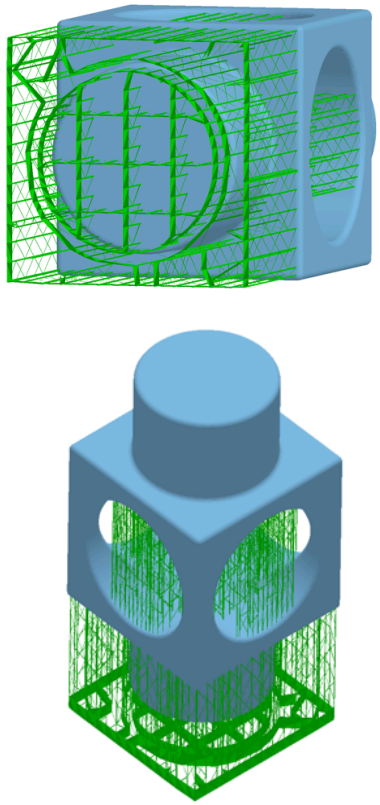
Input regions



Support layout by region covering



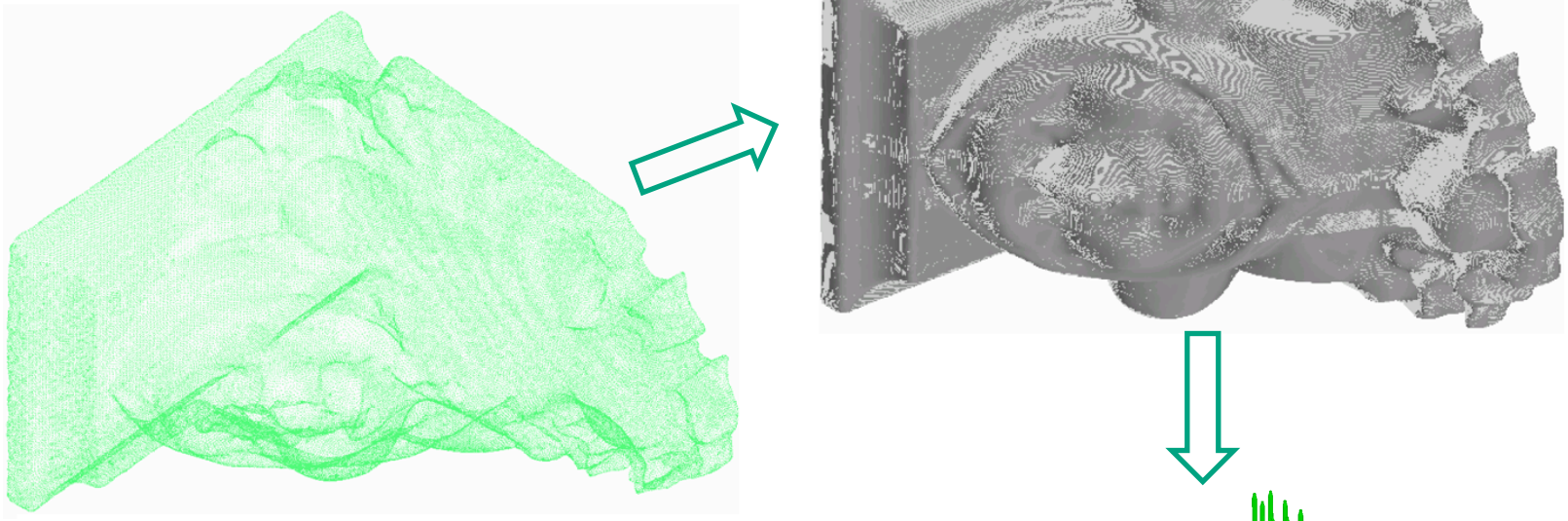
CAD model of supports (Contours based)



CAD model of support by Lightyear system (STL based)

Support generation examples

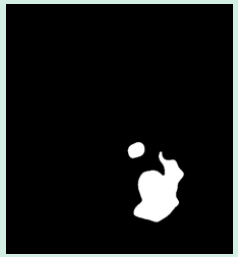
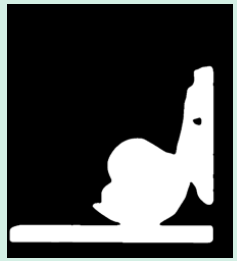
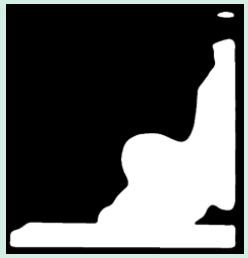
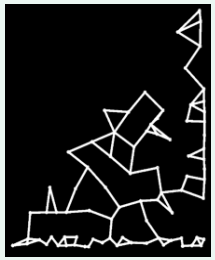
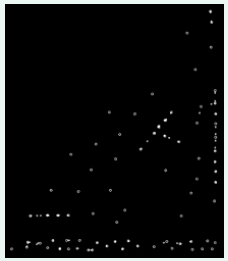
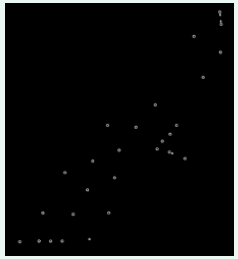
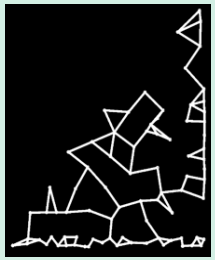
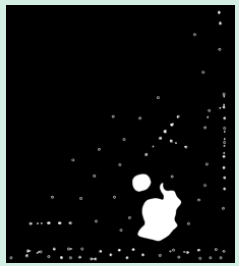
Sliced model



Point cloud

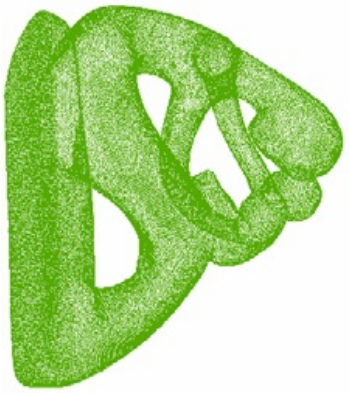
Support structure

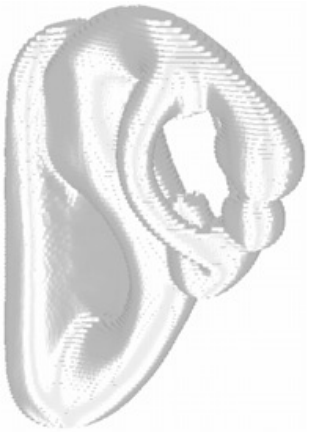
Mask image planning: Image projection of layers

Layer ID	1	100	200	300
Mask image of part				
Mask image of support				
Projection mask image				

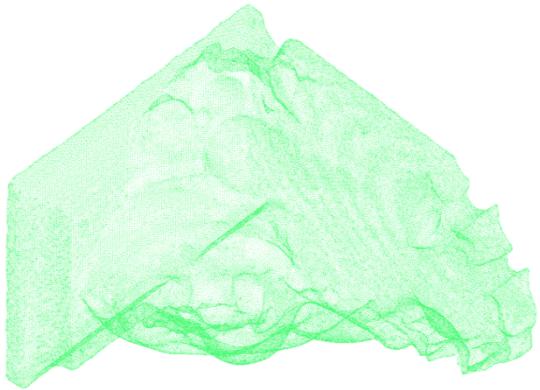
Fabrication example

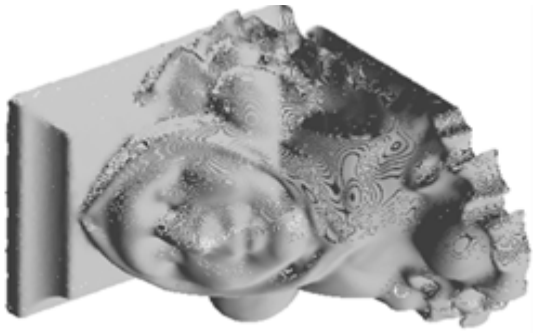
(1)





(2)



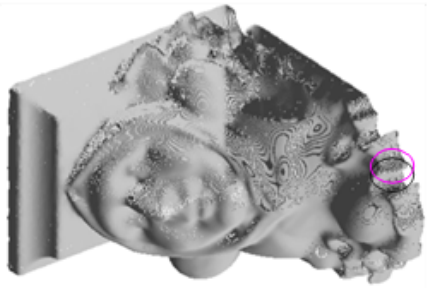
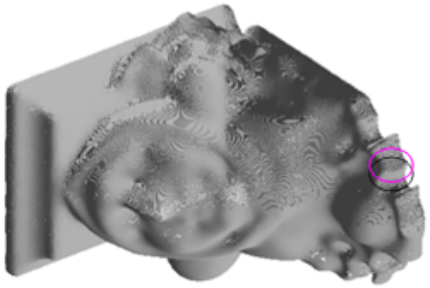
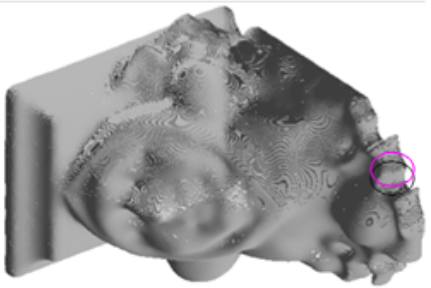
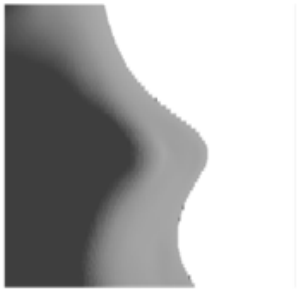
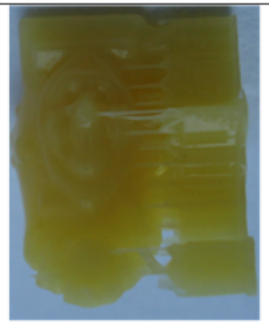


Point cloud

Sliced model

Fabricated model

Manufacturing compatibility with different layer thickness

	AM System Compatibility	Sliced model: Global view	Sliced model: Local view (0.1mm)	Support structure	Manufactured model
Macro →	Option A Platform size 260 X 160 mm XY resolution 0.14 mm Z layer 0.15 mm				
Meso →	Option B Platform size 48 X 36 mm XY resolution 0.047 mm Z layer 0.05 mm				
Micro →	Option C Platform size 14 X 10.5 mm XY resolution 0.014 mm Z layer 0.01 mm				

Summary

- Tele-fabrication is critical for future product design and manufacturing
- Developed a tele-fabricating approach by integrating 3D scanning and printing
- Presented a direct geometry data flow method in such an integration system
- Performed physical experiments to verify the effectiveness of the direct geometry method.

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Questions?