3D Printing Oriented Design: Geometry and Optimization

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Part 2: Fabrication Principles

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Outline

- Different Types of Additive Manufacturing
  - Six different types

- Numerical Robustness
  - Problem of B-rep in approximate arithmetic
  - Computation in image space

- Basic Computing for Fabrication
  - Slicing
  - Support structures
Six Types of AM – Different Principles

- **Lasers:**
  - Stereolithography Apparatus (SLA)
  - Selective Laser Sintering (SLS)

- **Nozzles:**
  - Fused Deposition Modeling (FDM)

- **Printheads:**
  - Multi-jet Modeling (MJM)
  - Binder-jet Printing (3DP)

- **Cutters:**
  - Laminated Object Modeling (LOM)
Stereo Lithography Apparatus (SLA)

- Introduced in 1984 by Charles Hull who founded 3D Systems Inc.
- The first commercial Solid Freeform Manufacturing process;
- Based upon the use of an ultraviolet laser which is used to solidify a photocurable liquid polymer.
Monomer and Polymer

\[
\begin{array}{ccccccc}
H & H & H & H & H & H & H \\
\mid & | & | & | & | & | & | \\
C\equiv C & + & C\equiv C & + & \cdots & \rightarrow & C-C-C-C-C-C-C-C-C-C \\
\mid & | & | & | & | & | & | \\
H & R & H & R & H & R & H \\
\end{array}
\]

Monomer  \hspace{1cm} \text{Polymer}

Liquid  \hspace{1cm} \text{Solid}

Polymer injection molding  \hspace{1cm} \text{Stereolithography}

Heat / UV light
Example Parts
3D Models for Fabrication

- CAD Systems
- Implicit representations

STL (STereoLithography)

- 3D Scanners
- CT/MRI
Main Computation Steps in SLA

1. **CAD Model**
2. **Slicing**
3. **Adding Supports**
4. **Laser Drawing**
Support Generation Example

Point cloud → Sliced model → Fabricated Object

By Yong Chen (University of Southern California)
Selective Laser Sintering/Melting
Models Fabricated by SLS

Metal Part by SLS

Polymer Part by SLS
Fused Deposition Modeling

- Introduced in 1988 by Scott Crump who founded Stratasys
- The best-selling Rapid Prototyping technology in terms of installation number
Multi-Jet Modeling

Jetting of photopolymer in desired space, which is then cured by a flash of UV light.

Material Deposition

352-jet printhead
Binder-Jet Printing (3DP)

1. Powder layer is deposited
2. Ink-jet printing of areas that will become the part
3. Piston is lowered for next layer

Part strength is low if compared to SLS (binding instead of sintering)
ZPrinter – Z Corporation

An example of machine using 3DP technique
Laminated Object Manufacturing

Stacking layers of sheet stock, each an outline of the cross-sectional shape of a CAD model.

Starting material is sheet stock, such as paper, plastic, cellulose, metals, or fiber-reinforced materials.
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Numerical Robustness

- Computation in IEEE arithmetic
  - Limited precision of floating-point arithmetic
- Geometry becomes inexact after intersection
- Geometric predicates
  - Correct?
  - Self-intersected models?

Orientation

Does \( c \) lie on, to the left of, or to the right of \( ab \)?

\[
\begin{vmatrix}
    a_x & a_y & 1 \\
    b_x & b_y & 1 \\
    c_x & c_y & 1 \\
\end{vmatrix}
= \begin{vmatrix}
    a_x - c_x & a_y - c_y \\
    b_x - c_x & b_y - c_y \\
\end{vmatrix}
\]
Problem of Inexact B-rep

Can it be easily repaired?
Problem of Inexact B-rep (cont.)
Robust Computation in Image Space

Using Ray-rep by Layered Depth-Normal Images (LDNI) on GPUs

Semi-Implicit Representation

1D Solids on Rays

Sampled depth on $x$-LDNI coupled with surface normal

Sampled depth on $y$-LDNI coupled with surface normal
Layered-Depth Normal Images (LDNI)

Compact Representation can be generated by: Prefix-sum Scan


Two Arrays:
1) 2D Index Array
2) 1D Data Array
Boolean Operations on Rays

- Inherit the simplicity of Boolean on ray-rep – Robust
- Highly parallel – computing on rays of LDNI

Hollowing by Offsetting

Offsetting Result:
Exterior Offset = $P_H \cup P_S$
Interior Offset = $P_H - P_S$

Offsetting by Super-Union of Spheres
GPU-Based Offsetting

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Robust Slicing Algorithm

Implicit Solid $H$ (Input)

Stage 1: Sampling and Contour Generation

- Binary Image Sampling
- Marching Square Contour Generation

$\tilde{C}^0$

Stage 2: Contour Smoothing

- Constrained Laplacian Smoothing

$\tilde{C}^m$

Stage 3: Contour Simplification

- Variational Segmentation
- Topology and Distortion Verification

$\tilde{C}$ (Output)

Binary Image Sampling by using the concept of $r$-regular to guarantee the topological faithful

In the Stages 2 and 3, the self-intersection must be prevented by the stick-concept when sliding on the edges

Self-Intersection-Free Contours

Without snapping the contours on the edge-sticks, self-intersection happens.
Results of Contouring and Printing
Supporting Structure?

**Multi-Materials:** Resolvable materials for supporting structure

**Single Material:** Using structures to support
Region Subtraction Algorithm

- **Top-down Order:**
  - Step 1: calculate the shadow
  - Step 2: exclude the self-support region with growing-swallow
  - Step 3: project the support region from above layer down to current layer
Robust Region Subtraction (Multi-Material)

- Robustly computed in image space
- Dilation and erosion must be applied to remove those self-supported regions
Subtraction on Anchors (Single Material)

First scan: use a uniform grid to intersect the region to be support with the grid nodes

Second scan: Use the orthogonal rays forming the uniform grid to scan the remaining region

Third scan: perform pixel-wise scan for remaining region
After generating the anchor connection graph, the connection operation is applied to connect the pairs of anchors which have overlap range in building direction.

Support Structure Generation

Direct slicing and support generation resultant contour

Fabricated part with support

Fabricated part after removing support

Video
Benefits of Additive Manufacturing

- Very flexible: direction fabrication from CAD model
- Minimal material waste (Additive but not subtractive)
- Manufacturing is responsible for 33% of the world's carbon footprint

Subtractive Machining:

5000 lb. forged billet - 4750 lb. chips = 250 lb. finish machined part

20 : 1
Buy to fly
Limitations / Challenges

- High time cost (pre- and post-processing, etc.)
- Limited part sizes
- **Limited fabrication speed**
- Limited materials (20k vs. 200 materials)
- Poor surface finish
- Low dimensional accuracy and resolution
- Inconsistent part quality
Summary of Additive Manufacturing

- Direct way of fabricating products from digital models
- Provide tremendous freedoms in designing product shapes and material properties
- Has a lot of challenges by evolving quickly

- Recent development:
  1) adaptive slicing to reduce the time of fabrication
  2) hollowing to reduce both the material and time cost
  3) optimization for generating support structures
Adaptive Slicing

Adaptive Slicing

Adaptive Slicing

Optimizing Supporting Structures

Optimizing Supporting Structures

Optimizing Supporting Structures

Fast Fabrication by Mask-Projection

- Mask-Project SLA (also called Digital Light Projection)

Video
References

- P. Huang, C.C.L. Wang, and Y. Chen, "Intersection-free and topologically faithful slicing of implicit solid", ASME JCISE, 13(2), 021009 (13 pages), June 2013.
- Y. Chen, Manufacturing Processes, Seminar at USC.
Thank you!

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