Computational Tools for 3D Printing

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Existing Manufacturing Technologies
Casting: equaled manufacturing

- Pour a liquid material into a mold and then solidify
- History: over thousands of years
Forging: equaled manufacturing

- Shaping metal using localized compressive forces by a smith using a hammer
- History: over thousands of years
Modern CNC: **subtractive** manufacturing

- Cutting out material from a solid
- History: about 100 years
3D printing: additive manufacturing

- Can produce arbitrarily complex (either in geometry or in topology) objects
- History: less than 30 years
Manufacturing technologies: comparison

Casting or forging
- 1000+ years
- Mold is expensive
- Cannot be complex

CNC
- 100 years
- Waste of material
- Cannot be complex

3D printing
- 20+ years
- No waste of material
- Can be arbitrarily complex
Basics of 3D Printing

- What 3D printing is?
- How does it work?
- What are the applications?
3D Printing Hardware and Materials

Fused deposition modeling

Stereolithography
3D Printing Software Pipeline

- Input Model
- Orientation and Positioning
- Support Structures
- Slicing
- Path Planning
- Machine Instructions
Appearance Fabrication for 3D Printing

Base Materials → Mapping / Optimization → Fabrication → Output

Target Object
Designing Deformations for 3D Printing

Base Materials

Acquisition

Search & Simulation

Fabrication

Output

Target Object
More Inverse Modeling Examples

- Specification: shape and size
- Specification: balance
- Specification: strength to a given weight
Structural Analysis for Fabrication

• Need to analyze the “strength” or “weakness” of the shape

  Stress Relief: Improving Structural Strength of 3D Printable Objects [Stava et al. SIG 2012]

  Worst-case Structural Analysis [Zhou et al. SIG 2013]

  Cross-sectional Structural Analysis for 3D Printing Optimization [Umetani & Schmidt SIGA 2013]
Interactive Modeling for Fabrication

• Examples of interactive tools
  
  Modeling from Photographs

  Modeling by (Part) Examples

  Customization of Models
3D Printing Basics
3D Printing = Additive Manufacturing

https://commons.wikimedia.org/wiki/File:3D_printing_on_replicator_2.webm
3D Printing Process

• Slice 3D model into layers
3D Printing Process

• Slice 3D model into layers
• Manufacture layers one by one (e.g., bottom-up)

Source: https://commons.wikimedia.org
Subtractive Manufacturing

- Start with a block of material
- Remove material to obtain a given 3D shape

Source: https://commons.wikimedia.org
Additive Manufacturing Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- DLP 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)
Applications of 3D Printing
Why Additive Manufacturing?

• Good for custom parts or short production runs
• Can build objects with complex geometry
• No (or little) waste material
What Is 3D Printing Used For?

- Prototyping, Presentation, Education: 44%
- Manufacturing: 27%
- Functional Parts: 28%
- Other: 1%
Applications: Dental and Medical Industries

Crowns, copings, bridges

Custom Hearing Aids

Implants

Prosthetics

Source: Envisiontec, on3dprinting.com
Applications: Automotive

Honeycomb Tires

3D Printed Ventilation Prototype (High Temperature 3D Printing Material)

Source: [www.uprint3dprinting.com](http://www.uprint3dprinting.com), gizmodo.com
Applications: Automotive

Source: https://3dprint.com/36433/3d-printed-shelby-cobra/
Applications: Architecture

Source: http://web.ornl.gov/sci/eere/amie/
Applications: Architecture & Design

Source: aecbytes.com, Z Corp, object.com
Applications: Aerospace

3D printed fuel injection nozzle for a jet engine

Airbus wing brackets

Source: GE, 3dprintingindustry.com
Applications: Jewelry

• Direct metal printing and casting patterns

Source: Shapeways, replicatorinc.com
Applications: Footwear

Source: 3dprintingindustry.com, rapid3d.co.za
Applications: Consumer Home Products

Source: Shapeways
Applications: Art

Source: Shapeways, Carlo Sequin, techdigest.tv
Applications: Education

Source: printcountry.com, designfax.net
3D Printing Hardware and Materials
Additive Manufacturing Encompasses Many Different Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- DLP 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)
Fused Deposition Modeling (FDM)

- Fused Filament Fabrication (FFF)
- Filament is made of thermoplastic materials
  - e.g., ABS, polycarbonate, PLA
- Temporary support structure can be made from water-soluble material such as PVA
  - removed using heated sodium hydroxide solution

Source: http://reprap.org
Stereolithography (SLA)

- SLA uses liquid ultraviolet curable photopolymer resin
- Laser beam traces one layer on the surface of the resin
- Laser light cures and solidifies the layer
- The platform descends by one layer

**Photopolymers**

- Change from a liquid state to solid state when exposed with light of a certain wavelength

- Typical ingredients:
  - **Monomers**: small molecules, lower viscosity
  - **Oligomers**: relatively high molecular weight, e.g., acrylates, epoxies, etc.
  - **Photoinitiators**: generate reactive species (free radicals) under light exposure to initiate the polymerization
  - **Additives**: binders, surfactants, stabilizers, etc.
How Photopolymers Work

• Free Radical Polymerization
  – **Initiation:** Free radicals are generated through the initiator when exposed to light
  – **Propagation:** Free radicals react with monomer molecules to generate new reactive center, monomers react with reactive center repetitively to grow into a long chain
  – **Termination:** Chain termination occurs when two reactive centers come close and react with each other to yield complete macromolecules

Source: http://www.additive3d.com/photo.htm
3D Printing Software Pipeline
3D Printing Software Pipeline

- Input Model
- Orientation and Positioning
- Support Structures
- Slicing
- Path Planning
- Machine Instructions
Input File Formats

- **STL (Stereolithography)**
  - Triangle “soup” – an unordered list of triangular facets
  - Vertices ordered by the right hand rule

**ASCII**

```plaintext
solid name

facet normal n_i n_j n_k
outer loop
vertex v1_x v1_y v1_z
vertex v2_x v2_y v2_z
vertex v3_x v3_y v3_z
endloop
endfacet

endsolid name
```

**Binary**

```plaintext
UINT8[80] – Header
UINT32 – Number of triangles

foreach triangle
REAL32[3] – Vertex 1
UINT16 – Attribute byte count (0)
end
```
STL (Stereolithography) File Format

Source: Jackson 2000
3D Printing Software Pipeline

- Input Model
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Model Orientation

• Model orientation on the build platform influences
  – Mechanical properties
  – Build time
  – Support volume
  – Surface accuracy
  – Support contact area
Model Orientation: Mechanical Properties

Printing direction

strong

weak
Model Orientation: Mechanical Properties

- Weak printing direction: max load: 0.22kg
- Strong printing direction: max load: 3.51kg
Model Orientation: Build Time

- Build speed is slower for the z direction compared to the xy direction.
Model Orientation: Support Volume

more support volume

less support volume
Algorithms for Specifying Model Orientation

• Manual placement
  – User is responsible for placing parts on the build tray

• Semi-automated placement
  – User places parts on the build tray
  – System provides feedback on build time, support volume, support contact area, mechanical properties

• Automated placement
  – Orientation is computed using optimization according to one or more objectives (build time, support volume, support area, mechanical properties)
3D Printing Software Pipeline

- Input Model
- Orientation and Positioning
- Support Structures
- Slicing
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- Machine Instructions
Support Structure Generation

• Do not require special support
  – SLS, DMLS, LOM, Plaster-based
• Require support
  • SLA, DLP, FDM, phase-change inkjet
• Different goals
  – Prevent curling as the resin hardens
  – Supporting overhangs
  – Maintaining stability (part does not move or tip over)
  – Supporting large flat walls
  – Preventing excessive shrinkage
  – Supporting slanted walls
Support Structure Generation Depends on Manufacturing Method

• Different for FDM, SLA/DLP, inkjet printing
Simple Conservative Algorithm

• Use ray casting in the z direction to compute all intersections for a ray
• Sort intersections in the increasing z to determine intervals inside/outside of the object
• Any outside intervals before the last inside interval should contain support
Support Generation For FDM

- FDM printers can print at some draft angle
Support Generation For FDM

- Minimize the use of support material

Huang et al. 2009
Optimized Support Structures

Huang et al. 2009
Unoptimized vs. Optimized Support Structure

Huang et al. 2009
Advanced Algorithms: Photoshop
Advanced Algorithms: MeshMixer

Source: http://www.youtube.com/watch?v=aFTyTV3wwsE
Advanced Algorithms: Bridging the Gap

Source: Dumas, Siggraph 2014
3D Printing Software Pipeline

- Input Model
- Orientation and Positioning
- Support Structures
- Slicing
- Path Planning
- Machine Instructions
Slicing

- For a discrete $z$ value, compute an intersection of a plane with a model.
Slicing Algorithms: Voxelization

• For each voxel compute inside/outside
• Extract contours
Slicing Algorithms: Voxelization

- For each voxel compute inside/outside
- Extract contours (e.g., Marching Squares)
Slicing Algorithms: Direct Plane-Triangle Intersection

• For each triangle
  – Intersect triangle with the z plane
  – If they intersect, store the line segment
• Connect line segments, store contours

1. Intersect each edge with the plane
2. If two intersection points, connect them to form a line segment

Source: Choi and Kwok, 2002
Slicing Algorithms: Direct Plane-Triangle Intersection

• For each triangle
  – Intersect triangle with the z plane
  – If they intersect, store the line segment

• Connect line segments, store contours

Issues
• spurious line segments
• missing line segments
Slicing Algorithms: Direct Plane-Triangle Intersection

- STL models are not always watertight -> epsilons

Source: Marsan et al, 1998
Adaptive Slicing

- Slice height is adapted to the input geometry
- Adaptive slicing is rarely used
3D Printing Software Pipeline

- Input Model
- Orientation and Positioning
- Support Structures
- Slicing
- Path Planning
- Machine Instructions
What Does Path Planning Influence?

• **Build time**
  – repositioning the tool at the start of a new path
  – accelerating and decelerating for direction changes

• **Surface accuracy**
  – the filament size

• **Distortion**
  – materials with a high coefficient of thermal expansion
  – the top layer shrinks when it hardens and it distorts since it is tied to the bottom layer

• **Stiffness and strength**
  – fill pattern
  – the area and strength of bonds depends on spacing and the time interval between the tool traversal
Path Planning for Raster-based 3D Printing

• Superimpose a voxel grid and test whether a voxel is inside/outside the model
• Trivial for DLP 3D printing
• For inkjet-based 3D printing requires computing print head movement (many nozzles, distances between nozzles)
Path Planning for Vector-based 3D Printing

• Contour
• Contour + solid interior
• Contour + interior fill pattern
Path Planning for Vector-based 3D Printing: Contour

- Allows manufacturing hollow objects, some overhangs, some tilted surfaces
- Reduces frequency of tool repositioning
- Reduces support structures

Source: http://www.3ders.org
Path Planning for Vector-based 3D Printing: Contour

- Offset inwards by distance equal to the filament radius
Path Planning for Vector-based 3D Printing: Interior

- Tracing contours is combined with filling the interior
- The interior can be completely filled

Horton et al 1993
Han et al 2002
Path Planning for Vector-based 3D Printing: Interior

• Tracing contours is combined with filling the interior
• Many different fill patterns can be used

TriHatch

QuickCast

Horton et al 1993
Path Planning for Vector-based 3D Printing: Interior

- A *honeycomb-cell structure* is a good trade-off between overall weight and strength
Machine Instructions

- **Raster file formats**
  - DLP 3D printing, plaster-based 3D printing, phase-change inkjets
  - Proprietary, not exposed
  - Can be exported as image files (e.g., PNG, BMP)

- **Vector file formats**
  - G-Code
  - SLI by 3D Systems – machine-specific 2D format for the vector commands that control the laser beam
G-code

• Numerical control (NC) programming language
• Developed at MIT in 1950s
• Used for CNC milling machines, now for many 3D printers
• Sample Instructions
  – **G00**: Rapid move
    • does not necessarily move in a single straight line between start point and end point. It moves each axis at its max speed until its vector is achieved.
  – **G01**: Linear interpolation
    • specify the start and end points, and the control automatically calculates the intermediate points to pass through that will yield a straight line
  – **G02**: Circular interpolation, clockwise
G-code Example

This program draws a 1" diameter circle about the origin in the X-Y plane.

G17 G20 G90 G94 G54
G0 Z0.25
X-0.5 Y0.
Z0.1
G01 Z0. F5.
G02 X0. Y0.5 I0.5 J0. F2.5
X0.5 Y0. I0. J-0.5
X0. Y-0.5 I-0.5 J0.
X-0.5 Y0. I0. J0.5
G01 Z0.1 F5.
G00 X0. Y0. Z0.25

seek the Z-axis to 0.25”
travel to X=-0.5 and Y=0.0
lower back to Z=0.0.
draw a clockwise circle at a slow feed rate.
lift the Z-axis up 0.1“
seek back to X=0.0, Y=0.0, and Z=0.25
Representation of Multi-material Objects

- Each point in the Build Space \((x \in X)\) must map to a composition in the Material Space \((m(x) \in M)\)

Source: Jackson 2000
Basic Multi-Material 3D Printing Software Pipeline

• Input
  – A separate boundary representation for each material (e.g. an STL file)
• The rest of the pipeline is similar
Voxel Representation of Multi-material Objects

- Voxel-based modeling – Each voxel maintains information about its composition

1 Voxel
50% A
25% B
25% C
Voxel Representation of Multi-material Objects

- Voxel-based modeling
  - Each voxel maintains information about its composition
  - When printing this volume is dithered to obtain a halftoned representation
Software Architecture Challenges

- Giga voxels/inch$^3$, Tera voxels/foot$^3$
- Continuous gradation between materials
- Reusable material definitions
- Resolution and printer independence
OpenFab [Vidimce 2013]

- Inspired by rendering pipelines
- Fixed stages and programmable stages
- Procedural surface and material definitions
- Resolution independence
- Streaming architecture
OpenFab [Vidimce 2013]

input → tessellate → surface stage → voxelize → volume stage → dither → output

 textures

 materials
Extended 3D Printing Pipeline

Applications/Interactive Design
Functional Specification
Direct Specification
Hardware/Materials
Questions?