Computational Tools for 3D Printing
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Part 4: Modeling and Analysis
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Modeling 3D Objects

• A difficult problem on its own:
  • 3D world on 2D displays
  • 3D manipulation using 2D (or 2.5D) devices
  • Complex: mostly done by experts
  • Issues relating to the digital representation

Challenges Specifically for Fabrication & Printing (not just Graphics)

• Need to actually be constructed or printed:
  • Fitting parts
  • Finding intersections
  • Defining connectors
  • Checking printability
  \{ Geometry \}

• Need to be physically plausible:
  • Appearance
  • Materials
  • Weight
  • Forces
  \{ Physics \}
Two Approaches

1. Inverse Modeling

   Specification → Optimization → Model

2. Interactive modeling:

   Interaction → Model

Examples of Inverse Design

• Appearance fabrication
• Deformable objects fabrication
• Basic idea:

   Input
   A given shape
   +
   High level specification

   Output
   A recipe for fabricating
   the object (shape, material, structure...
More Inverse Modeling Examples

Chopper: Partitioning Models into 3D-Printable Parts
Linjie Luo, Ilya Baran, Szymon Rusinkiewicz, Wojciech Matusik
ACM Transactions on Graphics, 31(6), (SIGGRAPH Asia), 2012

Make It Stand: Balancing Shapes for 3D Fabrication
Romain Prévost, Emily Whiting, Sylvain Lefebvre, Olga Sorkine-Hornung, ACM Trans. Graph. 32, 4, Article 81 (July 2013)

Build-to-last: strength to weight 3D printed objects.
Lin Lu, Andrei Sharf, Haisen Zhao, Yuan Wei, Qingnan Fan, Xuelin Chen, Yann Savoye, Changhe Tu, Daniel Cohen-Or, and Baoquan Chen. 2014 ACM Trans. Graph. 33, 4, Article 97 (July 2014)

More Inverse Modeling Examples

Specify: shape and size

Specify: balance

Specify: strength to a given weight
Strati: First 3D Printed Car

- Made by Local Motors for the International Manufacturing Technology Show (IMTS)
- Strati = “layers” in Italian
- 18 months of design
- 44 hours of printing

Usually Print Volume is Limited

- Typically 10cm x 10cm x 10cm up to 50cm x 40cm x 30cm
- Printing large objects requires chopping and assembly
Chopper: Two Challenges

• How to segment?
  • Use planes to define parts
  • Cut top down recursively

• How to connect?
  • Use male/female connectors:
Overview

Pick a bunch of potential cuts
Evaluate them and find the best ones
Recurse on pieces that are still too big
Place connectors on cross-sections

Optimization Objective

- Connector feasibility
- Part fragility
- Structural soundness when assembled
- Number of parts
- Printing volume utilization
- Seam aesthetics
Optimization: Beam Search [Lowerre 1976]

Make It Stand Challenge

• Designing things that can really stand:
Overview

Input model → inner carving → shape deformation → balanced model

Optimization

\[
\argmin_{M_I, M_O} (1 - \mu) E_{CoM}(M_I, M_O) + \mu E_M(M_O)
\]

Does it stand? Similarity to original shape

Inner carving

Shape deformation
User Assistance

- Changing the shape using handles

Build-to-Last Challenge

- Reduce the object weight while providing a durable 3D printout sustaining given forces.
- Inspiration from porous structure
  - Lightweight
  - Strong
  - Ability to absorb energy, vibration
Basic Idea

Introducing the *honeycomb-cell structure*, which is of minimal material cost while providing strength in tension.

Overview

- Input (model & forces)
- Structural Analysis
- Voronoi Tessellation
- Pore Extraction
- Strength-to-Weight Optimization
- Result
β (Hollowing amount)  
\[ \beta = \{\beta_1, \ldots, \beta_\alpha\} \]

**Optimization**

- **Objective:**  
  \[ \arg\min_{\alpha, \beta} W_s(\alpha, \beta) \quad s.t. \quad SM(S, F) < \chi \]

- **Two loops for optimizing \( \alpha \) and \( \beta \)**
  - Outer loop: optimize \( \alpha \) for compactness
  - Inner loop: optimize \( \beta \) for sustaining stress

*Yield point = stress at which a material begins to deform plastically*
Results

Initial setting & Stress map

125.07 cm$^3$

Iterations

Optimal result

50.79 cm$^3$ (40.6%)

3D pores

More Examples of Inverse Design Objectives

Flight ability

Spin ability

[Umetsu et al., 2014]

[Brecht et al., 2014]
Inverse Design Methodology

- Given a 3D shape (usually boundary surface), optimize some objective (size, balance, strength) by changing shape parameters:
  - Inner shape – does not change outside appearance
  - Outer part – usually want to constrain not to differ too much from original shape

Modeling vs. Modifying a Given Input Shape

- Shape and size: finds segmentation
- Balance: modify internal and external shape
- Strength to weight: modify internal shape mostly
Creating a Whole New Model?

Yuki Koyama, Shinjiro Sueda, Emma Steinhardt, Takeo Igarashi, Ariel Shamir, Wojciech Matusik

AutoConnect: Computational Design of 3D-Printable Connectors
ACM Transactions on Graphics, Volume 34, Number 6, (SIGGRAPH Asia Conference Proceedings), Article No. 231, 2015

More »
Objective

• Input — Two geometries
  – Position / orientation
  – Weights
  – Auxiliary parameters (e.g., free directions)

• Output — A customized connector
  – Automatically generated
  – Fabricable (physics, geometry)

• No initial shape to begin with

Example
Example 2
Connectors Definition

- Two holder parts
  - Each holder connects/holds one of the target objects
- Bridge part
  - Simple bar connecting the two holders

Two Holder Types

1. Holder for standard shapes
   - Must have sufficient grip strength
2. Holders for freeform shapes
   - Object must not fall off (hold-ability)
Holders Database

Parametrized Holders

Every holder is parametrized by a few parameters:

- e.g. height
- e.g. closeness
Considering Grip Strength

Freeform Holders by Area Expansion
Two Types of Optimizations

• Optimizing holder parameters for Grip Strength

• Optimizing surface for Holdability
Physical Considerations

- Avoid cutting at weak points in the mesh
- Balancing
- Avoid large pores at weak points
- Avoid slipping or falling

Structural Analysis

- In many cases there is a need to analyze the “strength” or “weakness” of the shape
Yield

- A *yield strength* or yield point is the **material property** defined as the stress at which a material begins to deform plastically.
- Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.
Strain vs. Stress

Continuum Mechanics: Structural Analysis

- Standard method in engineering uses Finite Elements Methods
FEM

- Define a variational formulation
- Discretize the space
- Define basis functions
- Solve (iterative)
- Post processing

In Graphics

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]
Three Key Questions for Fabrication

1. What is the applied load?
2. What are failure locations?
3. How to fix failures?

Stress Relief – Pinching Load

- Compute “Pinch Grip” locations:
  - Label triangle on convex hull as potential grip site for first finger
  - Cast ray in predefined direction to determine second triangle
- Filter grips based on biomechanical criteria
- Compute load using model from biomechanics
Stress Relief

- Finite Element Analysis for all orientations and grip locations
- Fixing failures
  - Automatically thicken thin parts of the object
  - Add struts to support parts of the object
  - Hollow parts of the object to reduce weight

Worst-Case Structural Analysis

- Find a load that maximizes stress in the object

\[
\max_{\text{pressure}} |\sigma (\text{shape (pressure)})|\]

\(\sigma\)

Stress

Deformed Shape of Object

Pressure Applied
Worst-Case Structural Analysis

- Compute failure locations by finding stresses that exceed a threshold
- No fixing discussed

How does a structure break?

Structure breaks at **slender parts**

Structure breaks by **bending**

How a beam bends?
Cross-sectional Structural Analysis

- Requires just the surface mesh to perform analysis of the stress
- Treats objects as if they are beams

Compute Cross Sections

Fixed boundary
Divide object into two pieces using a cutting plane

Fix boundary on one piece
Apply Forces

Compute maximum stress on cross sections
Weak Cross Sections Performance

- 13 directions of cross section, 32 slices in each direction

\[
|T| = 17k
n-sample = 60k
time = 0.18sec
\]

\[
|T| = 34k
n-sample = 200k
time = 0.31sec
\]

\[
|T| = 600k
n-sample = 414k
time = 3.8sec
\]

Application

- Not fixing but choosing the printing direction

max load: 0.41kg

max load: 3.91kg
Structural Analysis Using Finite Elements

• Choose loading conditions
• FEM Solve for each loading condition

Worst-Case Analysis

• Solving for multiple forces is too slow, so find most destructive force

• Finding this single force sample is slow and it may be unrealistic
New: Stochastic Finite Elements

• Succinctly describe many forces as distributions
• Perform Finite Element Analysis on Force Distributions Instead

Stochastic Structural Analysis for Context-Aware Design and Fabrication
Timothy Langlois, David I.W. Levin, Daniel Dror, Ariel Shamir, Wojciech Matusik - Conditionally Accepted SIG Asia 2016

Generate Distributions via Sampling

Linear Velocity
Angular Velocity
1.5m
Scene – Drop Test

Operate in Reduced Sample Space
Fast Stochastic Analysis using Reduced Space

1. Unlike previous methods, encodes context efficiently
2. Handles complicated contact scenarios
3. Expresses reliability compactly as a single failure percentage

Probability of Failure: 71%

Stochastic Topology Optimization

• Because distributions are easy to compute via sampling, the method can be used for topology optimization
Back to Modeling

1. Inverse Modeling

   Specification → Optimization → Model

2. Interactive modeling:

   Interaction → Model

Modeling from Scratch is a Challenge
**Interactive Modeling**

- We can still allow the user some control and design intelligent tools
- Three attempts to allow more interactive tools:
  - Modeling from Photographs
  - Modeling by (Part) Examples
  - Customization of Models
3Sweep Motivations

- Modeling from an image is challenging for automatic computer algorithms
- It is a challenge for humans
- Can we combine forces?

3-Sweep: Image Based Object Modeling

- A simple intuitive gesture to define 3D primitives using 3 mouse sweeps:
Modeling One Primitive

3Sweep Overview

Pre-Processing

Input image → Extracted edges → Drawing two strokes to form the profile of a primitive 3D model of the object

Applying geometric-semantic constraint to achieve final model

Sweep to form 3D model of the object

Editing and pasting the object

3-Sweep: Modeling One Primitive

Optimization: Modeling Composite
Behind the Scene: Outline Snapping Rules

- Prefer the outline that is parallel to the 3rd stroke
- Stick to the same outline, change to the one with minimal angle change if necessary
- Use symmetry and continuity to deal with missing outline
- Fit to uniform or linearly changing diameters and use diameters smoothing (assumption: the profile can only be scaled uniformly).

Behind the Scene: Geo-Semantic Constraints
Expert Knowledge: Geo-Semantic Constraints

- Defined in terms of major axes of the primitives.
- Support six constraint types:
  - parallelism
  - orthogonality
  - collinear anchors
  - overlapping anchors
  - coplanar anchors
  - coplanar axes

\[(\mathbf{C}_{m,1} - \mathbf{C}_{m,2}) \times (\mathbf{C}_{n,1} - \mathbf{C}_{n,2}) = \mathbf{0}\]

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Modeling Session

3-Sweep on Bent Generalized Cylinder
Virtual vs. Real

Many Parts (~300)
The Design for Fabrication Process

Fabrication by Example Motivation

- Designing objects that can be really fabricated:
  - Requires many small details
  - Includes how to connect parts
  - Involves materials, physics...
Key Idea: Database of Example

Modeling Session

Full Session
Approach

Input → Expert Data → Composition Tool → Fabrication

Examples
Customizable Models:
Parameters & Constraints

Part Based Modeling
Snapping

- User interaction
- Preserve alignment constraints

Connectors
Customization

- Instead of the user involved in modeling – design customizable objects and allow the user to modify them before fabrication

Difficulties

- Which parameters to expose?
- It takes time to compute after change of parameters
- Changing parameters may break the design in various ways:
  - Geometrical (self intersections, invalid boundary, holes)
  - Physical (too thin, unstable, un-printable)
Fab Forms

Fab Form

1. Customizable
2. Valid
3. Interactive

Overview

Our Method

Parametric Design

User

Designer

Fab Form
Fab Form Implementation

- Parametric Design
- Valid Regions of the Design Space
- Geometry Cache

Fab Form Requirements

- 1. Customizable ✓
- 2. Valid ✓
- 3. Interactive ✓

Inputs and Outputs

1. Parametric Design
design space

2. Automatic Tests
- Printability analysis
- Design-specific tests


Precomputation

Fab Form Implementation

- Parametric Design
- Valid Regions of the Design Space
- Geometry Cache
Design Space Sampling

Sampling objectives:
• approximate the valid region
• populate geometry cache

Intuition:
• sample more where geometry changes
• sample more where validity changes
Using the Valid Region

Non-convex, non-contiguous regions difficult to navigate with sliders alone.

[Marks et al. ‘97, Talton et al. ‘09, Shapira et al. ‘09, Koyama et al. ‘14]

Design Exploration Points
Summary

• 3D Modeling for the physical world involves additional challenges: Geometric and Physical Analysis
• Three points of views need to work together for effective modeling:
  
  ![Designer](image)
  ![Engineer](image)
  ![User](image)

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Summary

• 3D Modeling for the physical world involves additional challenges: Geometric and Physical Analysis
• Three points of views need to work together for effective modeling: Designer, Engineer, User
• Inverse modeling: mostly changes existing models to fit certain specification
• Interactive modeling: still very difficult for novices – need for intelligent tools to assist