Computational Tools for 3D Printing

Nobuyuki Umetani
Bernd Bickel
Wojciech Matusik
Part 3: Design and Fabrication of Deformable Objects

Bernd Bickel
Deformable Objects

[shapeways.com]

[RBO Hand, TU Berlin]

[Festo]
From Functional 2 Direct Specification

Base Materials → Search & Simulation → Fabrication → Output

Target Object
Manufacturing Deformable Materials

- **Intrinsic**
  - [Hiller and Lipson 2009]
  - [Bickel et al. 2010]
  - [Skouras et al. 2013]
  - [Chen et al. 2013]
  - [Schumacher et al. 2015]
  - [Panetta et al. 2015]

- **Extrinsic**
  - [Bickel et al. 2012]
  - [Chen et al. 2014]
From Functional 2 Direct Specification

Base Materials

Target Object

Search & Simulation

Fabrication

Output
Material Representation

Stress-Strain relationship in 1D

- Strain $\varepsilon = \frac{u}{L}$
- Stress $\sigma = \frac{F}{A}$
Linear Representations Do Not Work

- Stress-strain relationship is non-linear

Choice of material model
- Linear Elastic
- Hyperelastic
- Plasticity
- Creep
Acquiring mechanical properties

Option 1: “Standard” Material Tests

• Common types of tests: Uniaxial Tension, Uniaxial Compression, Biaxial Tension, Torsion
• “Simple” to construct stress-strain curve
• Fitting material parameters easy
• Intuitive inspection of experimental data and material parameter fits
• Requires specific shape of specimen

Typical specimen shape

Gauge length = 50mm
12.5 mm

Tensile test machine
Acquiring mechanical properties

Option 2: Acquire Force/Displacement Pairs

- Capturing boundary conditions accurately can be challenging
From Functional 2 Direct Specification

Base Materials → Search & Simulation → Fabrication → Output

Target Object
Manufacturing Deformable Materials

- [Hiller and Lipson 2009]
- [Bickel et al. 2010]
- [Skouras et al. 2013]
- [Chen et al. 2013]
- [Chen et al. 2014]
- [Bickel et al. 2012]
- [Schumacher et al. 2015]
- [Panetta et al. 2015]
Goal
Approach 1: Topology Optimization

[Sigmund 2009]
[Schumacher et al. 2015]
Approach 1: Topology Optimization

\[ O(\alpha) = \| C_{goal} - \tilde{C}(\alpha) \|_F^2 + R \]
Approach 1: Topology Optimization

\[ O(\alpha) = \left\| C_{goal} - \tilde{C}(\alpha) \right\|_F^2 + R \]
Approach 2: Systematic Topology Enumeration

[Panetta et al. 2015]
Approach 2: Systematic Topology Enumeration

[Panetta et al. 2015]
Microstructure Shape Optimization

- **Thickness** and **offset** parameters continuously control microstructure’s **shape**, $\omega$

- Fit the microstructure to an elasticity tensor:

\[
J(\omega) = \left|\left|C^H(\omega) - C^*\right|\right|^2
\]

[Panetta et al. 2015]
Shape Optimization Results

[Panetta et al. 2015]
Shape Optimization Results

[Panetta et al. 2015]
Manufacturing Deformable Materials

- [Hiller and Lipson 2009]
- [Bickel et al. 2010]
- [Skouras et al. 2013]
- [Chen et al. 2013]
- [Bickel et al. 2012]
- [Chen et al. 2014]
- [Schumacher et al. 2015]
- [Panetta et al. 2015]
From Functional 2 Direct Specification

**Input**
- Shape with assigned Material Parameters
- Deformation Specification

**Output**
- Spatially-varying material structure
From Functional 2 Direct Specification

**Input**
- Shape with assigned Material Parameters
- Deformation Specification

**Output**
- Spatially-varying material structure
Challenge: Find optimal combinations

[Schumacher et al. 2015]
Challenge: Find optimal combinations
From Functional 2 Direct Specification

**Input**
- Shape with assigned Material Parameters
- Deformation Specification

**Output**
- Spatially-varying material structure

optimization
Problem Formulation

Design Parameters

\[ E(x, p) = E_{match}(x, x_{target}) \quad \text{subject to} \quad f^{total}(x, p) = 0 \]
Problem Formulation

Design Parameters

\[ E(x, p) = E_{match}(x, x_{target}) \]

subject to \[ f^{total}(x, p) = 0 \]

Optimization Strategies:
- Discrete ([Bickel et al. 2010])
- Continuous ([Skouras et al. 2013])
Discrete Optimization: Material Search Tree

[Bickel et al. 2010]
Discrete Optimization: Material Search Tree

[Bickel et al. 2010]
Pruning the Search Space

- Bounds from physical constraints

[Bickel et al. 2010]
Pruning the Search Space

- Clustering at each level

[Bickel et al. 2010]
Ready to Wear
Problem Formulation

Design Parameters

\[ E(x, p) = E_{match}(x, x_{target}) \]

subject to \[ f^{total}(x, p) = 0 \]

Optimization Strategies:
- Discrete ([Bickel et al. 2010])
- Continuous ([Skouras et al. 2013])
Continuous Material Distribution Optimization

[Skouras et al. 2013]
Material Distribution Optimization
Material Distribution Optimization

pose 1

pose 2

pose 3

stiff

soft
Results

Rest Pose

Target Pose

Stiff

Soft
Manufacturing Deformable Materials

- Intrinsic
  - [Hiller and Lipson 2009]
  - [Bickel et al. 2010]
  - [Skouras et al. 2013]
  - [Schumacher et al. 2015]
  - [Panetta et al. 2015]

- Extrinsic
  - [Bickel et al. 2012]
  - [Chen et al. 2013]
  - [Chen et al. 2014]
Thickness Optimization

- Works with a single base material
- Idea: modulate local stiffness by modifying the skin thickness

Target surface  Undeformed bar

[Bickel et al. 2013]
Thickness Optimization

- Minimization problem

\[(p, x) = \arg\min_{p,x} \left( E_{match}(x, x_{target}) \right) \]

[Bickel et al. 2013]
Thickness Optimization

Forehead inner side

Rest shape

Target geometry
Results

Simulation  Robotic head
Spec2Fab

• Spec2Fab processes use a similar structure
• Small set of common components

[Chen et al. 2013]
Common Components

Reducer Tree

Tuner Network

Reduced Parameters

Simulate

Optimization

Compare to goal

[Chen et al. 2013]
Spec2Fab for Deformation and Texture

Goal: deformation

Goal: texture

[Chen et al. 2013]
Conclusion

• Summary
  – Control at various levels
  – Techniques could be combined
  – Interactive vs. Specification-Based Design

• Limitations / Future Work
  – Scaling
  – Non-linear material behavior can be very complex
  – Fabrication constraints often quite specific
  – 3D printer
    • Durability of materials
    • Handling of materials
Thank you!

Acknowledgements
Melina Skouras and Julian Panetta for providing slides/image material.

References


