Build-to-Last: Strength to Weight 3D Printed Objects

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3D Printing is very popular...
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Architecture

Aerospace

Medical treatment

Automotive

Entertainment & Fashion & Consumer products
Issues in 3D Printing

- Strength
- Material cost
- Time
- Mechanics
- Functions
- Appearance
- ...
Strength-to-Weight

A: uniform hollowing
B: honeycomb structure
C: solid
Our Goal

Optimize the “Strength-to-Weight Ratio”.

Reduce the object weight while providing a durable 3D printout sustaining given forces.
Basic Idea

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

Porous Structure / Porous Media
Inspiration

- Lightweight
- Ability to absorb energy, vibration etc.

porous metal (metal foam)

Ariane rocket cone

BMW engine mounting bracket
Related Work

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

Make It Stand: Balancing Shapes for 3D Fabrication [Prévost et al. 2013 SIG]

Spin-It: Optimizing Moment of Inertia for Spinnable Objects [Bächer et al. 2014 SIG]
Related Work

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

Cost-effective Printing of 3D Objects with Skin-Frame Structures
[Wang et al. 2013 SIGA]
Overview

Input (model & forces)

Structural Analysis

Voronoi Tessellation

Pore Extraction

Strength-to-Weight Optimization

Result
Control Parameters

\[ \alpha \quad - \text{# of cells} \quad \alpha \in N \]

\[ \beta \quad - \text{Hollowing ratio for each cell} \quad \{\beta_1, \ldots, \beta_\alpha\} \quad \beta_i \in [0, 0.9] \]
\( \beta = \{\beta_1, \ldots, \beta_\alpha\} \)
**Structural Analysis**

- Tetrahedralize the given model
- Compute stress for each node

*stress value color encoded.*
Initial Point Distribution

- Error diffusion
- Higher stress values $\rightarrow$ denser sites dispersion

$\alpha = 100$

$\alpha = 200$
Adaptive Centroidal Voronoi Tessellation

- Each site coincides with the centroid $c_i$ of its Voronoi cell $\Omega_i$

$$c_i = \frac{\int_{x \in \Omega_i} \rho(x) x d\delta}{\int_{x \in \Omega_i} \rho(x) d\delta}$$

$d\delta$ – area differential

$\rho(x)$ – density function
Pore Extraction by Harmonic Distance Field

- Harmonic distance field inside each Voronoi cell:
  \[ \nabla^2 \varphi(p) = 0 \]

- Boundary conditions: cell’s boundary and the centroid
Strength-to-Weight Optimization

Objective:

\[
\text{argmin}_{\alpha, \beta} W_s(\alpha, \beta) \quad \text{s.t.} \quad SM(S, F) < \chi,
\]

- **Weight (volume)**
- **Strength (stress map)**

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

Plastic region

Elastic region

4.1e7 N/m²

Forces

Shape

PC-ABS

Plastic

P

Stress

Strain
Strength-to-Weight Optimization

- The strength-to-weight ratio behavior is highly non-convex and non-linear.
- We devise a local optimization coupled with an adaptive Monte-Carlo sampling.
Strength-to-Weight Optimization

Two loops for optimizing $\alpha$ and $\beta$:

**Outer loop**
- Optimize $\alpha$ for compactness

**Inner loop**
- Optimize $\beta$ for sustaining stress

$\alpha = 50$

$\beta = 0.9$

$\beta = [0.5 - 0.9]$

$\alpha = 20$

$\beta = [0.5 - 0.9]$

$\beta = [0.1 - 0.9]$
Results

Initial setting & Stress map

Iterations

Optimal result

3D pores

719.24 cm³

472.03 cm³ (65.6%)
Results

Initial setting & Stress map

Iterations

Optimal result

3D pores

214.40 $cm^3$

89.33 $cm^3$ (41.7%)
Results

Initial setting & Stress map

Iterations

Optimal result

3D pores

125.07 cm³

50.79 cm³ (40.6%)
Results

Initial setting & Stress map

15.22 cm³

Iterations

54.24 cm³

9.64 cm³ (63.3%)

Optimal result

20.02 cm³ (36.9%)

3D pores
Results
Comparison

[Wang et al. 2013] (resists 5N with the weight 109.3g)  [Ours] (resists 20N with the weight 92.5g)
Physical Test

Partial optimal

\[ \alpha = 50 \]
\[ \beta = 0.9 \]

Optimal

\[ \alpha = 50 \]
\[ \beta = [0 - 0.9] \]

27.087g

27.551g

108.0N

194.6N

SANS CMT5105
Future Work

- Dynamic forces
- Elastic materials
- Powder-based 3D printers (Connected porous structures)
Conclusions

- Voronoi-guided porous structure for sustaining given forces
- Trade-off between strength and weight
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Shark model: http://www.123dapp.com/123C-3D-Model/Shark/1100655

http://irc.cs.sdu.edu.cn/BuildtoLast/