Introduction to Computational Fabrication
Print me a Stradivarius
The manufacturing technology that will change the world

This violin was made using an EOS laser-sintering 3D printer (and it plays beautifully)
Additive Manufacturing

$7B \rightarrow $640B

Global manufacturing Market:

0.04% \rightarrow 5\%
The Third Industrial Revolution
The Third Industrial Revolution
The Third Industrial Revolution

Material waste

Shipping costs

Complexity

The Third Industrial Revolution
The Third Industrial Revolution
Agenda

- What is additive manufacturing?
- Challenges
- Computational fabrication and graphics?
- Computational fabrication in graphics
Agenda

• What is additive manufacturing?
  • Technologies
  • Applications
• Challenges
• Computational fabrication and graphics?
• Computational fabrication in graphics
Additive Manufacturing

- Additive vs. Subtractive
  - Most of current manufacturing is subtractive
- “3D Printing” coined at MIT in 1995
Additive Manufacturing Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- Digital Light Projector (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)
Additive Manufacturing Technologies

- **Fused deposition modeling (FDM)**
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Fused deposition modeling (FDM)

Filament is led to the extruder

The extruder uses torque and a pinch system to feed and retract the filament precise amounts.

A heater block melts the filament to a useable temperature.

The heated filament is forced out the heated nozzle at a smaller diameter.

The extruded material is laid down on the model where it is needed.
Fused deposition modeling (FDM)
Fused deposition modeling (FDM)

OBJET Connex
$250K

MakerBot Replicator 2
~$2K

More units sold per month than OBJET Connex ever
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Stereolithography (SLA) & DLP
Stereolithography (SLA) & DLP
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Laser Sintering
Laser Sintering
Consumer Level SLS

Industrial quality prints from the most available desktop 3D SLS printer.

Buy online

from 4990€*

*concerns EU excluding special member states territories
Consumer Level SLS

https://www.youtube.com/watch?time_continue=4&v=Q8al0846stk
Laser Sintering
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- Thermal Phase Change Inkjets
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Photopolymer Phase Change Inkjets
Photopolymer Phase Change Inkjets
Photopolymer Phase Change Inkjets

- Bio-compatible
- High-temperature
- ABS-like
- Transparent
- Opaque
- Rigid
- Rubber-like
Photopolymer Phase Change Inkjets
Exotic Technologies

- Food
Exotic Technologies

- Food
- 3D Pens
Exotic Technologies

- Food
- 3D Pens
- Construction
Copper PLA Filament
Conductive Filament
Markforged – Mark One

https://www.youtube.com/watch?v=Y5wjjDBdgeE
Ceramics Printing
Robotic Clay Printing
Rapid Liquid Printing

https://www.youtube.com/watch?v=8p7CSNbX8vM
Applications

- Jewelry
- Dental and Medical Industries
- Footwear
- Architecture, Engineering and Construction
- Aerospace
- Automotive
- Consumer Home Products
- Toys and Gadgets
- Art
- Education
Applications

Jewelry (direct metal printing and casting patterns)
Applications

Dental and Medical Industries

- Crowns, copings, bridges
- Custom Hearing Aids
- Implants
- Prosthetics
Applications

Footwear
Applications

Architecture

Models

Molds
Applications

Aerospace

3D printed wing structure resembling the skeleton of birds

Airbus wing brackets
Applications

Automotive

Honeycomb Tires

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

Consumer Home Products

Lamp
Egg cup
Espresso Cup
Platter
Pencil bowl
Applications
Toys, Art & Education
Additive Manufacturing

- Consumer electronics (~20%)
- Automotive industries (~20%)
- Medical device industry (~15%)
- Consumer products

The U.S. hearing aid industry converted to 100% 3D printing in less than 500 days.
Agenda

- What is additive manufacturing?
- Challenges
  - Disciplines
- Computational fabrication and graphics?
- Computational fabrication in graphics
Challenges

Mechanical + Electrical Engineering Challenges

- Slow – Printing 5” x 5” x 5” object takes 10+ hours
- Expensive – $100 / lb
- Print Volume
Challenges

- **Material Challenges**
  - Better control over physical properties:
    - Strength / weight
    - Deformability (stretchy, flexible)
    - Magnetism, conductivity
    - Heat resistance and transfer
  - Better control over optical properties:
    - Color
    - Shininess
    - Reflectivity
    - Roughness
    - Translucency
    - BRDF...
  - Interface between materials
Additive Manufacturing Challenges

Software
Challenges

Software Challenges
Challenges

Software Challenges

- Data Requirements & Representations
- Giga voxels/inch$^3$, Tera voxels/foot$^3$
Challenges

Software Challenges

- Data Requirements & Representations
- Measurement & Simulation
Challenges

Software Challenges

- Data Requirements & Representations
- Measurement & Simulation
- Optimization
Challenges

Software Challenges

- Data Requirements & Representations
- Measurement & Simulation
- Optimization
- Design
Agenda

- What is additive manufacturing?
- Challenges
- Computational fabrication and graphics?
  - Appearance
  - Physical simulation
  - Geometry Processing
  - Animation
- Computational fabrication in graphics
Fabrication and Graphics

Appearance

- Halftoning

Dual-Color Mixing for Fused Deposition Modeling Printers [2014]
Fabrication and Graphics

Appearance

- Halftoning

Pushing the limits of 3d color printing: Error diffusion with translucent materials [2015]
Fabrication and Graphics

Appearance
- Halftoning
- Caustics
- Reflectance
- ...

ShadowPIX: Multiple Images from Self-Shadowing [2012]

Bi-Scale Appearance Fabrication [2013]

Reliefs as images [2010]

Goal-Based Caustics [2011]
Agenda

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• **Computational fabrication and graphics?**
  • Appearance
  • Physical simulation
  • Geometry Processing
  • Animation
• Computational fabrication in graphics
Fabrication and Graphics

Physically-based simulation

- Computational Sciences
  - Reproduction of physical phenomena
  - Predictive capability (accuracy!)
  - Substitute for expensive experiments
Fabrication and Graphics

Physically-based simulation
- Computational Sciences
  - **Reproduction** of physical phenomena
  - Predictive capability (accuracy!)
  - Substitute for expensive experiments
- Computer Graphics
  - **Imitation** of physical phenomena
  - Visually plausible behavior
  - Speed, stability, art-directability
Fabrication and Graphics

Physically-based simulation
Fabrication and Graphics

Physically-based simulation
Fabrication and Graphics

Physically-based simulation

- Fluid Simulation

http://lgg.epfl.ch/research_physicsbased_animation.php
Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
Fabrication and Graphics

Physically-based simulation
- Fluid Simulation
- Rigid Body
- Fracture
Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound

Inverse-Foley Animation: Synchronizing rigid-body motions to sound [2014]
Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**
Fabrication and Graphics

Physically-based simulation
- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- Elasticity
  - FEM
Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**
  - FEM
  - Rods, shells

Discrete Elastic Rod model [2008]

A Consistent Bending Model for Cloth Simulation with Corotational Subdivision Finite Elements [2006]
Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- Elasticity

An asymptotic numerical method for inverse elastic shape design [2014]
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  • Appearance
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  • Geometry Processing
  • Animation
• Computational fabrication in graphics
Fabrication and Graphics

Geometry Processing

- Representations
  - Giga voxels/inch$^3$, Tera voxels/foot$^3$
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree

Spin-it: Optimizing moment of inertia for spinnable objects [2014]
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree

Spin-it: Optimizing moment of inertia for spinnable objects [2014]
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree
  - Medial axis

Stress relief: Improving structural strength of 3d printable objects [2012]
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree
  - Medial axis

Stress relief: Improving structural strength of 3d printable objects [2012]
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree
  - Medial axis
  - Spectral decomposition

Order Reduction

We use Manifold Harmonics
- Smooth
- Orthogonal
- Encode surface geometry

Reduced-order shape optimization using offset surfaces [2015]
Geometry Processing

- Representations
- Curvature

Reduced-order shape optimization using offset surfaces [2015]
Fabrication and Graphics

Geometry Processing
- Representations
- Curvature
- Vector fields

Designing unreinforced masonry models [2013]
Fabrication and Graphics

Geometry Processing

- Representations
- Curvature
- Vector fields

Field-aligned mesh joinery [2014]
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Fabrication and Graphics

Animation
- Rigs
- Kinematic Chains
- Motion Capture
- Motion curves
- Motion features

Pipeline Overview

Fabricating articulated characters from skinned meshes [2012]
Fabrication and Graphics

Animation
- Rigs
- Kinematic Chains
- Motion Capture
- Motion curves
- Motion features

Fabricating articulated characters from skinned meshes [2012]
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• What is additive manufacturing?
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• **Computational fabrication in graphics**
  • Appearance
  • Integrity and deformation
  • High-Level Design
  • Process optimization
  • Frame works
Fabrication in Graphics

Appearance

Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices [2012]

Computational light routing: 3D printed fiber optics for sensing and display [2014]
Fabrication in Graphics

Appearance

Synthesis of filigrees for digital fabrication [2016]
Fabrication in Graphics

Integrity

Build-to-last: Strength to weight 3d printed objects [2014]
Fabrication in Graphics

Integrity

A System for High-Resolution Topology Optimization

Jun Wu, Christian Dick, Rüdiger Westermann
Fabrication in Graphics

Integrity

Worst-case structural analysis [2013]
Fabrication in Graphics

Deformation Behavior

Design and fabrication of materials with desired deformation behavior [2010]
Design and fabrication of materials with desired deformation behavior [2010]
Fabrication in Graphics

Deformation Behavior

- Cellular structures

Elastic textures for additive fabrication [2015]
Fabrication in Graphics

Deformation Behavior
• Cellular structures

Microstructures to control elasticity in 3d printing [2015]

Procedural voronoi foams for additive manufacturing [2016]
Fabrication in Graphics

Deformation Control

Computational design of actuated deformable characters [2013]
Fabrication in Graphics

High-level design

Airplanes designed by the Pteromys system.

Pteromys: Interactive design and optimization of free-formed freeflight model airplanes [2014]

Screen capture of Pteromys design tool.
Fabrication in Graphics

High-level design

Omniad: Data-driven omni-directional aerodynamics [2015]
Fabrication in Graphics

High-level design

Acoustic voxels: Computational optimization of modular acoustic filters [2016]
Fabrication in Graphics

High-level design

Acoustic voxels: Computational optimization of modular acoustic filters [2016]
Fabrication in Graphics

High-level design
Fabrication in Graphics

High-level design

Autoconnect: Computational design of 3d-printable connectors [2015]
Fabrication in Graphics

High-level design

Computational Design of Mechanical Characters [2013]
Fabrication in Graphics

Process optimization

Clever support: Efficient support structure generation for digital fabrication [2014]
Fabrication in Graphics

Process optimization

Chopper: Partitioning models into 3D-printable parts [2012]
Fabrication in Graphics

Process optimization

Multifab: A machine vision assisted platform for multi-material 3d printing [2015]
Fabrication in Graphics

Frameworks

Spec2Fab: A reducer-tuner model for translating specifications to 3D prints [2013]

Openfab: A programmable pipeline for multi-material fabrication [2013]
Fabrication in Graphics

LOTS more
Discussion
Discussion

- Small scale, initial concept

- Separate design and manufacturing processes

- Under considered technologies
  - Metal sintering
  - Composite materials

- Large collections remain unexploited
Discussion

• A design gap
  • A fundamental change in design concepts

• Design through objectives
Future of Fabrication

Fabrication Research
Future of Fabrication

Fabrication Research

Design

Practical Objectives

High-res topopt, reduction, Skouras, Skinned meshes
Future of Fabrication

Fabrication Research

Design

Practical

Objectives
  • Types

[Luo et al. 12]
[Bharaj et al. 12]
KTSDESIGN/Getty Images
Wikipedia
Future of Fabrication

Fabrication Research

Design

Practical

Objectives
• Types
• Learn
• Balance
Future of Fabrication

Fabrication Research

Design
- Practical
- Objectives
  - Types
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  - Balance

Representation
Future of Fabrication

Fabrication Research

Representation
- Hierarchical
- Abstraction
- Generic

[Image of hands and gears]

M2P Marketing
Future of Fabrication

Fabrication Research

Representation
- Hierarchical
- Abstraction
- Generic
- Informative
Thank you