EUROGRAPHICS 2017
The 38th annual conference of the
EUROPEAN ASSOCIATION FOR COMPUTER GRAPHICS

Topology Optimization for Computational Fabrication

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Inria INVENTEURS DU MONDE NUMÉRIQUE

Part One: Advanced Manufacturing

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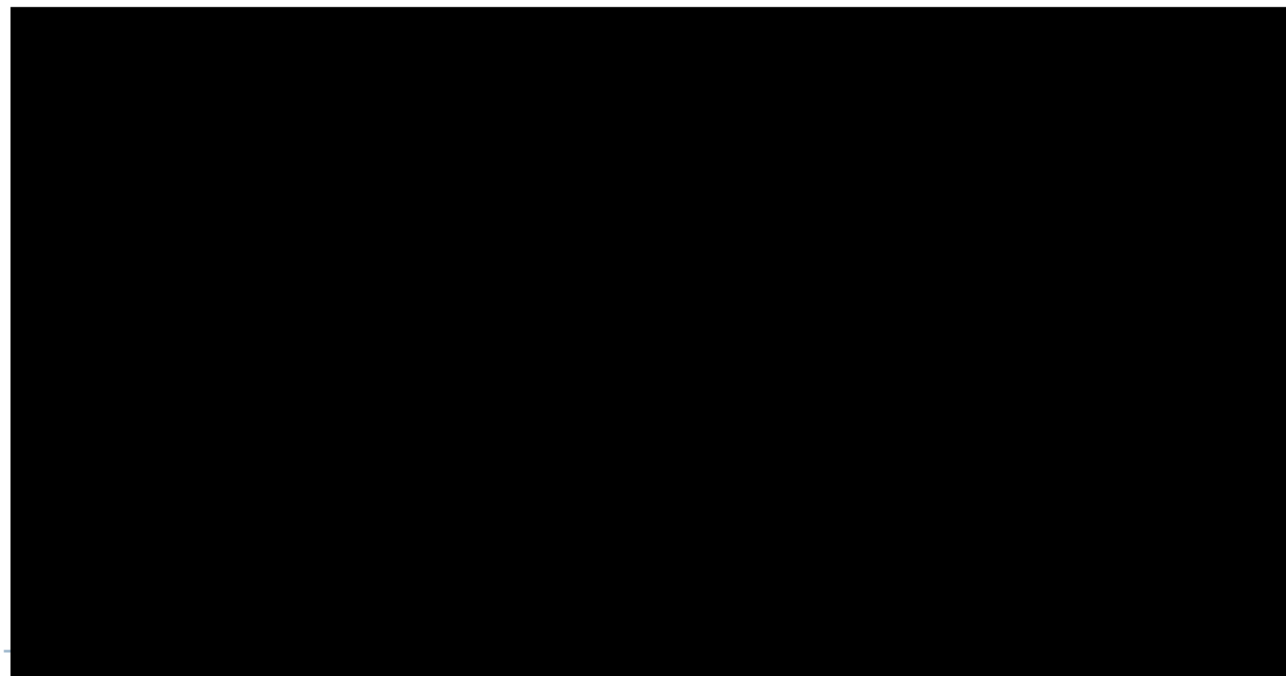
April 24, 2017

Conventional Manufacturing Processes

- Net Shape Processes
  - Forging, drawing, extrusion, rolling
  - Sheet metal forming, bending
  - Die casting, investment casting
  - Injection modeling
- Subtractive Processes
  - Lathing, milling, grinding, drilling,
  - Water jetting, laser cutting, etc.

Challenges for Designers (An Example)

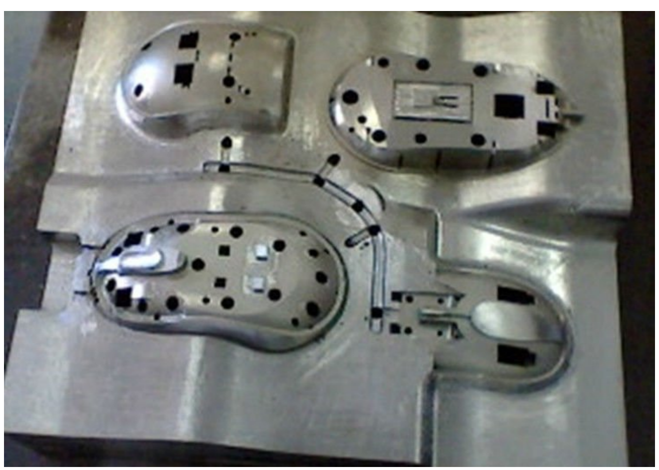


http://www.pyottdesign.com/

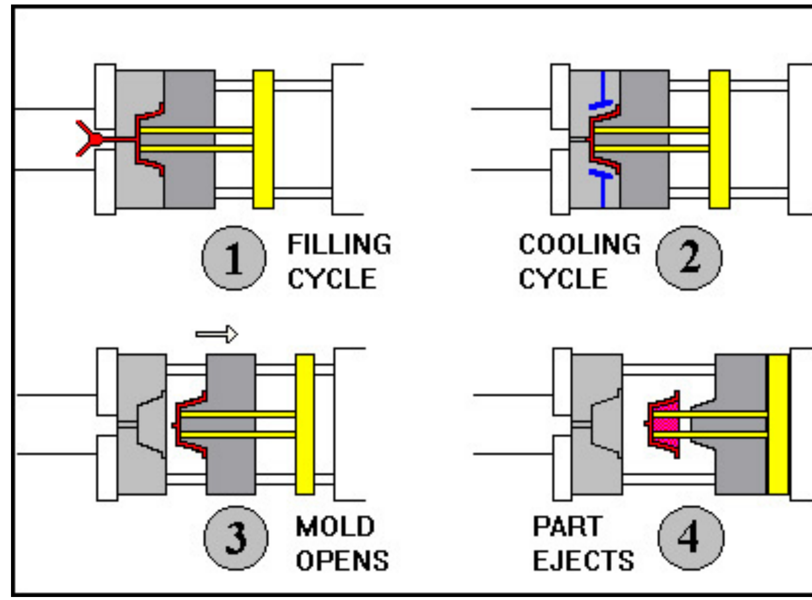
https://en.wikipedia.org/wiki/Apple_Mouse

Challenges for Designers (Cont.)

- Conventional Mouse – produced by Injection Molding
- Problems:
  - Complex shape? No
  - Moldability? Important
  - Flexibility? No
  - Customization? No



http://www.imould.com



http://mold-technology4all.blogspot.nl/

- Process to make a mold
  - Mold design (professional)
  - CNC machining (expensive)

Challenges for Designers

- Design a product
  - Cannot be fabricated
  - Shape limitation
  - Cannot have too many parts
  - Otherwise, having a high cost
- Design for manufacturing [1]
  - Rule 1: Reduce the total number of parts
  - Rule 2: Design for easy-to-fabrication
  - Rule 3: Use of standard components
- Main Problem:
  - Conventional manufacturing lacks of flexibility

[1] *Computer-Aided Manufacturing*, 2nd Ed., T.-C. chang, R.A. Wysk, and H.-P. Wang, Prentice Hall, 1998.

Additive Manufacturing

- Defined by ASTM as:
  - Process of joining materials to make objects from 3D model data, usually layer upon layer
- Six Different Types of AM:
  - Lasers: Stereolithography Apparatus (SLA), Selective Laser Sintering (SLS)
  - Nozzles: Fused Deposition Modeling (FDM)
  - Print-heads: Multi-jet Modeling (MJM), Binder-jet Printing (3DP)
  - Cutters: Laminated Object Modeling (LOM)
- Mainly used for Rapid Prototyping (Past)
- More and More used for 'Mass'-Production (Present)

Benefit of Additive Manufacturing

- Very flexible: direct digital fabrication from CAD models
- Rapid fabrication
- Excellent for customization
- Manufacturing is responsible for 33% of the world's carbon footprint – AM has minimal material waste

Subtractive Machining:

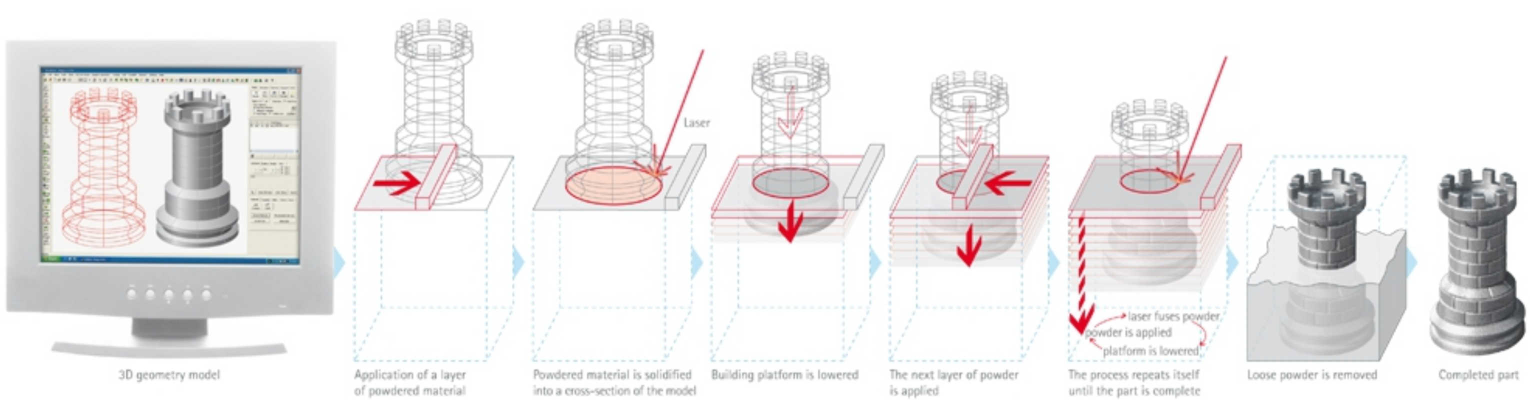
5000 lb. forged billet − 4750 lb. chips = 250 lb. finish machined part

20 : 1
Buy to fly

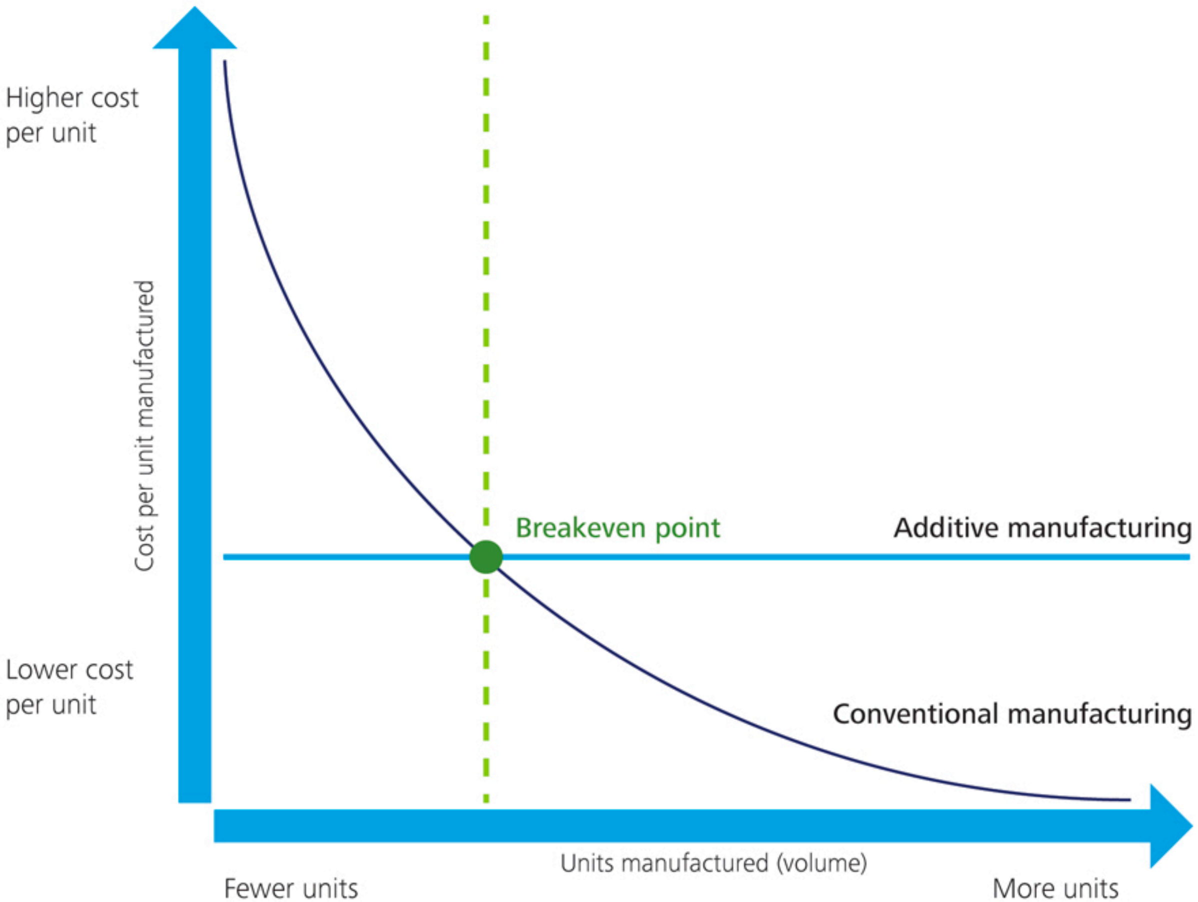
Limitations / Challenges

- Limited part sizes
- Limited fabrication speed
- Limited materials (20k vs. 200 materials)
- Poor surface finish / low accuracy
- Inconsistent part quality
- High cost (machine, material, pre- and post-processing)

General functional principle of laser-sintering



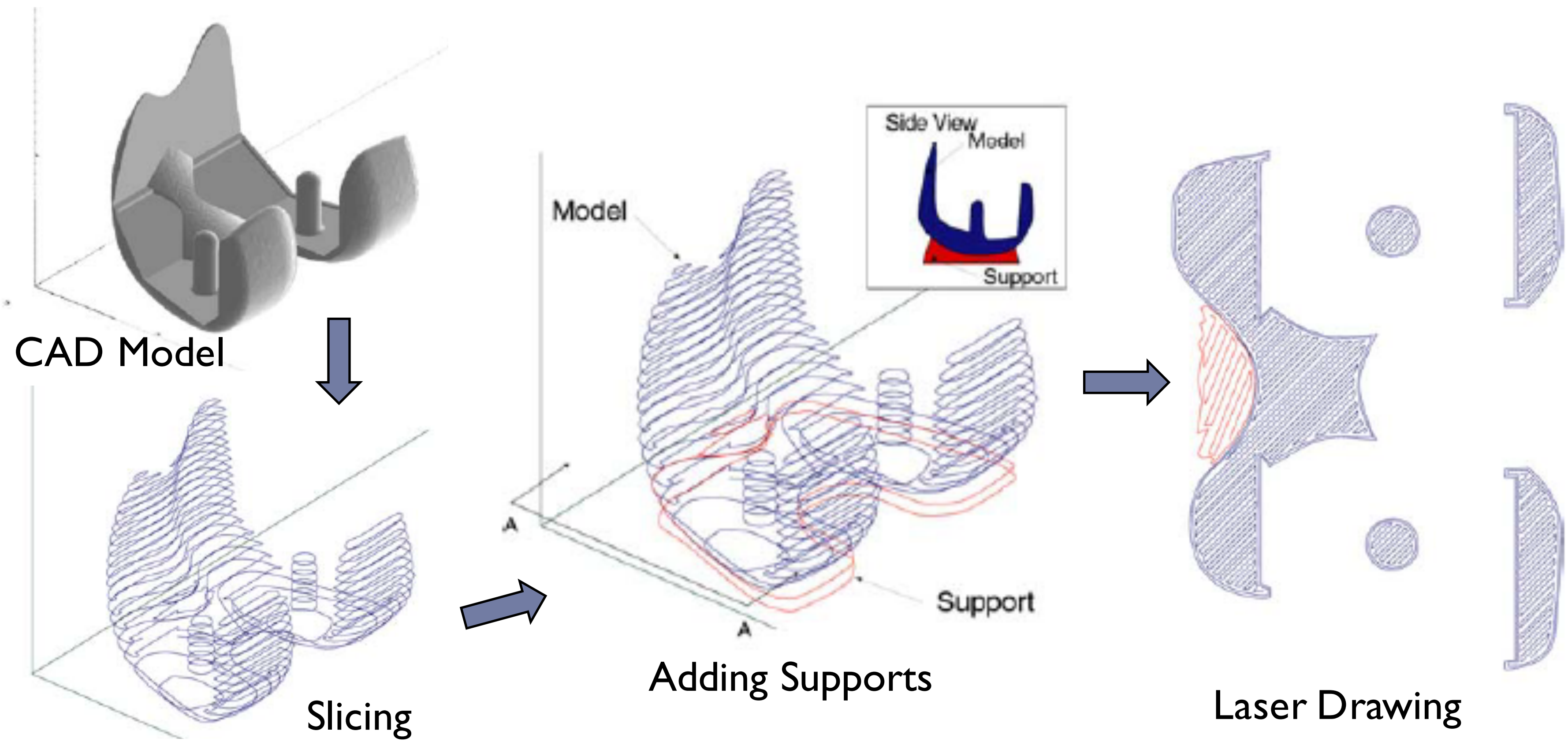
Break-even Analysis of Conventional Manufacturing and 3D Printing



Source: Mark Cotteleer and Jim Joyce, *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*, Deloitte University Press, http://dupress.com/articles/dr14-3d-opportunity/, accessed March 17, 2015.

Graphic: Deloitte University Press | DUPress.com

Main Computation Steps in AM

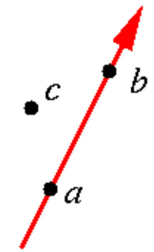


Numerical Robustness

- Computation in IEEE arithmetic
  - Limited precision of floating-point arithmetic
- Geometry becomes inexact after intersection
- Geometric predicates
  - Correct?
  - Self-intersected models?

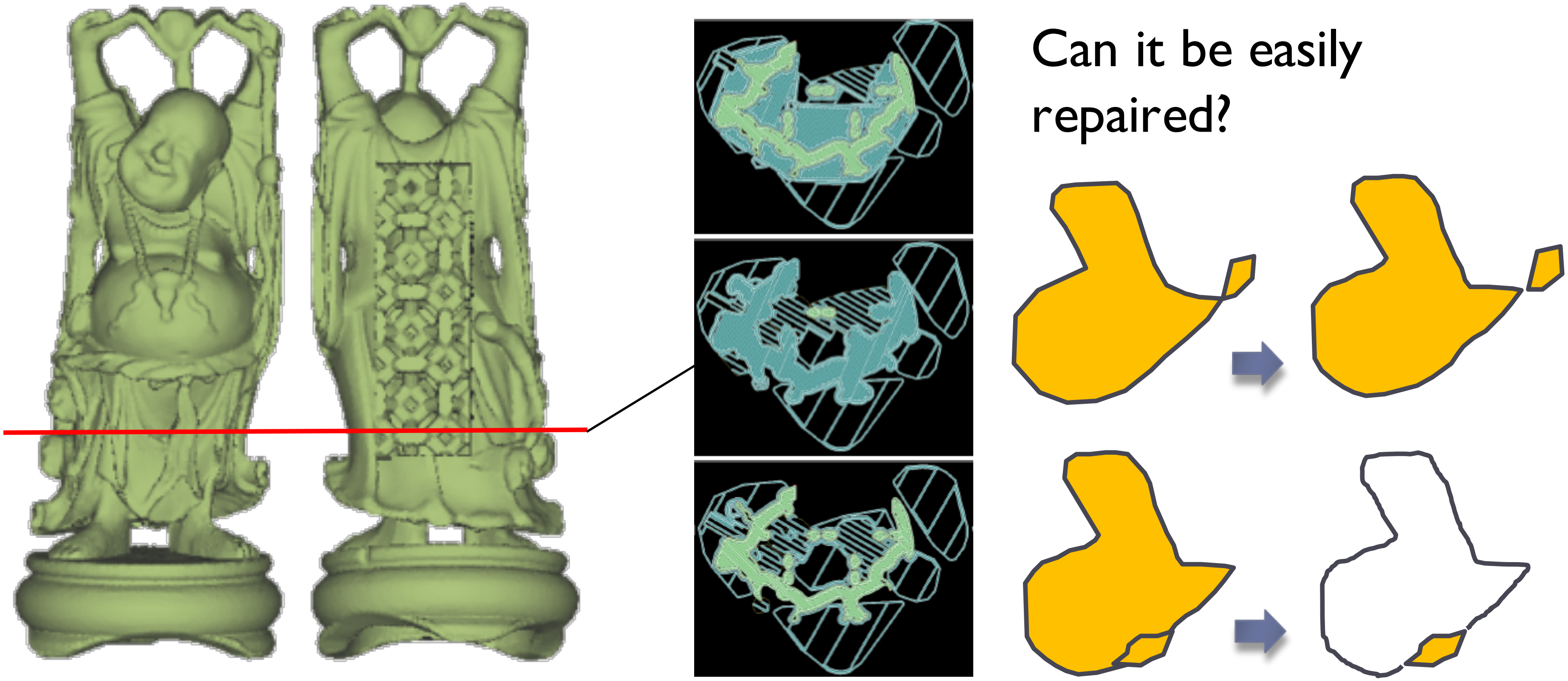
Orientation

Does c lie on, to the left of, or to the right of $\overrightarrow{ab}$?



$$\begin{vmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ c_x & c_y & 1 \end{vmatrix} = \begin{vmatrix} a_x - c_x & a_y - c_y \\ b_x - c_x & b_y - c_y \end{vmatrix}$$

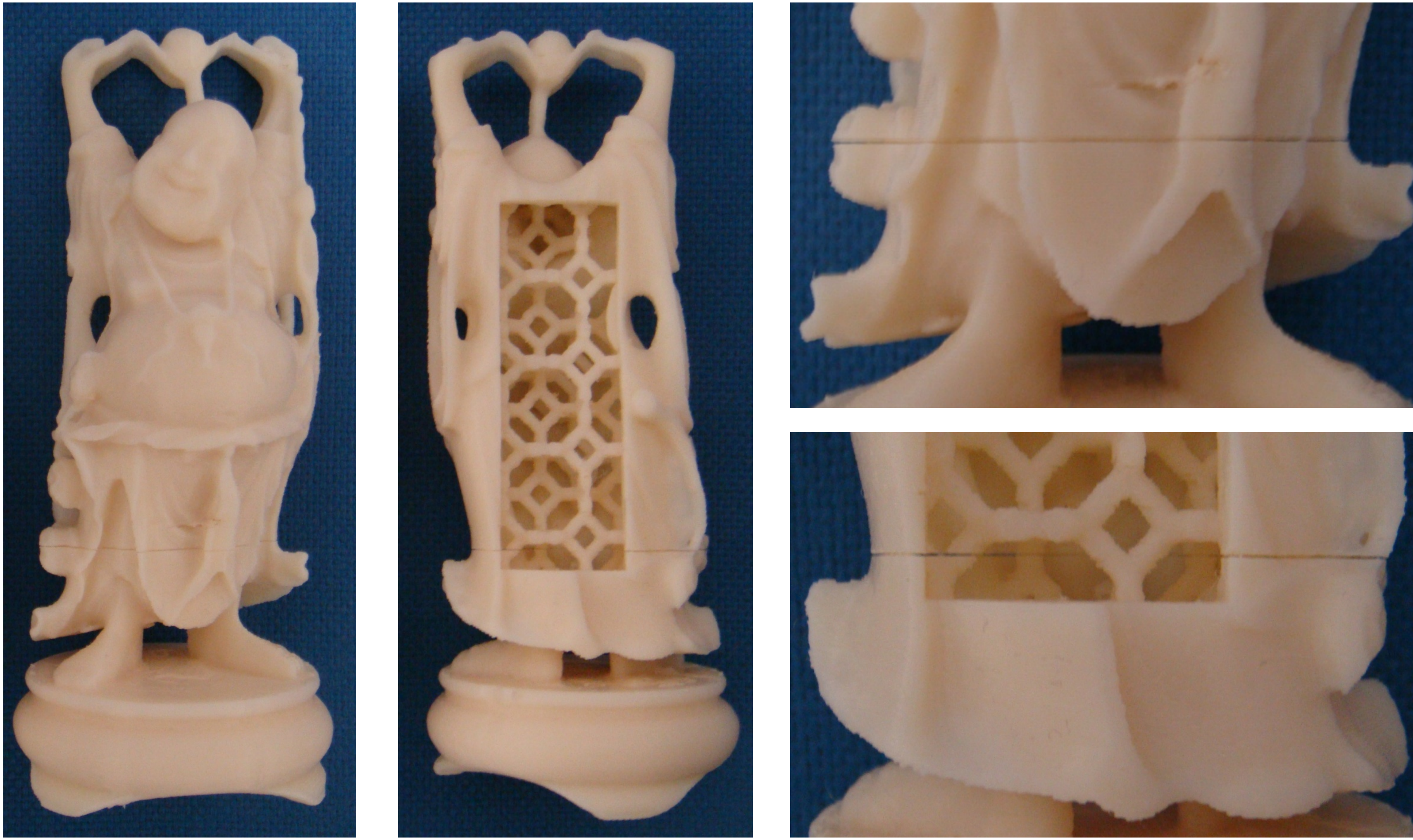
Problem of Inexact B-rep



Can it be easily repaired?

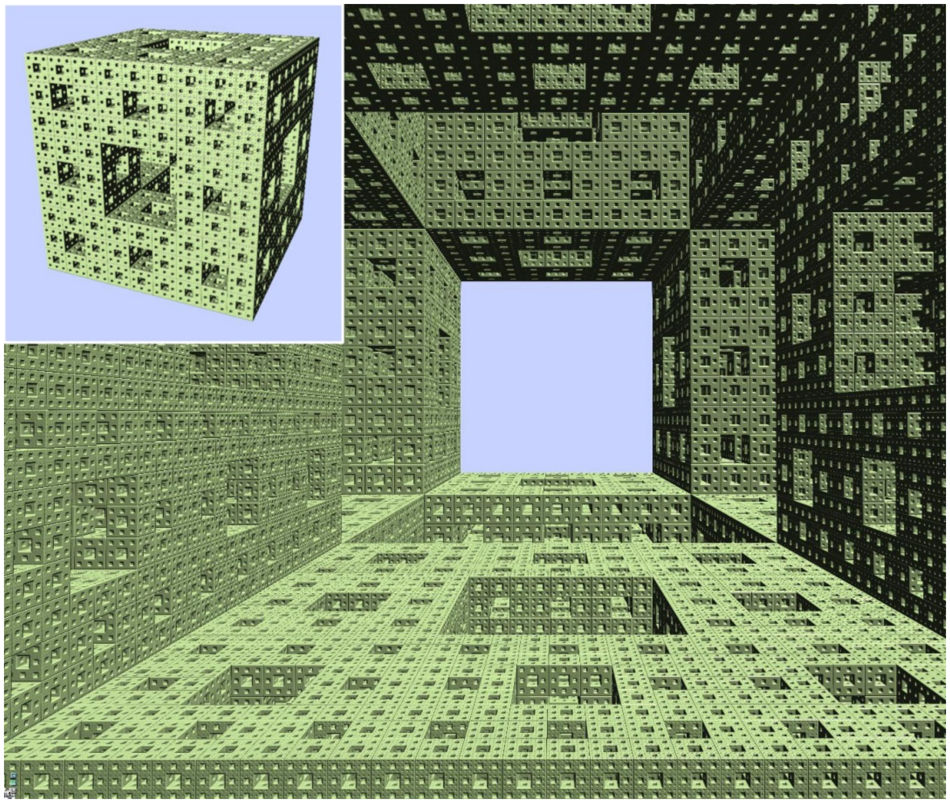
P. Huang, C.C.L. Wang, and Y. Chen, "Intersection-free and topologically faithful slicing of implicit solid", ASME Transactions - Journal of Computing and Information Science in Engineering, vol.13, no.2, 2013.

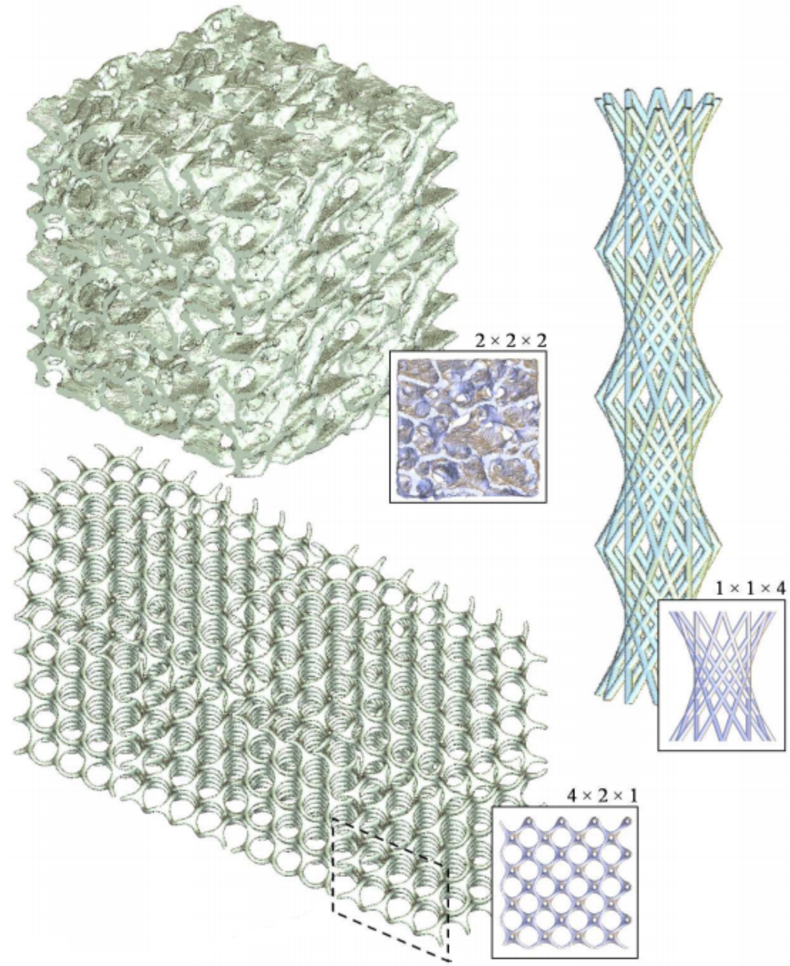
Problem of Inexact B-rep (Cont.)



Robust Computation in Image Space

- Voxel representation



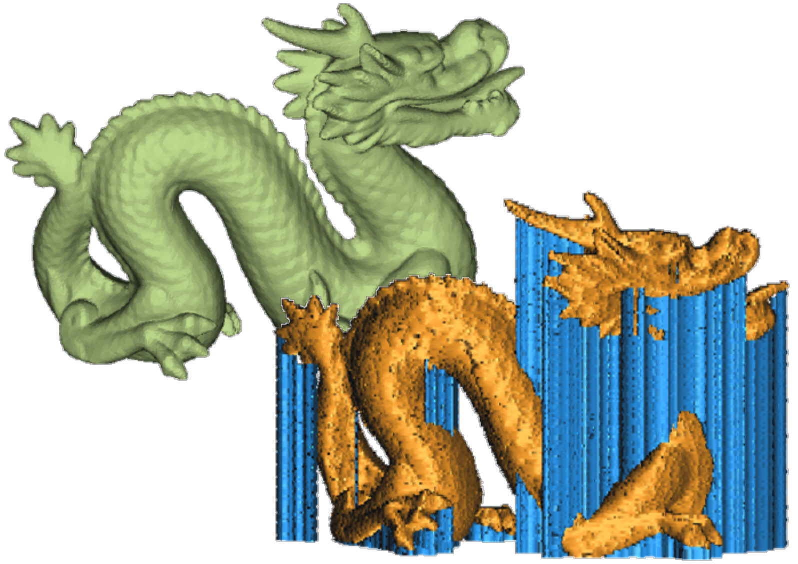


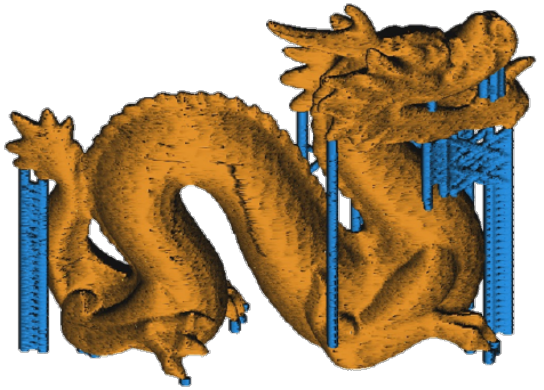
Problem: Memory Cost is extremely high

Yuen-Shan Leung, and Charlie C.L. Wang, "Conservative sampling of solids in image space", IEEE Computer Graphics and Applications, vol.33, no.1, pp.14-25, January/February, 2013.

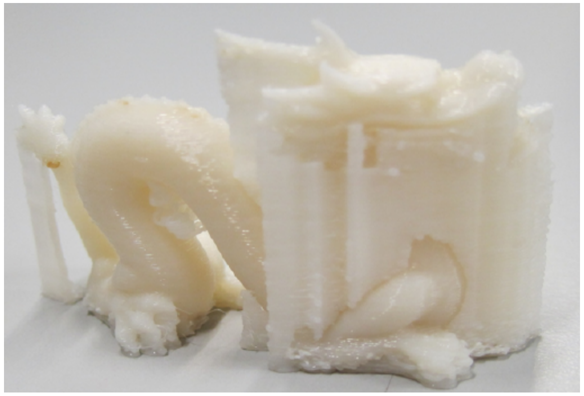
Supporting Structure?

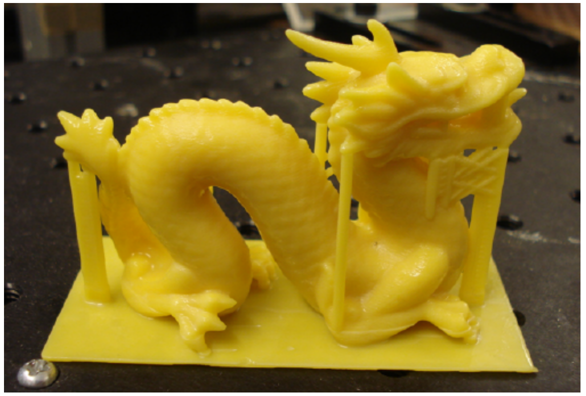
Difference? Why and how?





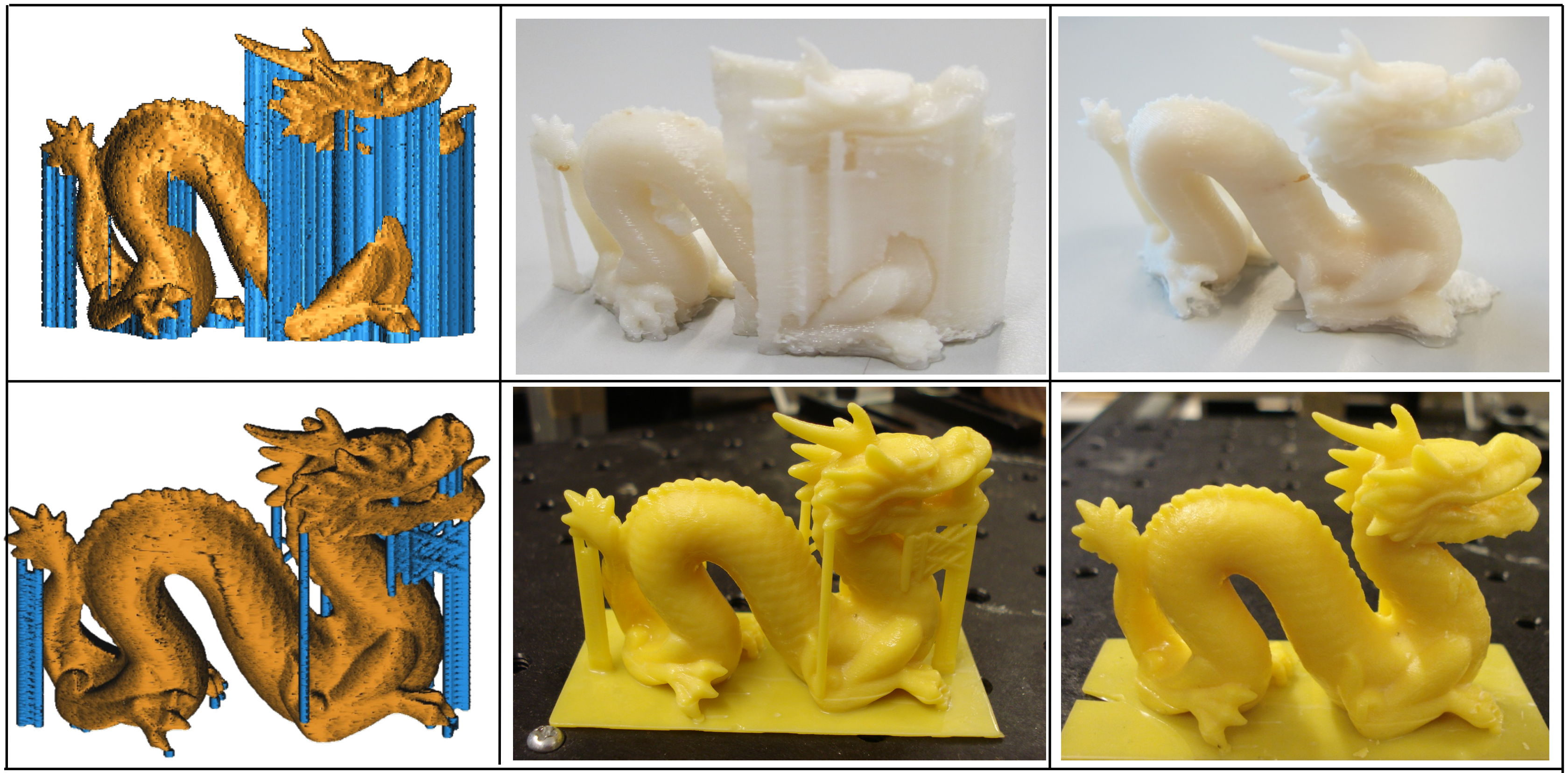
Multi-Materials: Resolvable materials for supporting structure





Single Material: Using structures to support

Support Structure Generation



Direct slicing and support generation resultant contour | Fabricated part with support | Fabricated part after removing support

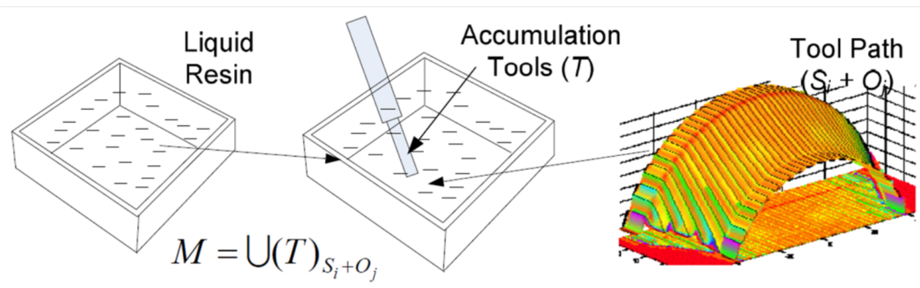
Pu Huang, Charlie C.L. Wang, and Yong Chen, "Algorithms for layered manufacturing in image space", Book Chapter, ASME Advances in Computers and Information in Engineering Research, vol.1, pp.377-410, 2014.

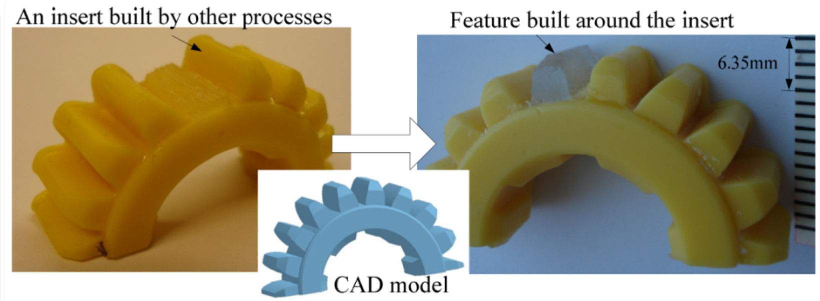
GPU-based Implementation

https://youtu.be/G75mS1VGqx0

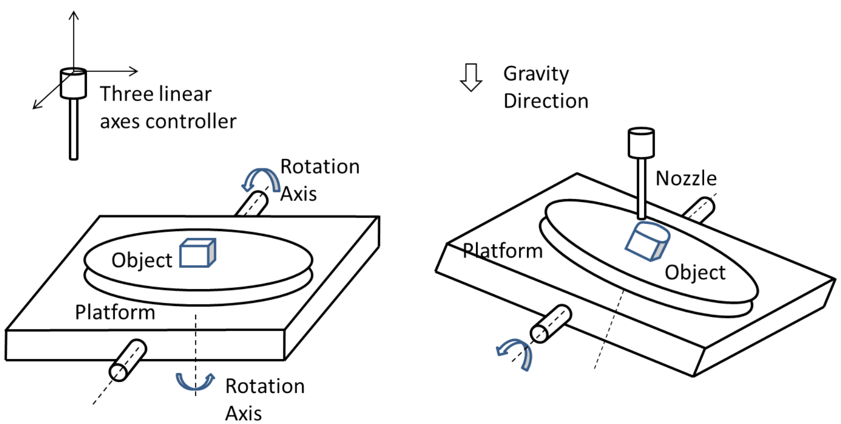
http://ldnibasedsolidmodeling.sourceforge.net/

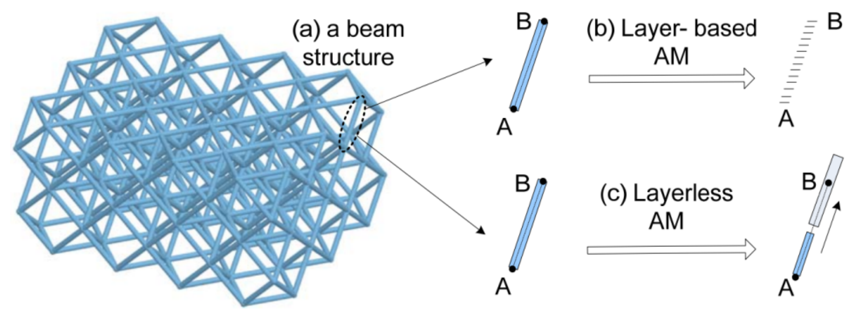
2.5D vs 3D Printing

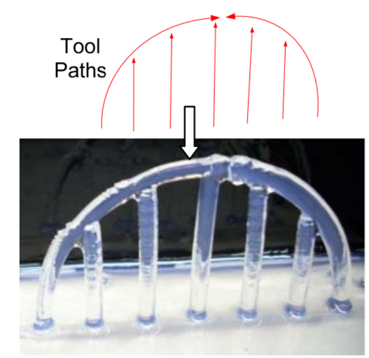




CNC accumulation for build-insert-around







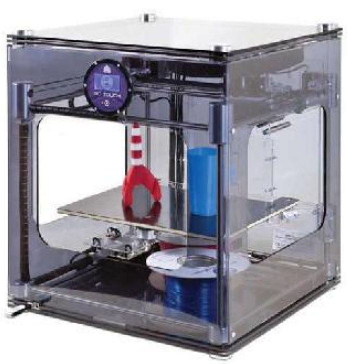
Develop a new non-layered AM

- Fused Deposition Modeling (FDM)
- Multi-axis motion introducing more flexibility

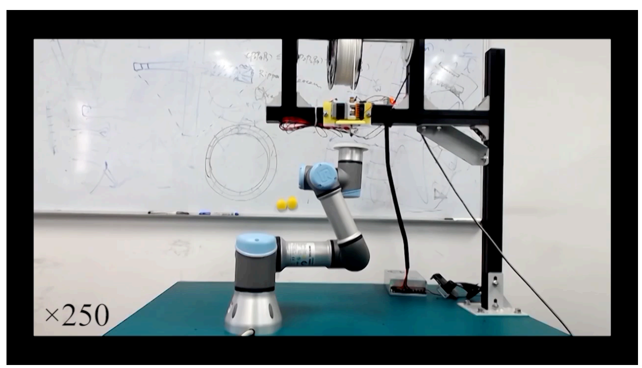
X. Zhao, Y. Pan, C. Zhou, Y. Chen, and C.C.L. Wang, "An integrated CNC accumulation system for automatic building-around-inserts", Journal of Manufacturing Processes, vol.15, no.4, pp.432-443, 2013.

Robot-Assisted Additive Manufacturing

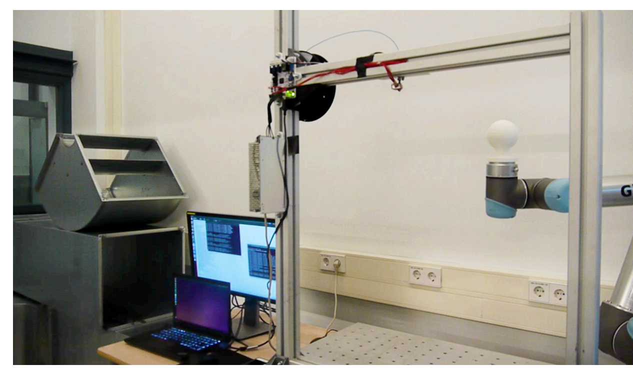
- Using robot arms as device for motion control in AM
- Collaborative operations on two arms – More DoFs to fabricate curved regions / layers
- Challenges:
  - Model decomposition
  - Collision-free tool path generation
  - Configurations in joint-angle space



vs



https://youtu.be/mrR7lKpHo9k



https://youtu.be/5B37oz4cw9s

C. Wu, C. Dai, G. Fang, Y.-J. Liu, and C.C.L. Wang, "RoboFDM: a robotic system for support-free fabrication using FDM", IEEE International Conference on Robotics and Automation (ICRA 2017).

From 3D to 4D Printing

- 3D Printed Self-Assembly Structures
- How to predict the shape of fabricated model?
- Pattern Design / Process Optimization / New Triggers

https://youtu.be/vQB49vNFu14

T.-H. Kwok, C.C.L. Wang, D. Deng, Y. Zhang, and Y. Chen, "Four-dimensional printing for freeform surfaces: design optimization of Origami and Kirigami structures", ASME Journal of Mechanical Design, 2015.

Summary Remarks

- Conventional Manufacturing vs. Additive Manufacturing
- Reduce the challenges for designers
- Slicing and support generation
- Numerical robustness
- Multi-axis 3D printing
- Robot-assisted 3D printing
- 3D printed self-assembly structures (4D printing)

Thanks for Your Questions

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