Computational Fabrication:

From Design Automation to New Manufacturing

Charlie C. L. Wang (王昌凌)

Dept. of Mechanical and Auto. Eng., Chinese University of Hong Kong

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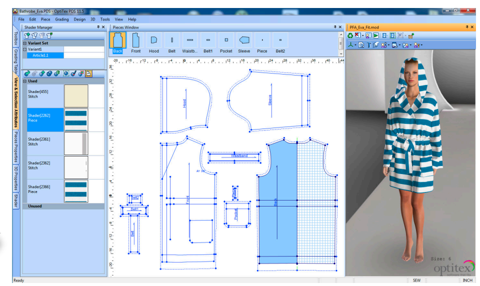
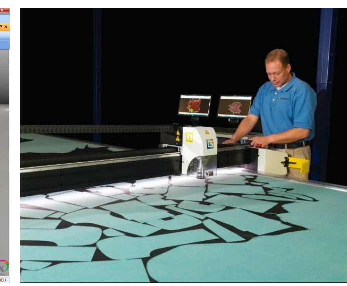
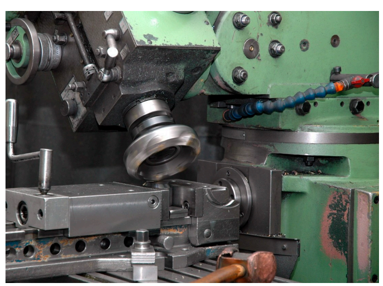
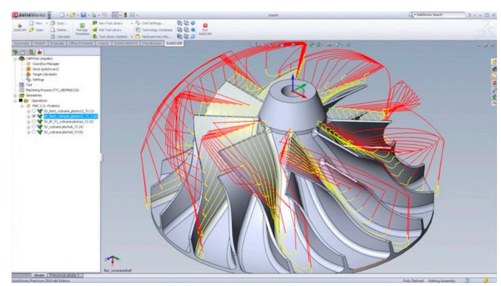
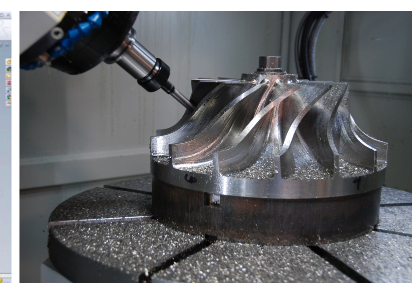
Computational Design & Manufacturing

- History can be traced back to 1970s
  - How to advance conventional production?
  - Make it better, faster and more economical
  - Revolution of conventional industrial by Digitization
  - How about future?



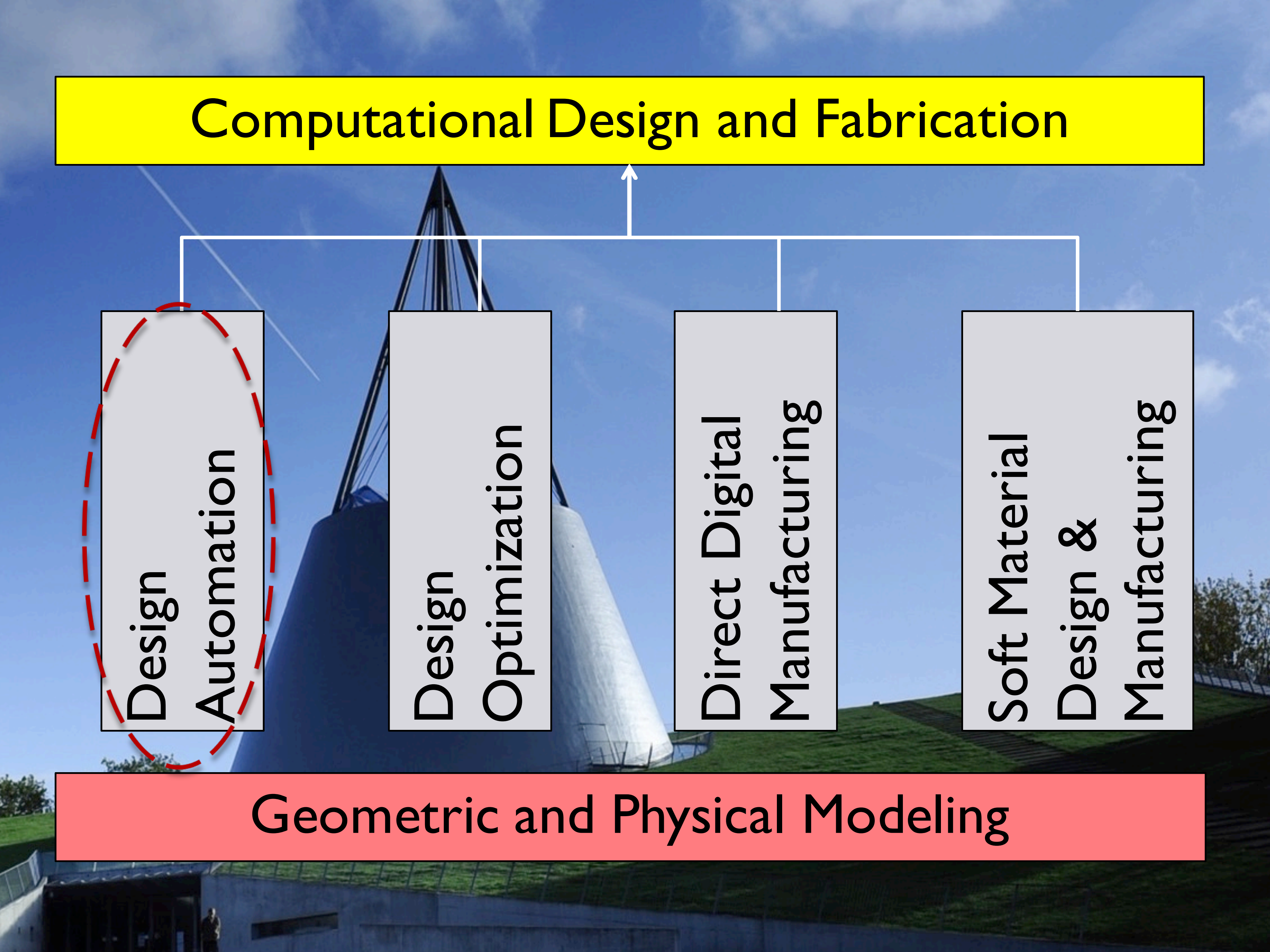




Computational Design and Fabrication

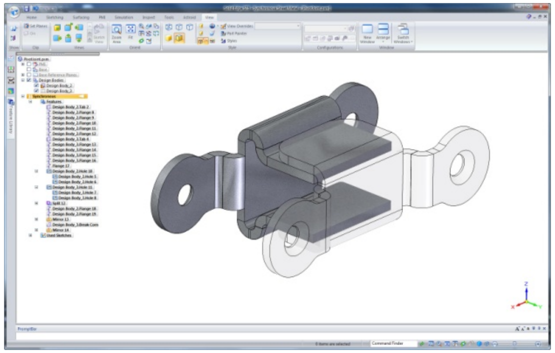
CAD ≠ **C**omputer-**A**ided **D**rafting

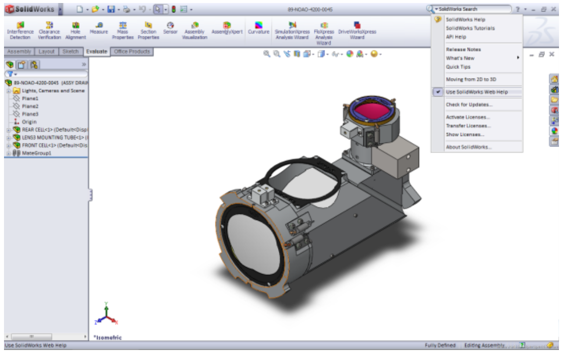
CAD ≠ **C**omputer-**A**ided **D**ocumentation

- **Demand:** tools completely integrated into the process of design practice
  - Automatic design process (Design Automation)
  - Design better products (Design Optimization)
  - Called Generative Design in Industry (e.g., Autodesk)
- **Our vision** in **A**dvanced **D**esign and **M**anufacturing
  - Making the design process more automatic, intelligent and systematic
  - Solving manufacturing problems at the design phase
- **Our focus:** inventing advanced computational tools to face the grand challenges of design and manufacturing


Computational Design and Fabrication
Design Automation
Design Optimization
Direct Digital Manufacturing
Soft Material Design & Manufacturing
Geometric and Physical Modeling

Design Automation: Ultra Personalized Products Driven by Body Shape

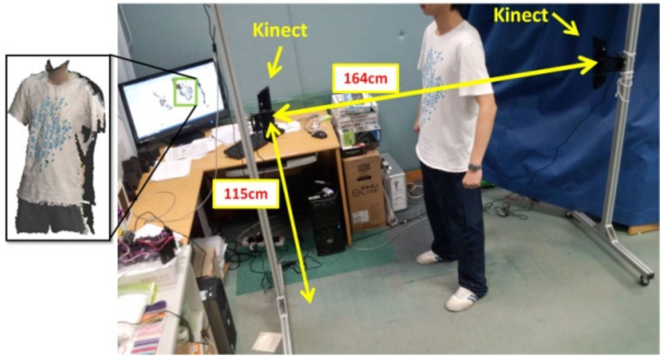


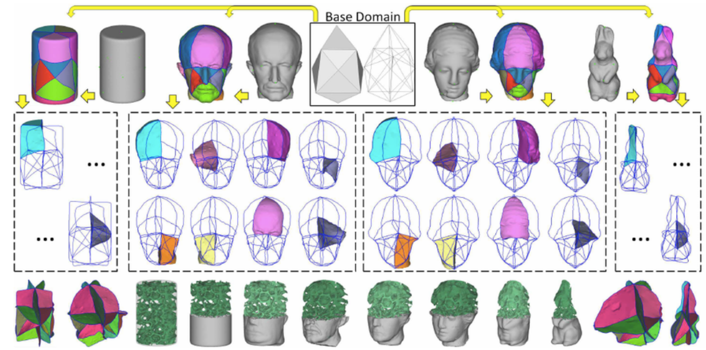


- Design automation in commercial CAD/CAM systems (parametric design)
  - Developed for products with regular shape
  - Usually driven by dimensional parameters
- Technology has been developed for overcoming these challenges – shape drive design automation
  - Consistent modeling of digital human bodies
  - Encoding/decoding the spatial relationship between human body and product
  - Geometric optimization for fabrication

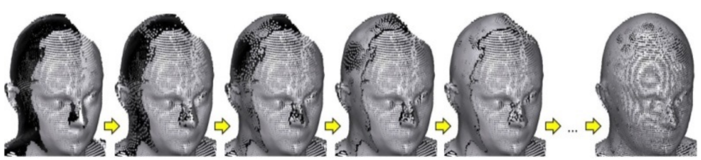
Exoskeleton as a future product: freeform geometry and conformal to the shape of human body

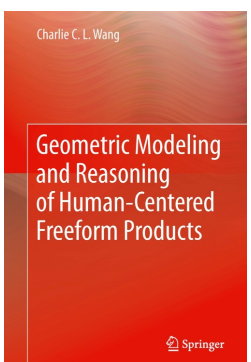
Design Automation: Consistent Modeling of Digital Human Bodies

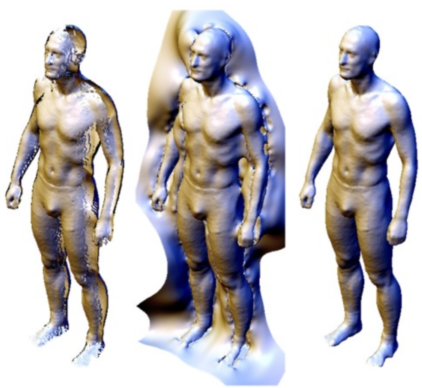


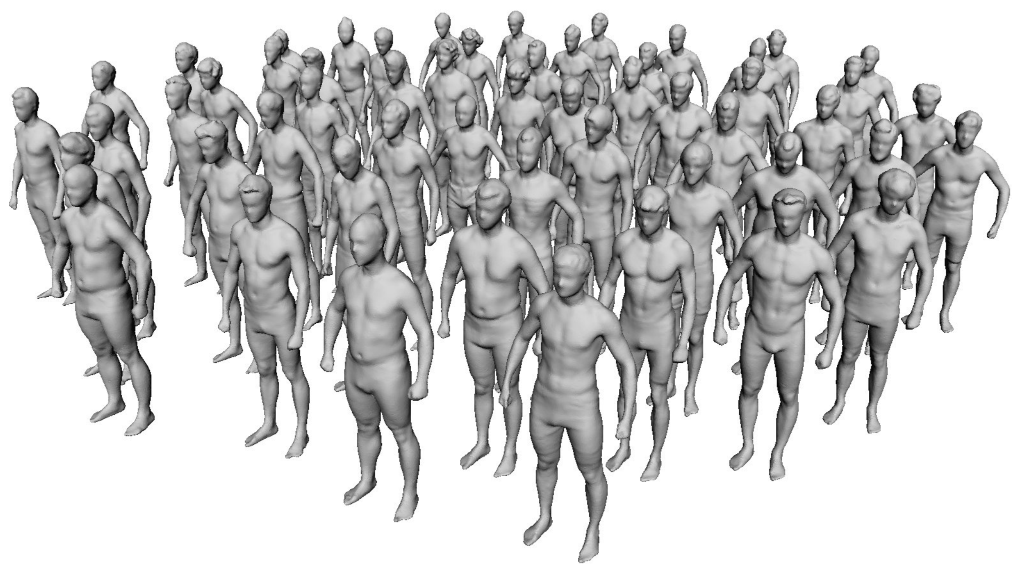


Scanning ⇨ Completion ⇨ Surface Reconstruction ⇨ Cross-Parameterization

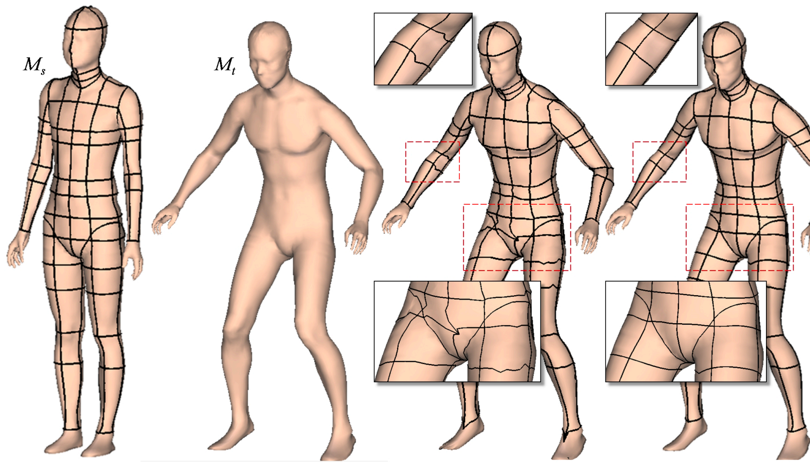


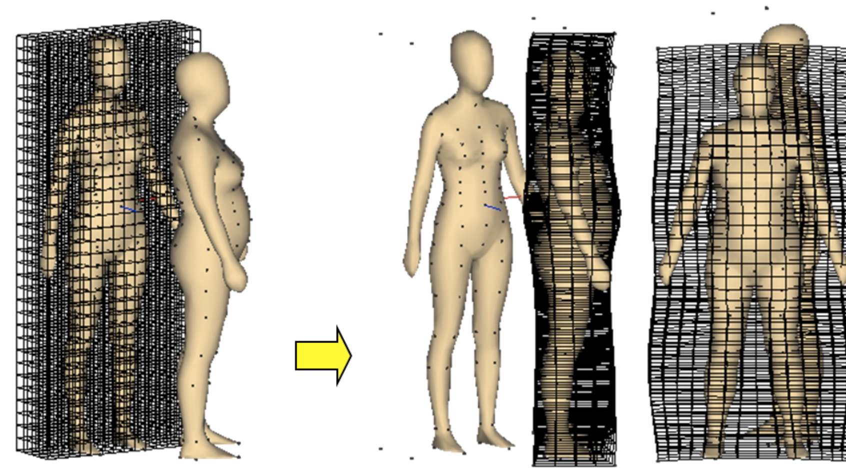


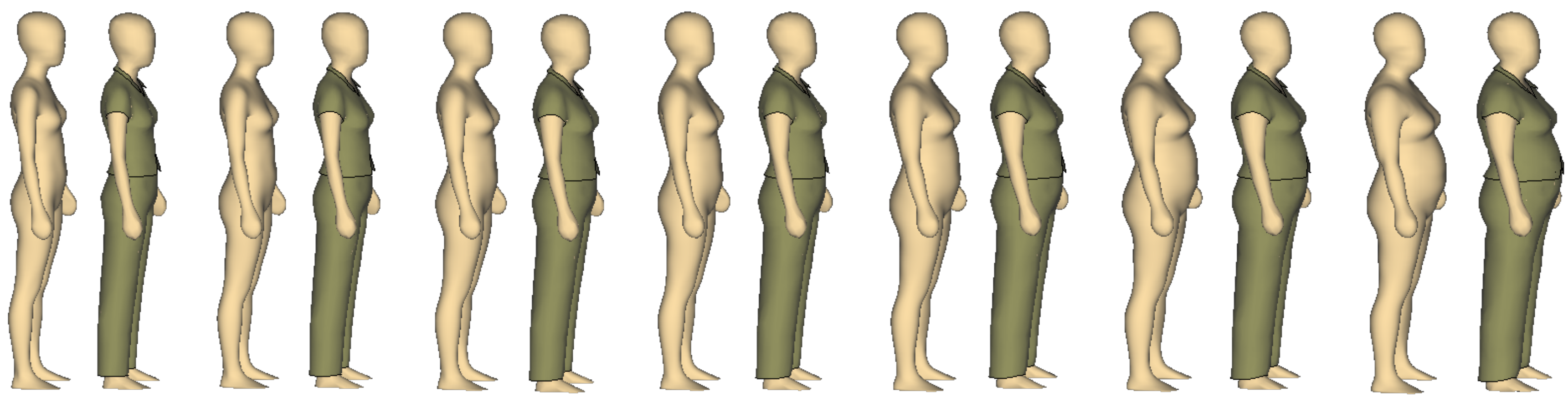




Design Automation: Design Transfer for Wearable Products







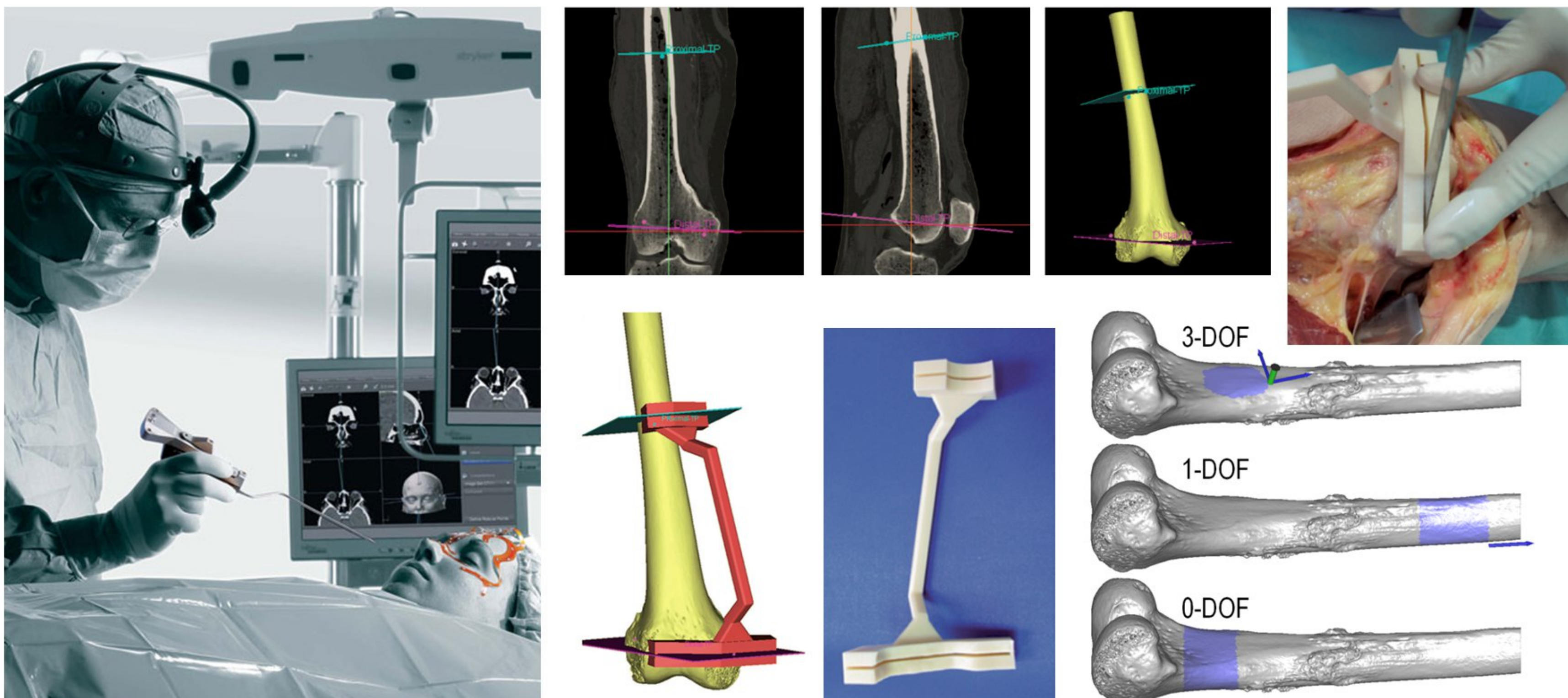
Charlie C.L. Wang, K.-C. Hui, and K.M. Tong, "Volume parameterization for design automation of customized free-form products", *IEEE Transactions on Automation Science and Engineering*, 2007.

Design Automation for Personalized Wearable Products

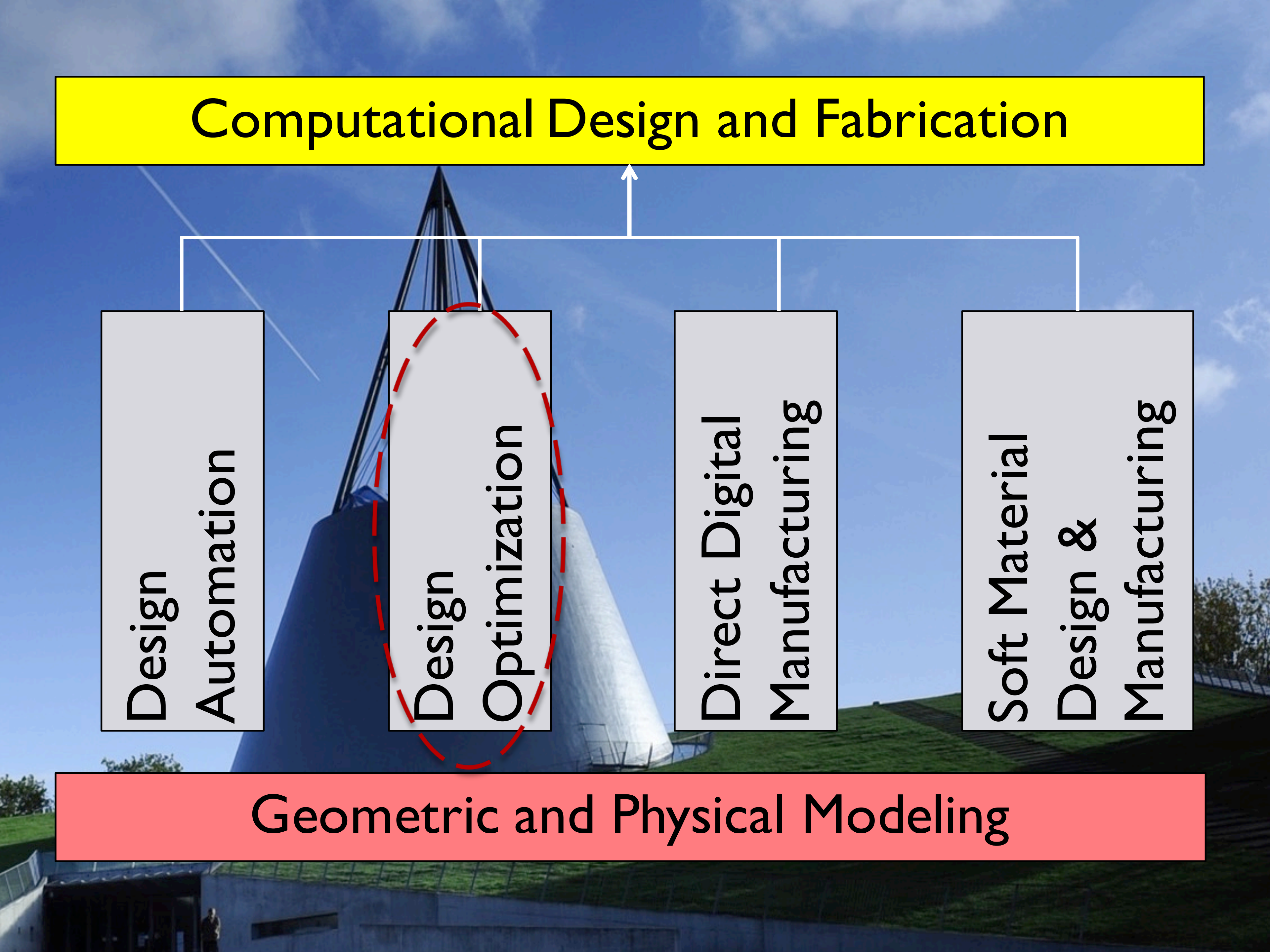
 C.C.L. Wang, Y. Zhang, and H. Sheung, "From designing products to fabricating them from planar materials", IEEE Computer Graphics and Applications, 2010.

Design Automation: Searching for 'Best'-Fit is General for All Wearable Instruments

- Computing unique footprint to align the image / patient coordinate systems – **P**atient **S**pecific **I**nstruments (PSI)
- Preoperatively planned resection path can be precisely realized



Collaborating with Orthopaedics Departments of CUHK & Leiden University Medical Center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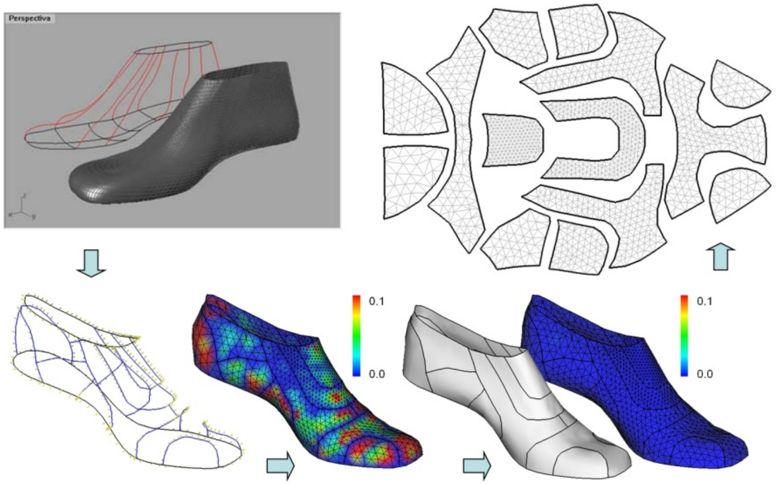
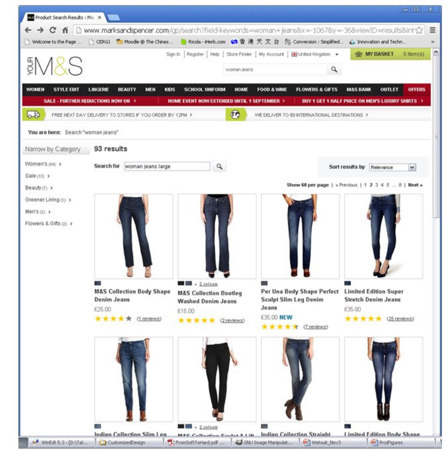
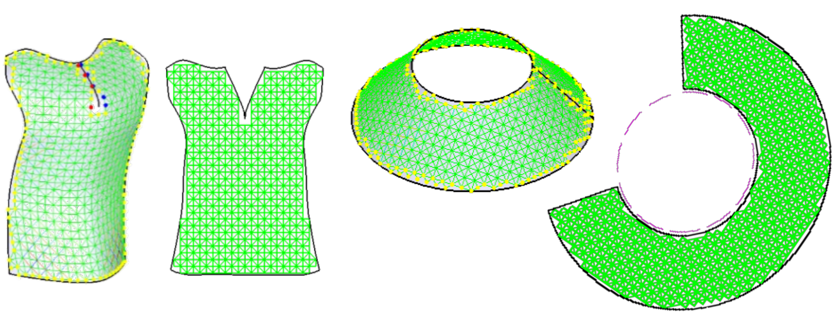
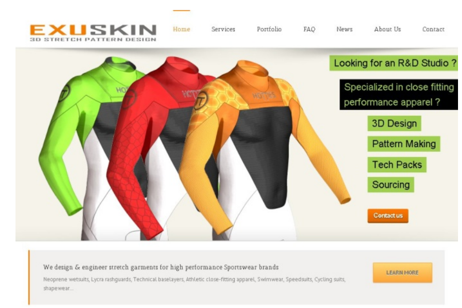
Design Optimization for Manufacturing (i): Flattening Solution for Planar Materials

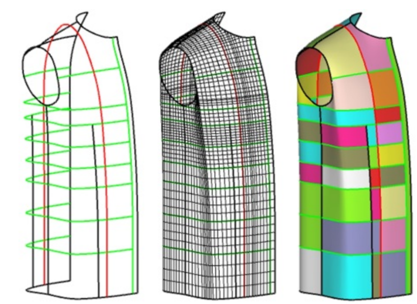


WireWarping++









- Charlie C.L. Wang, "Methods for Flattening a 3D Surface into a 2D Piece", U.S. Patent 8,411,090, April 2, 2013.
- Yunbo Zhang, and Charlie C.L. Wang, "WireWarping++: Robust and flexible surface flattening with length control", *IEEE Transactions on Automation Science and Engineering*, vol.8, no.1, pp.205-215, 2011.
- Charlie C.L. Wang, "Towards flattenable mesh surfaces", *Computer-Aided Design*, vol.40, no.1, pp.109-122, 2008.

Design Optimization for Manufacturing (ii): Flattening Solution for Glass Production


Figure 77: Mould of variation 2


Figure 78: Result of variation 2


Figure 79: Mould of variation 3


Figure 80: Result of variation 3


Figure 81: Mould of variation 4


Figure 82: Result of variation 4


Figure 83: Mould of variation 5


Figure 84: Result of variation 5


Figure 85: Mould of variation 6


Figure 86: Result of variation 6


Figure 87: 'Mould' of variation 7

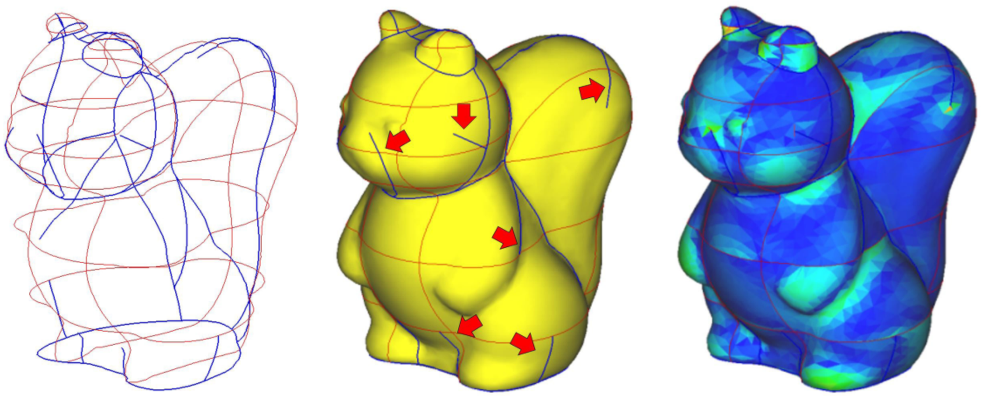
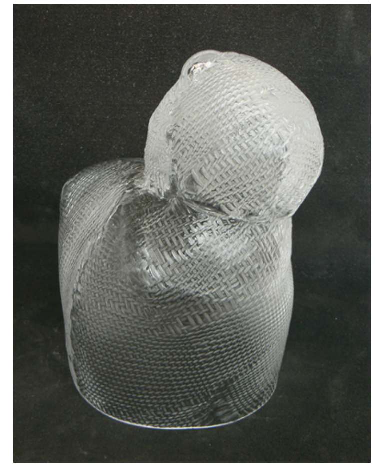
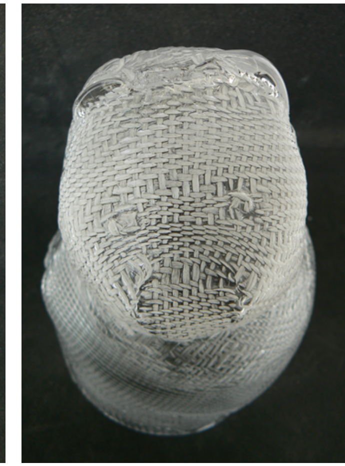
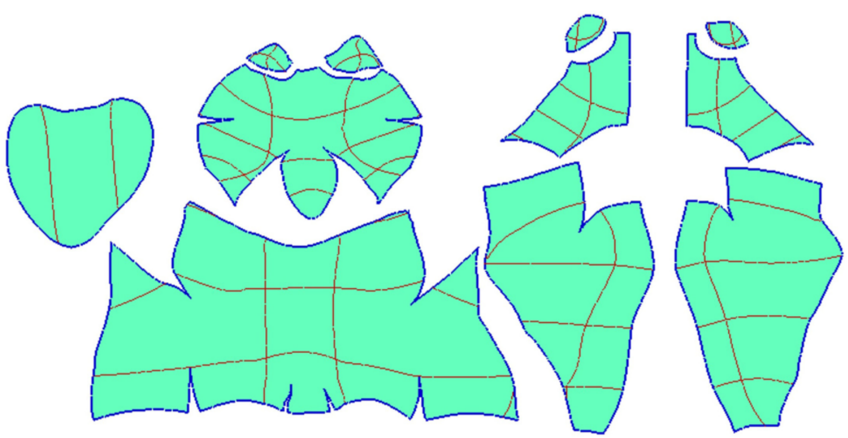

Figure 88: Result of variation 7

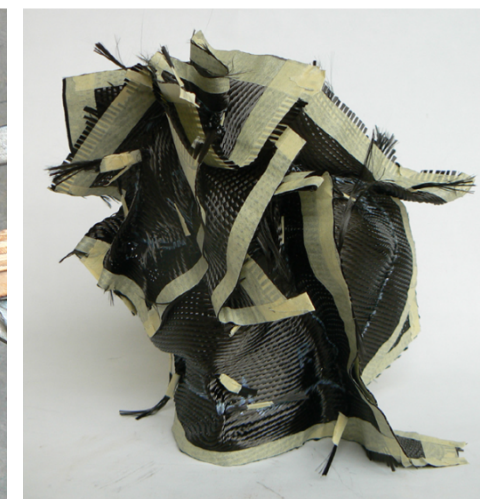
Design Optimization for Manufacturing (ii): Flattening Solution for Glass Production

Design Optimization for Manufacturing (ii): Flattening Solution for Glass Production

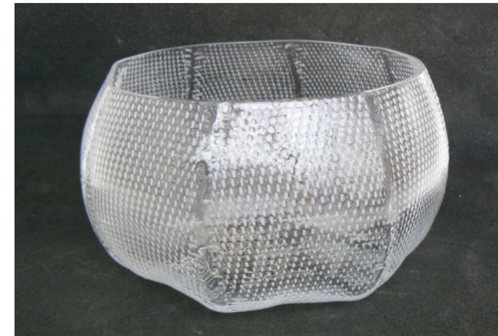
Design Optimization for Manufacturing (ii): Flattening Solution for Glass Production

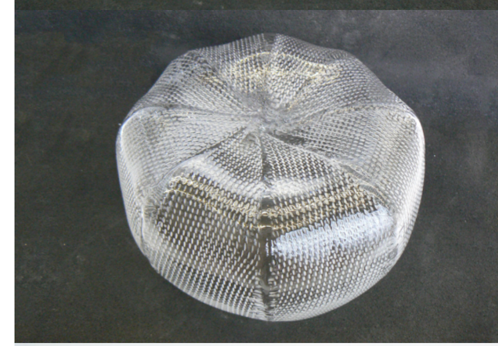
- Molding by carbon fibers



Design Optimization for Manufacturing (ii): Flattening Solution for Glass Production



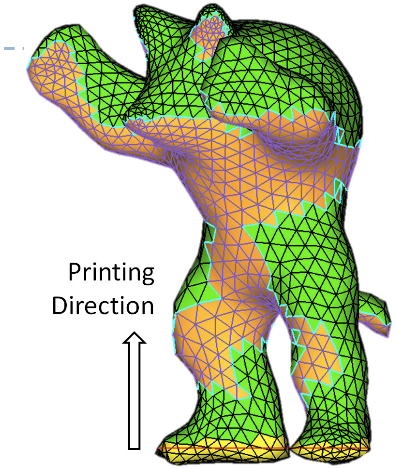


3D Printing is NOT Completely Flexible

- Definition by ASTM for Additive Manufacturing (AM)
  - Process of joining materials to make objects from 3D model data, usually layer upon layer
- Good choice for personalized products
- Overhangs – collapse during fabrication
- Supporting structures – hard to remove

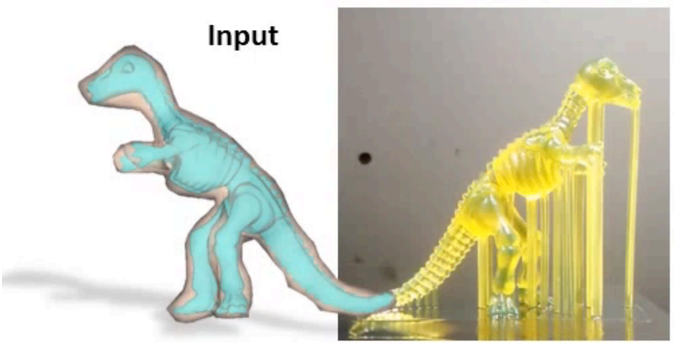


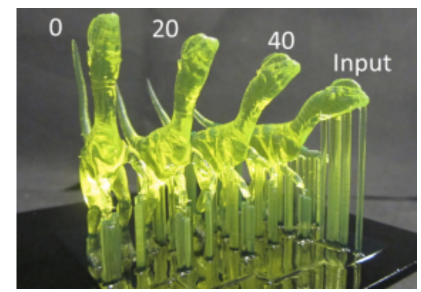
Design Optimization for Manufacturing (iii): Deformation to Reduce Overhang



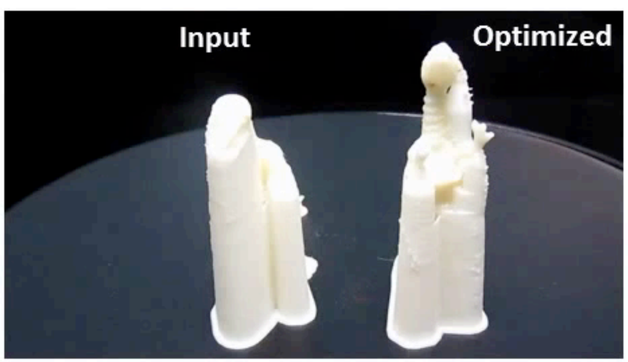
Reduce the usage of support by deformation

Dino

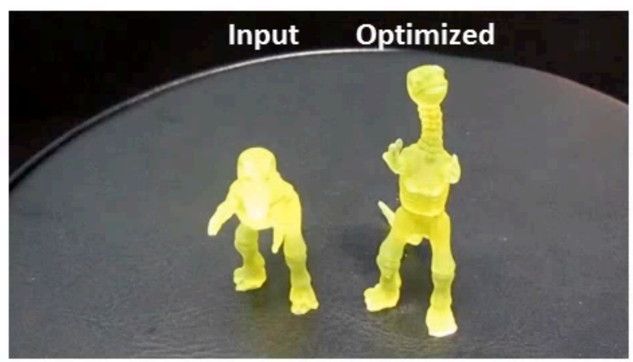


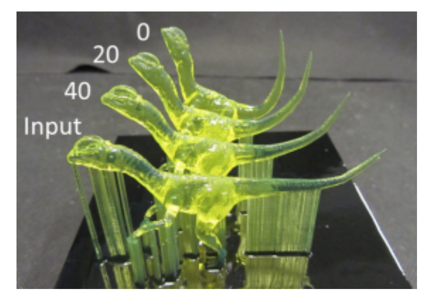


Fabricated by FDM



Fabricated by MIP-SLA

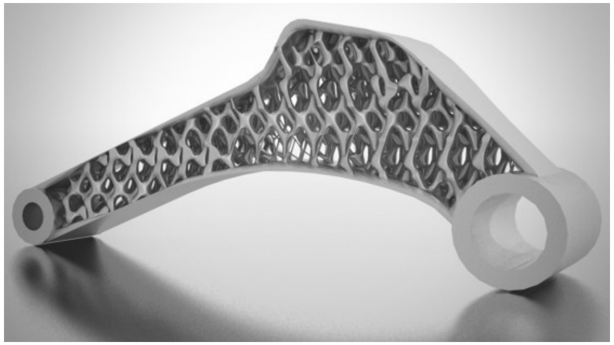




Kailun Hu, Shuo Jin, and Charlie C.L. Wang, "Support slimming for single material based additive manufacturing", Computer-Aided Design, vol.65, June 2015.

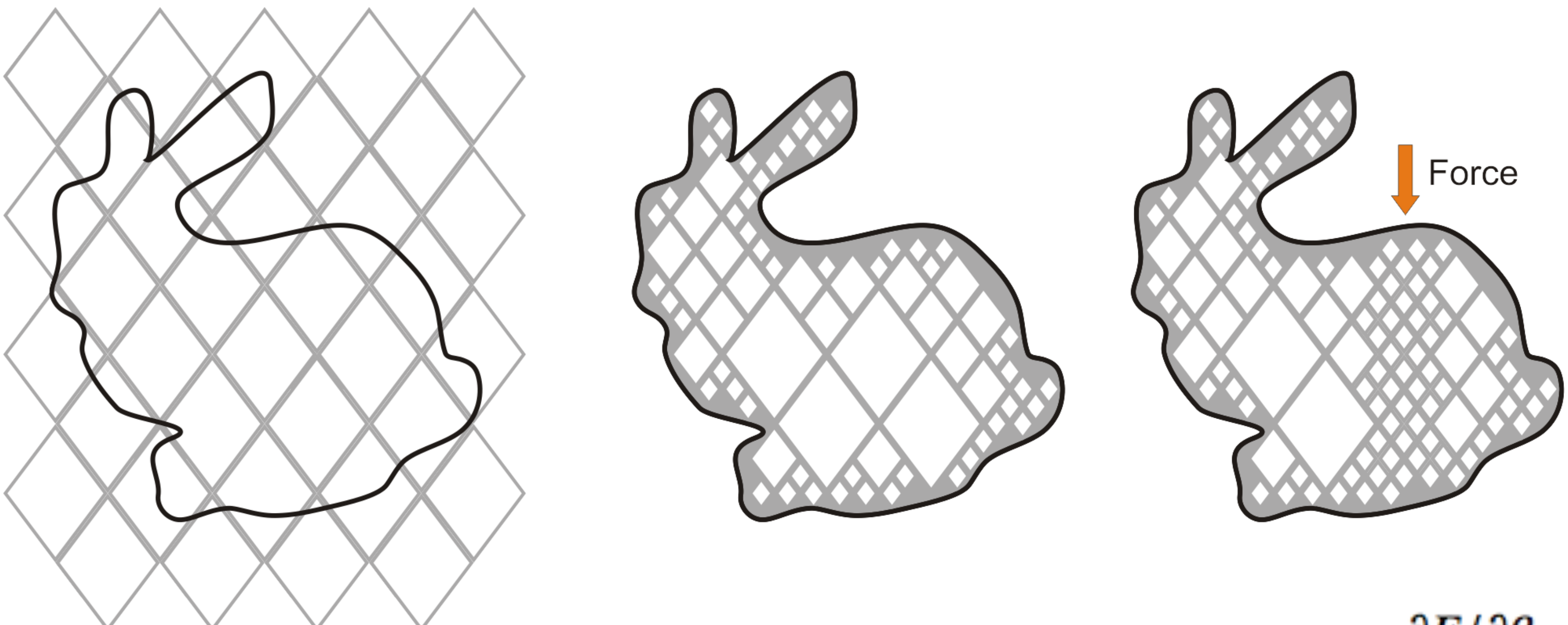
Fabrication-Aware Design Optimization: Infill Optimization for Mechanical Strength

- A lot of recent work in topology optimization



- Problem: Manufacturability? Especially for infill
- **Our solution:** by restricting topology optimization to generate structures in a manufacturability-ensured space
  - Use of grid refinement and grid-to-cell operators to efficiently perform the optimization
  - Manufacturable structure ensured by rhombic structures
  - Optimization of mechanical stiffness effectively and efficiently

Fabrication-Aware Design Optimization: Infill Optimization for Mechanical Strength



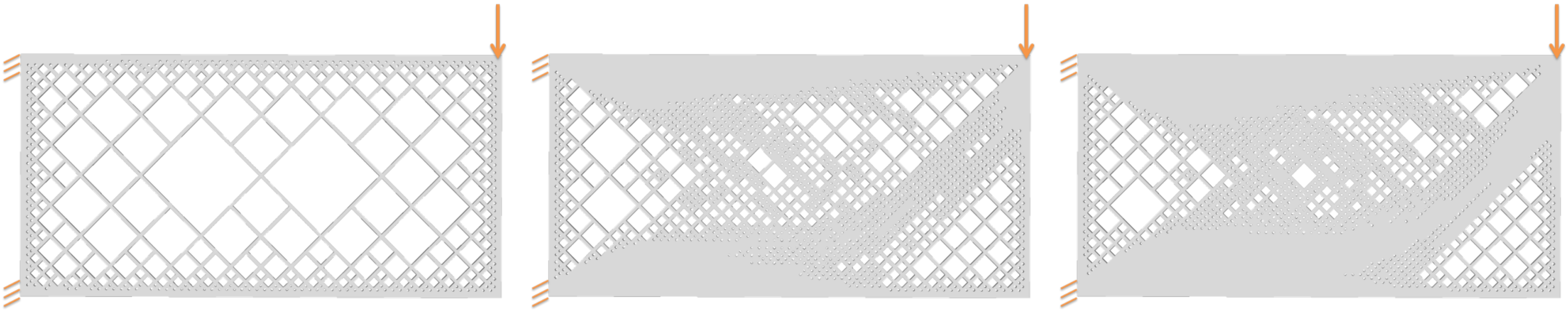
- An iterative process by sensitivity analysis:

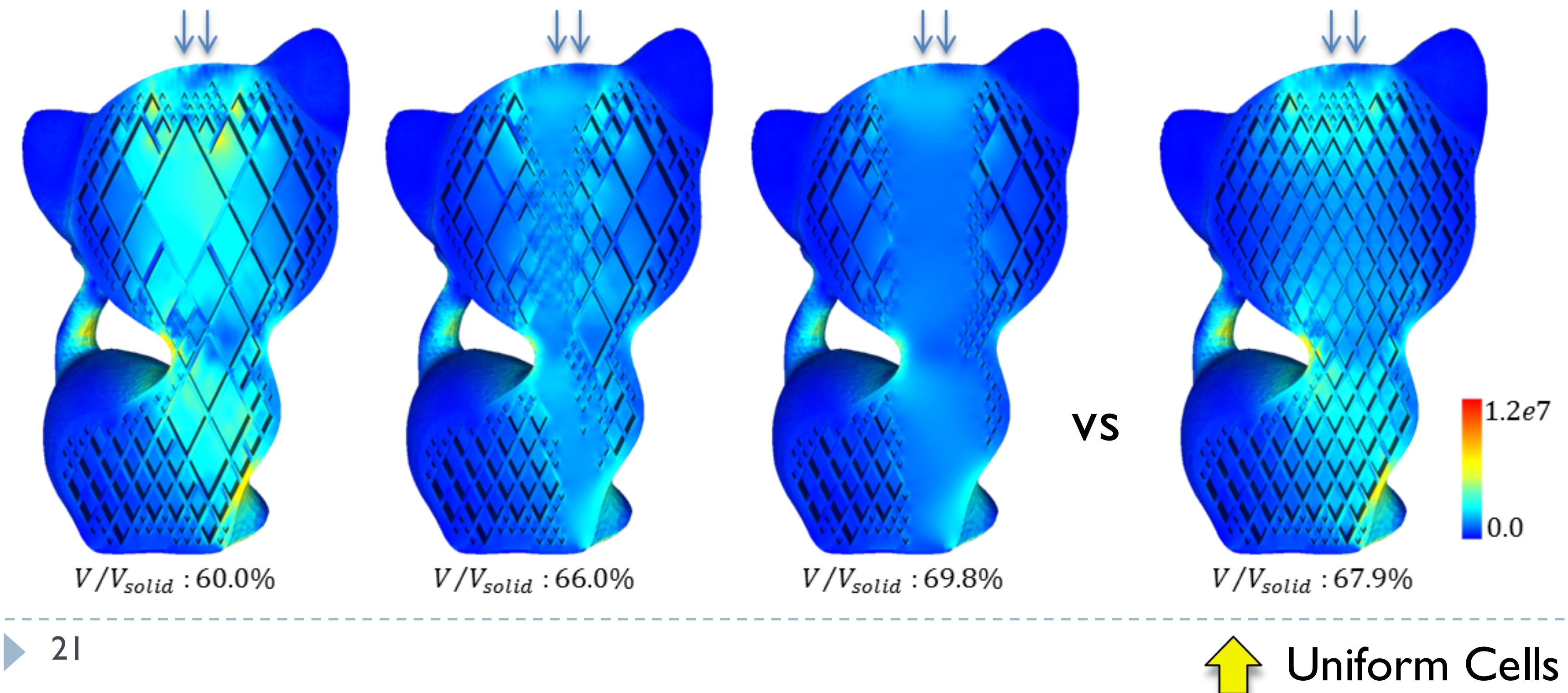
$$G_c = \frac{-\partial E / \partial \beta_c}{\partial V / \partial \beta_c}$$

1. Finite Element Analysis of elasticity
2. Evaluate the sensitivity
3. Update the rhombic structure by subdividing selected cells

Top 2% with high sensitivity

Fabrication-Aware Design Optimization: Infill Optimization for Mechanical Strength

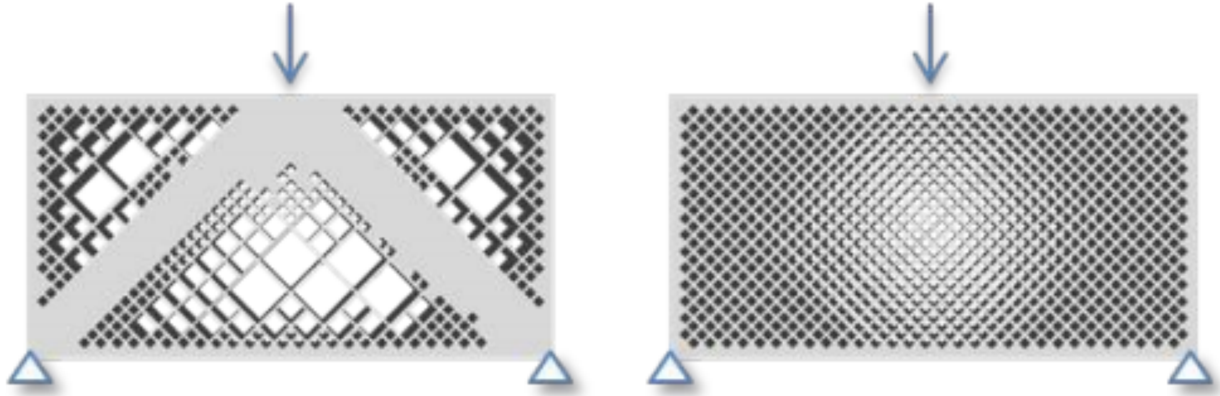


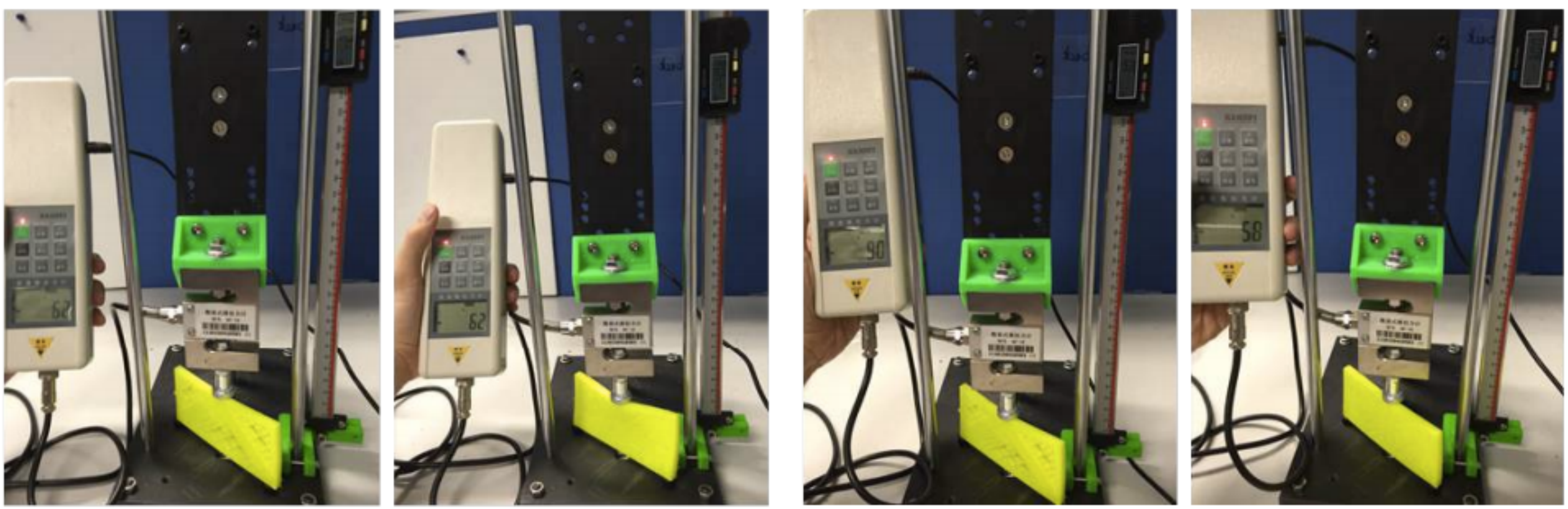


Fabrication-Aware Design Optimization: Infill Optimization for Mechanical Strength

- Physical Tests

(for comparison)



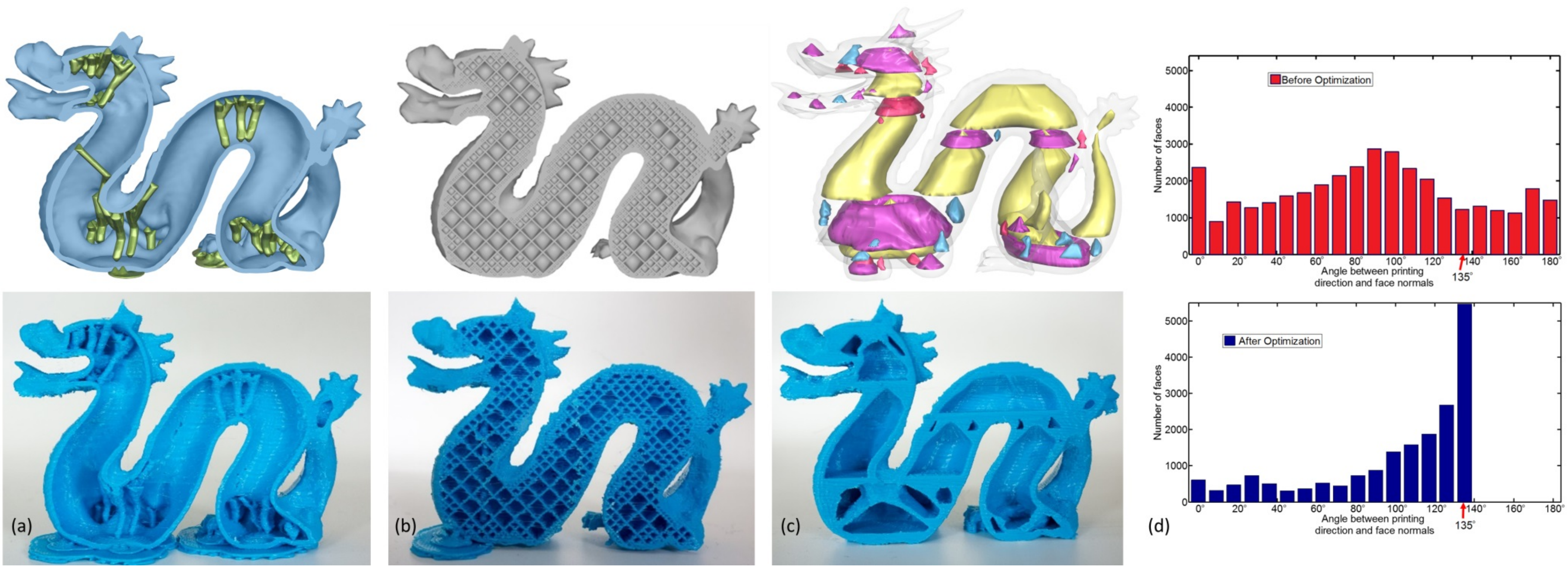


Applying the same loading (2.11 vs 4.08mm) Under the same displacement (3mm)

Jun Wu, Charlie C.L. Wang, Xiaoting Zhang, and Rudiger Westermann, "Self-supporting infill optimization on rhombic cells", *Computer-Aided Design*, 2016.

Fabrication-Aware Design Optimization (ii): Support-Free Hollowing

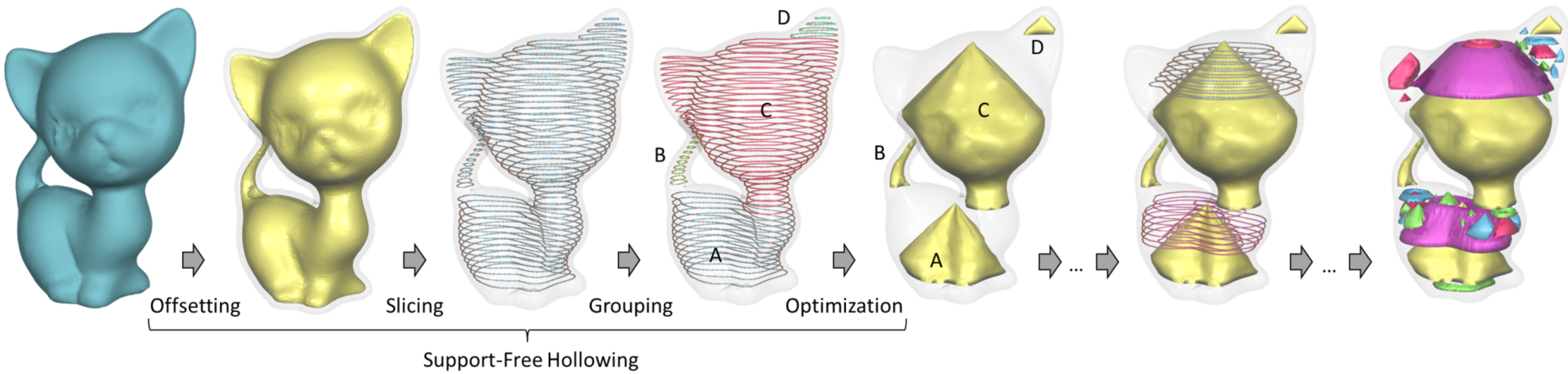
- To further enhance the sparsity of infill structures
  - Support-free hollowing operator based on layered formulation
  - A repetitive hollowing strategy to enlarge the solution space
  - Intrinsic solution for physics optimization



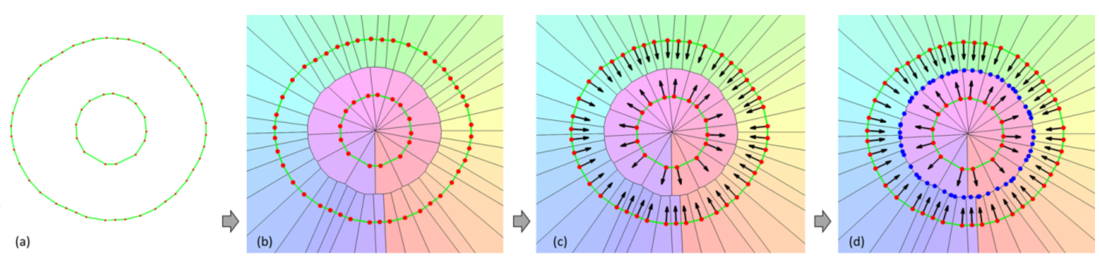
Reduce 38.0% Weight

Reduce 69.9% Weight

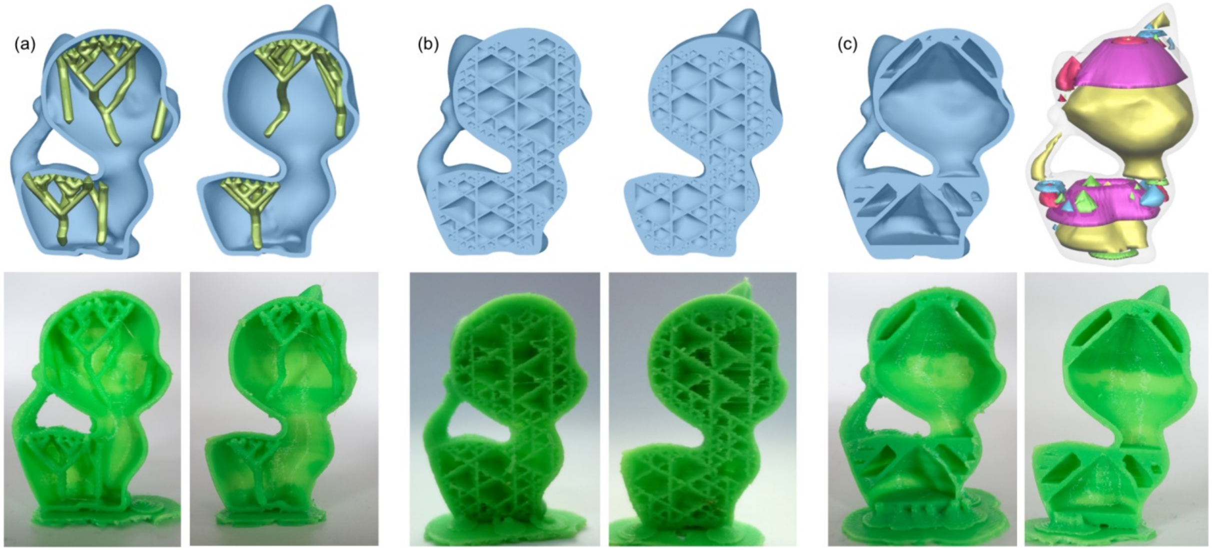
Fabrication-Aware Design Optimization (ii): Support-Free Hollowing



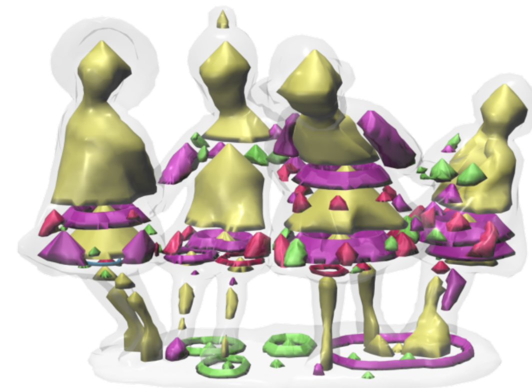
- Pipeline of iterative computation:
  - Generate uniform offset surface as initial shape
  - Slicing offset and cluster cross-sections into groups according to topology variation
  - Planar Voronoi-Diagram governed collision-free optimization
  - Repeat above steps

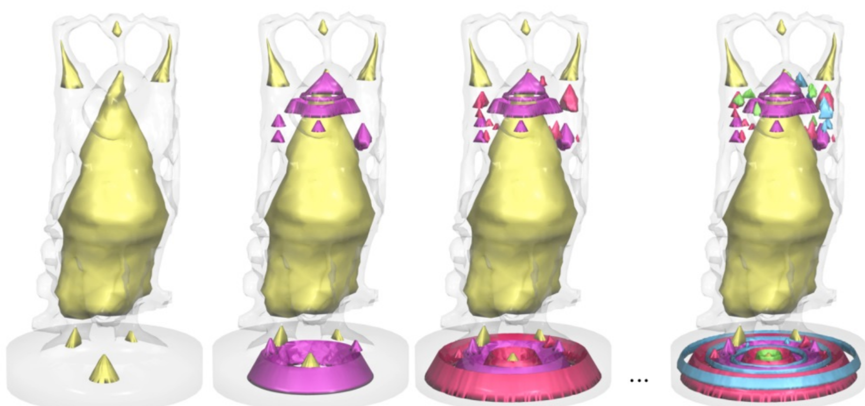


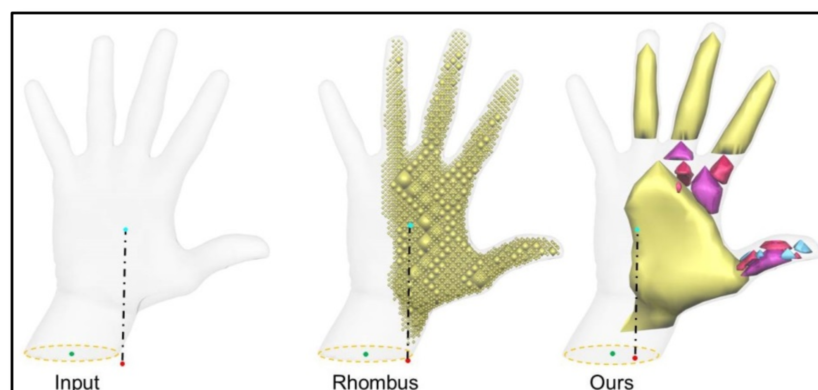
Fabrication-Aware Design Optimization (ii): Support-Free Hollowing



Reduce 45.5% Weight Reduce 75.3% Weight

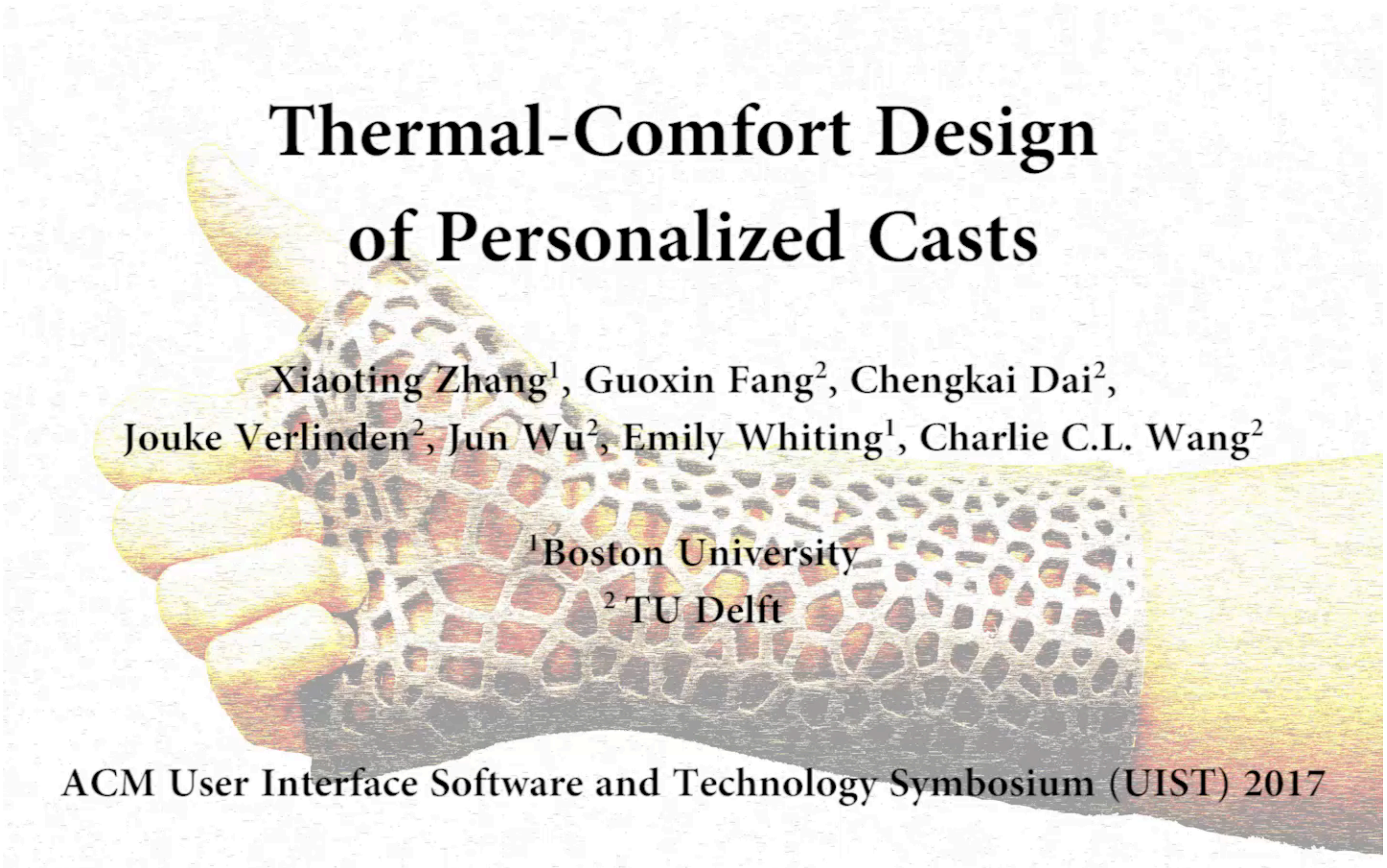




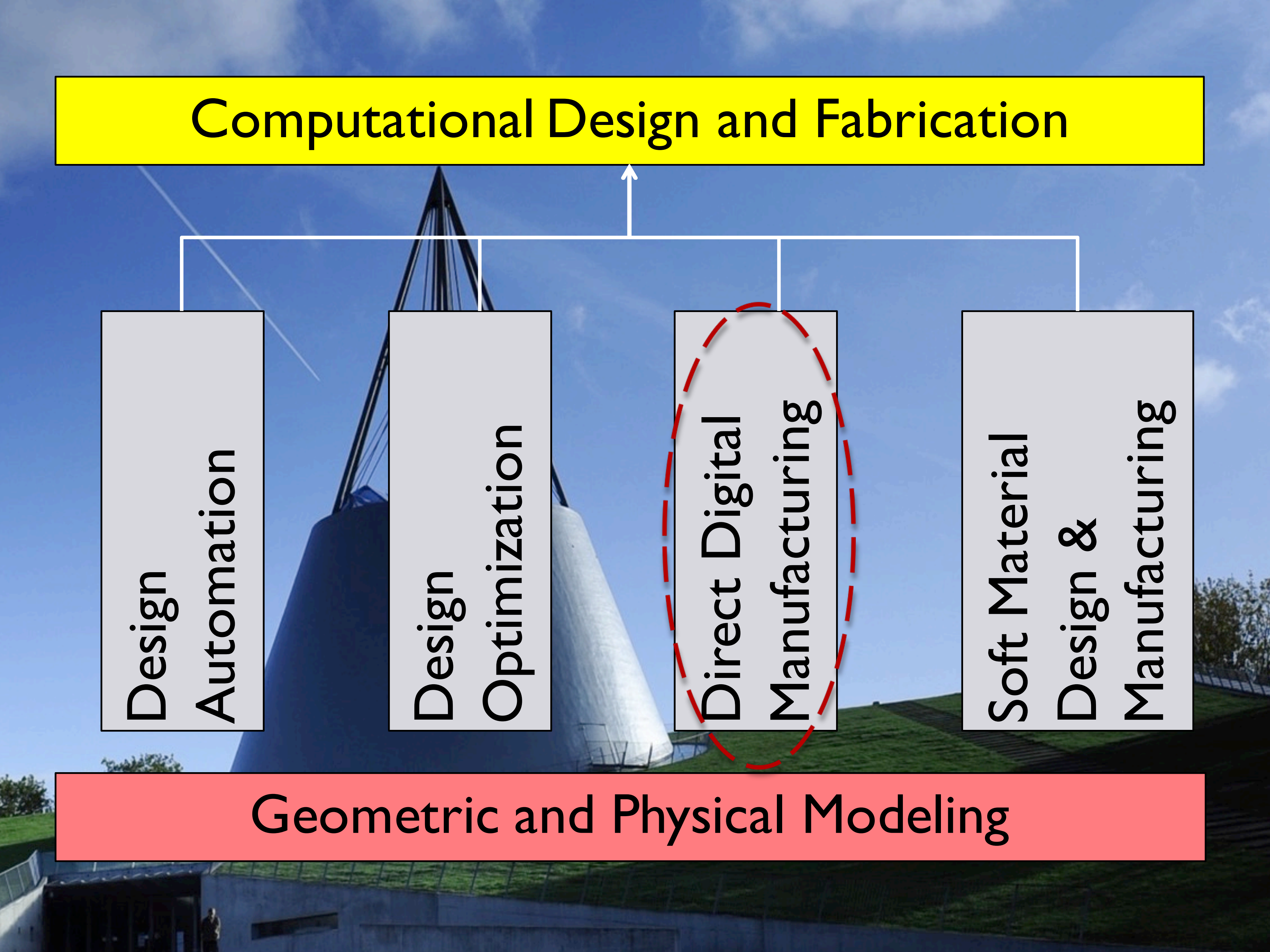


Weiming Wang, Yong-Jin Liu, Jun Wu, Shengjing Tian, **Charlie C.L. Wang***, Ligang Liu, and Xiuping Liu, "Support-free hollowing", IEEE Trans. on Visualization and Computer Graphics, 2017.

Optimization for Comfort: Thermal-Comfort Design of Personalized Casts



 X. Zhang, G. Fang, C. Dai, J. Verlinden, J. Wu, E. Whiting, and **C.C.L. Wang**, "Thermal-comfort design of personalized casts", *ACM Symposium on User Interface Software and Technology* (UIST), 2017, accepted.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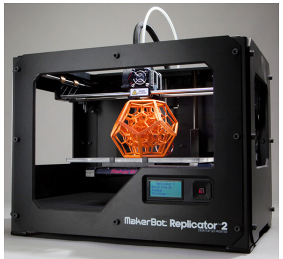
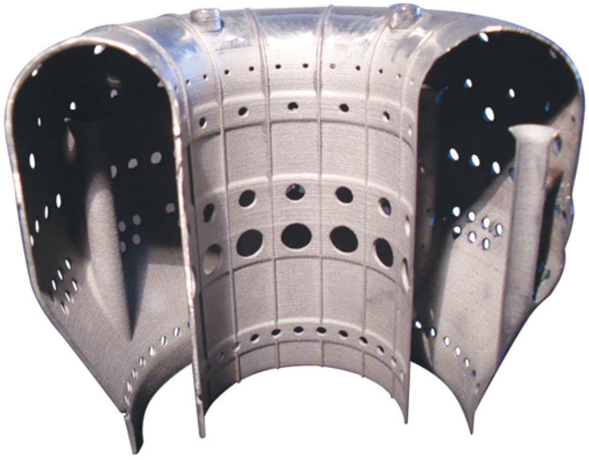
Direct Digital Manufacturing: Benefit and Challenge

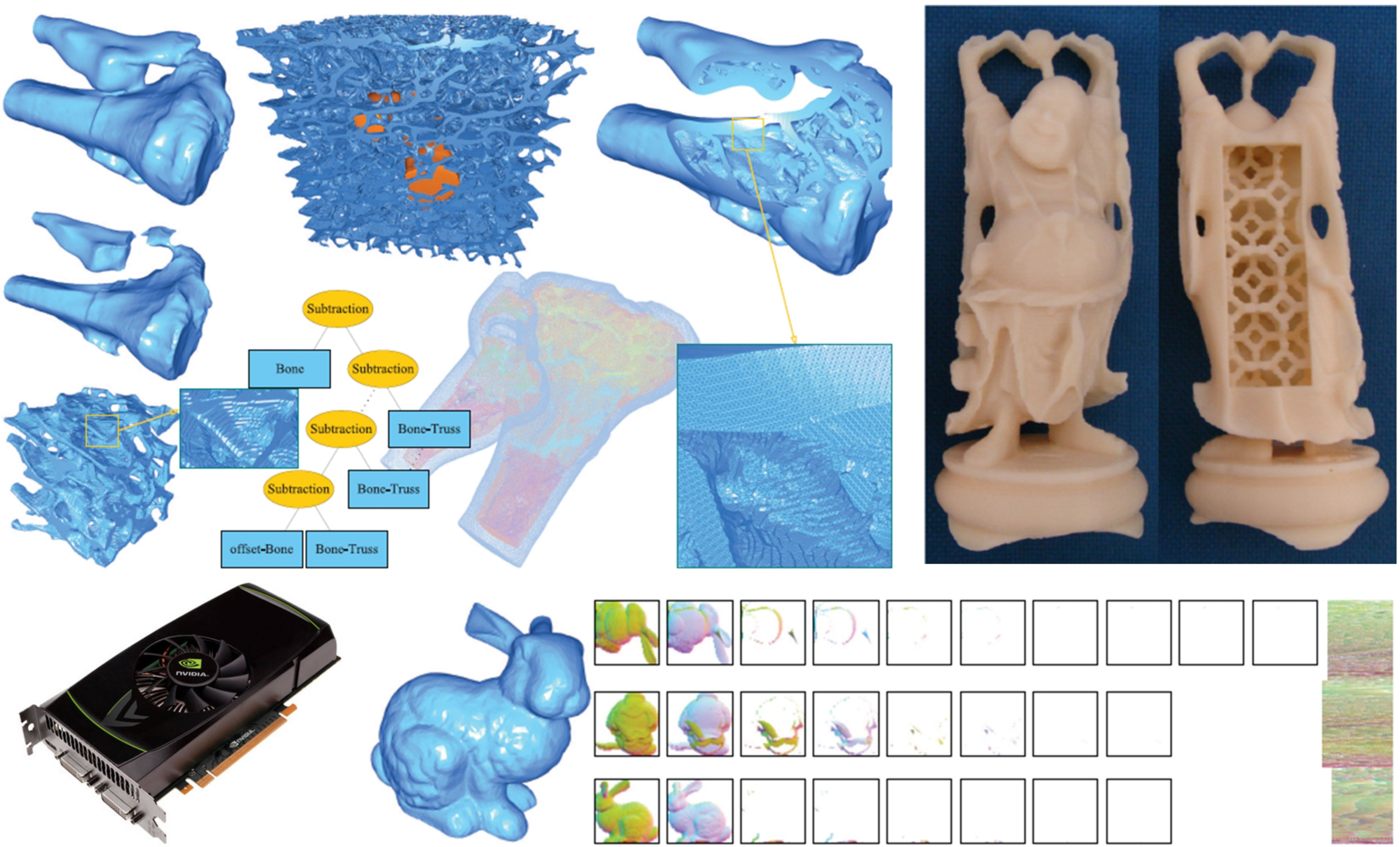
- Advantages: flexibility of fabricating complex shape and structure
- Software for Computational Fabrication becomes a bottleneck for new manufacturing methods
  - A new modeling kernel for complex shape and topology
  - Control & optimization for new manufacturing processes



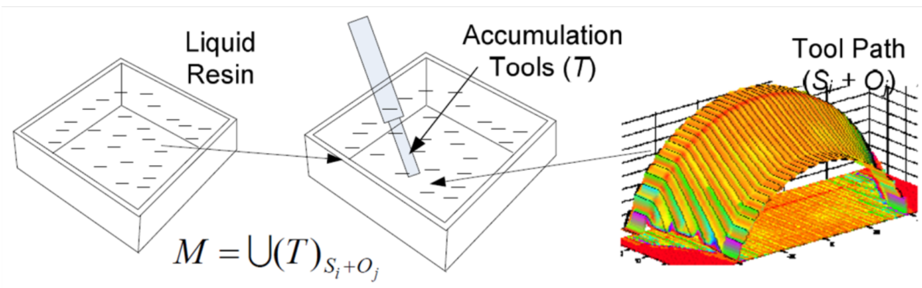


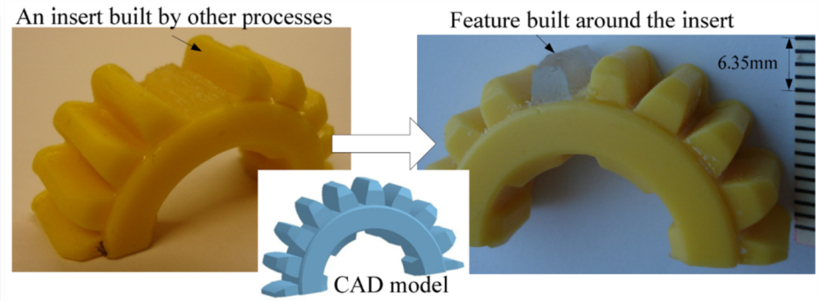
Geometric Kernel for 3D Printing: Highly Parallel Solid Modeling on GPUs



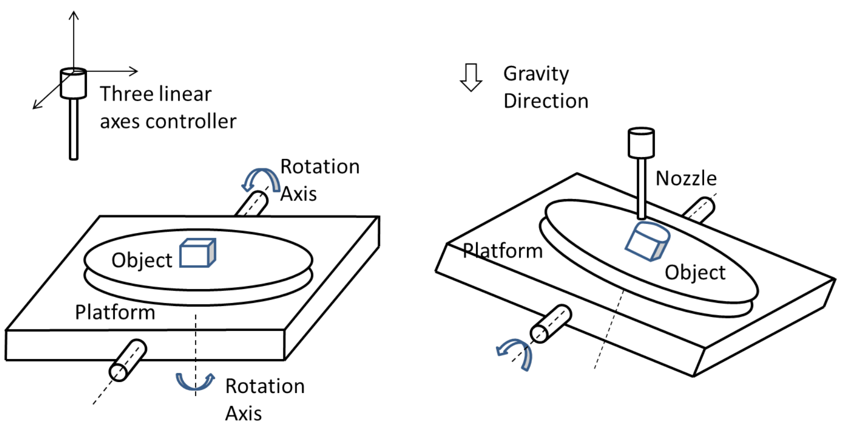
http://ldnibasedsolidmodeling.sourceforge.net

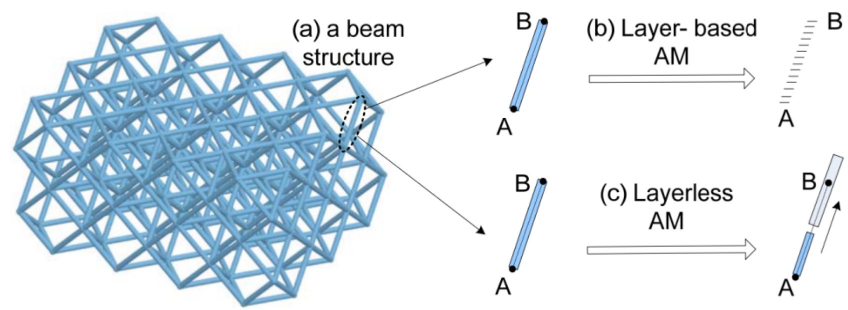
2.5D vs. 3D Printing: Simple or More DOF?





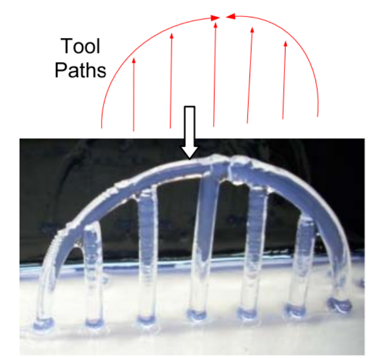
CNC accumulation for build-insert-around





Develop a new non-layered AM

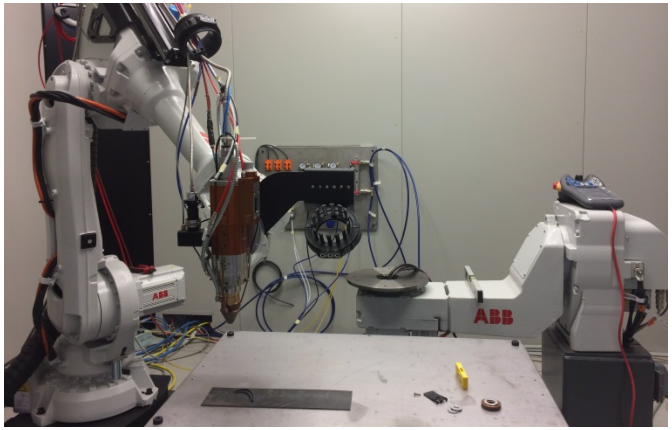
- Fused Deposition Modeling (FDM)
- Multi-axis motion introducing more flexibility



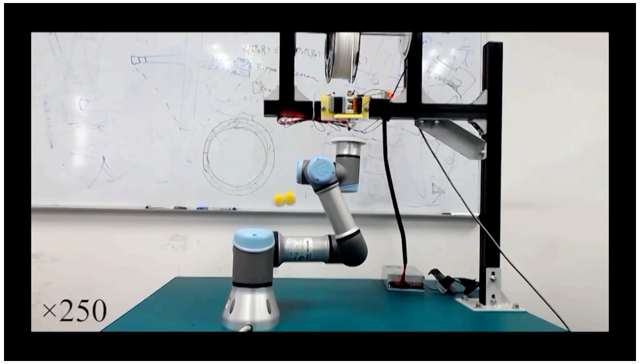
X. Zhao, Y. Pan, C. Zhou, Y. Chen, and C.C.L. Wang, "An integrated CNC accumulation system for automatic building-around-inserts", Journal of Manufacturing Processes, vol.15, no.4, pp.432-443, 2013.

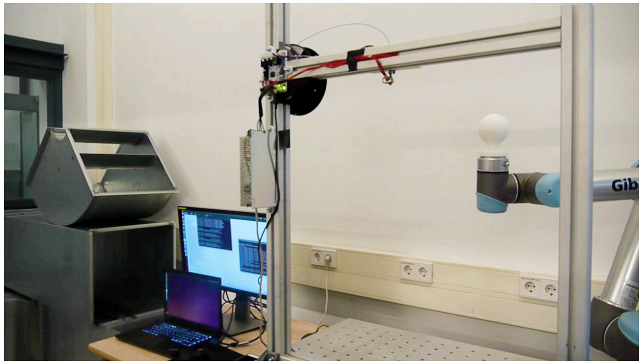
Robot-Assisted Multi-Axis AM

- 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

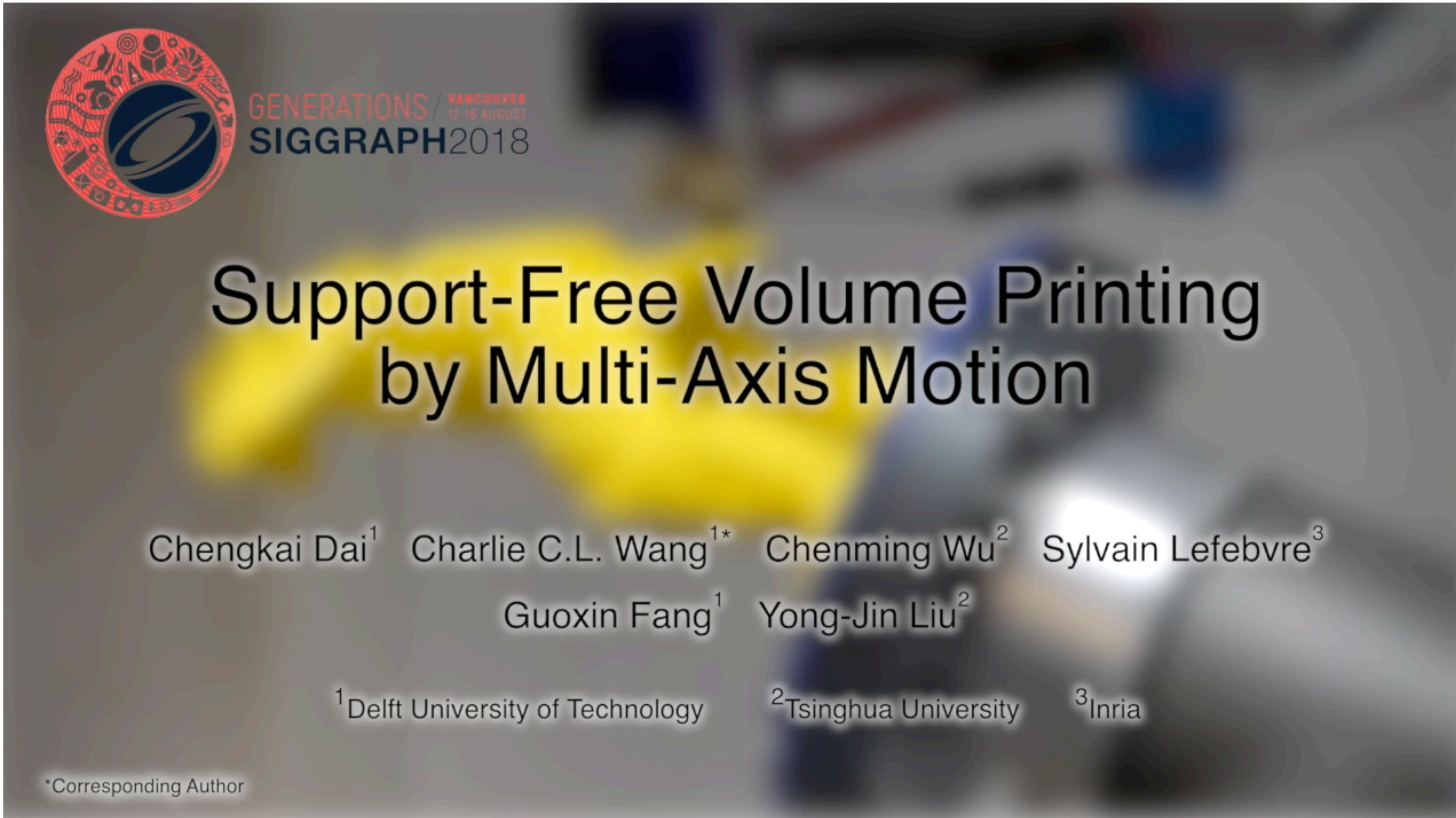




Decomposition by 3-half-half Axis AM

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).

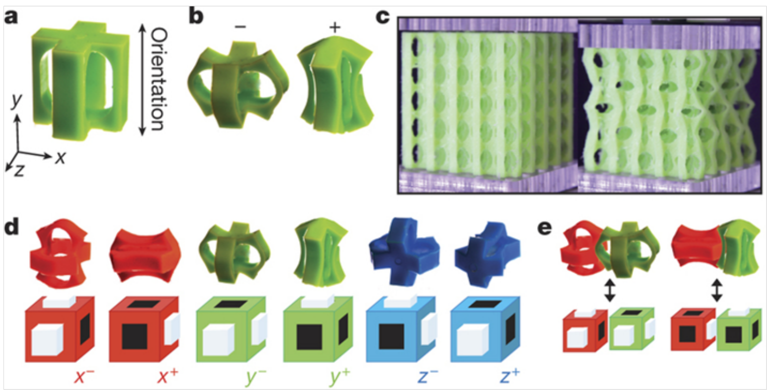
Field-Governed 5DOF Volume Printing



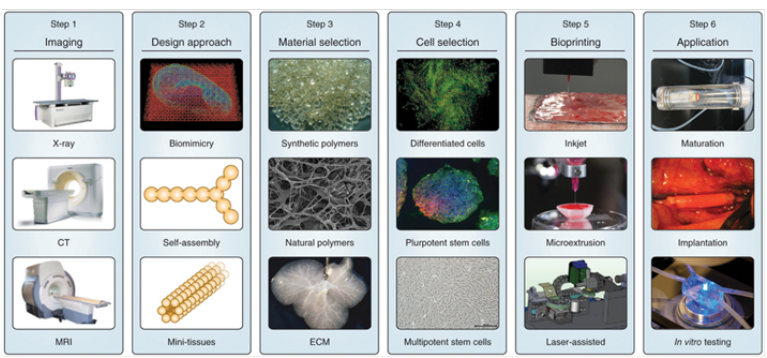
C. Dai, C.C.L. Wang, C. Wu, S. Lefebvre, G. Fang, and Y. Liu, "Support-free volume printing by multi-axis motion", ACM Transactions on Graphics (SIGGRAPH 2018).

Impact of Developing "Real" 3D Printing

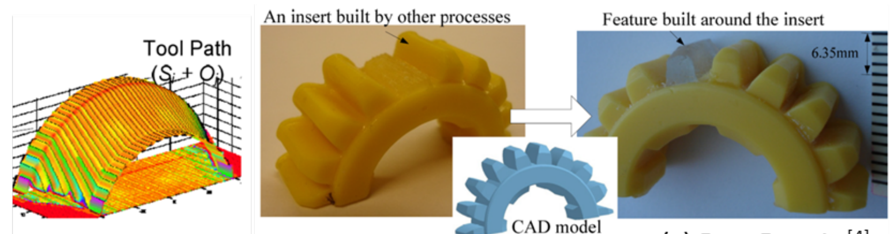
- Accumulating materials in space but not planar layers



(a) Mechanical Meta-Materials [2] (Applied Physics)



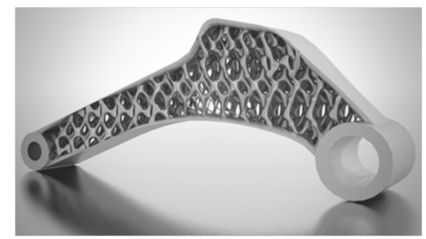
(b) Tissue Engineering [3] (Life Science)



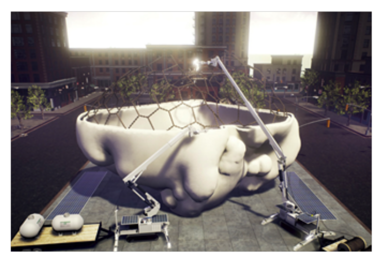
(c) Part Repair [4]

Multi-Axis Additive Manufacturing (Next Generation of 3D Printing)

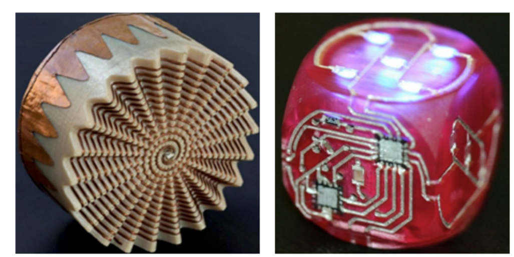
Geometric Computing



(d) Lightweight Structure (www.autodesk.com)



(e) Large-Scale Construction [6]

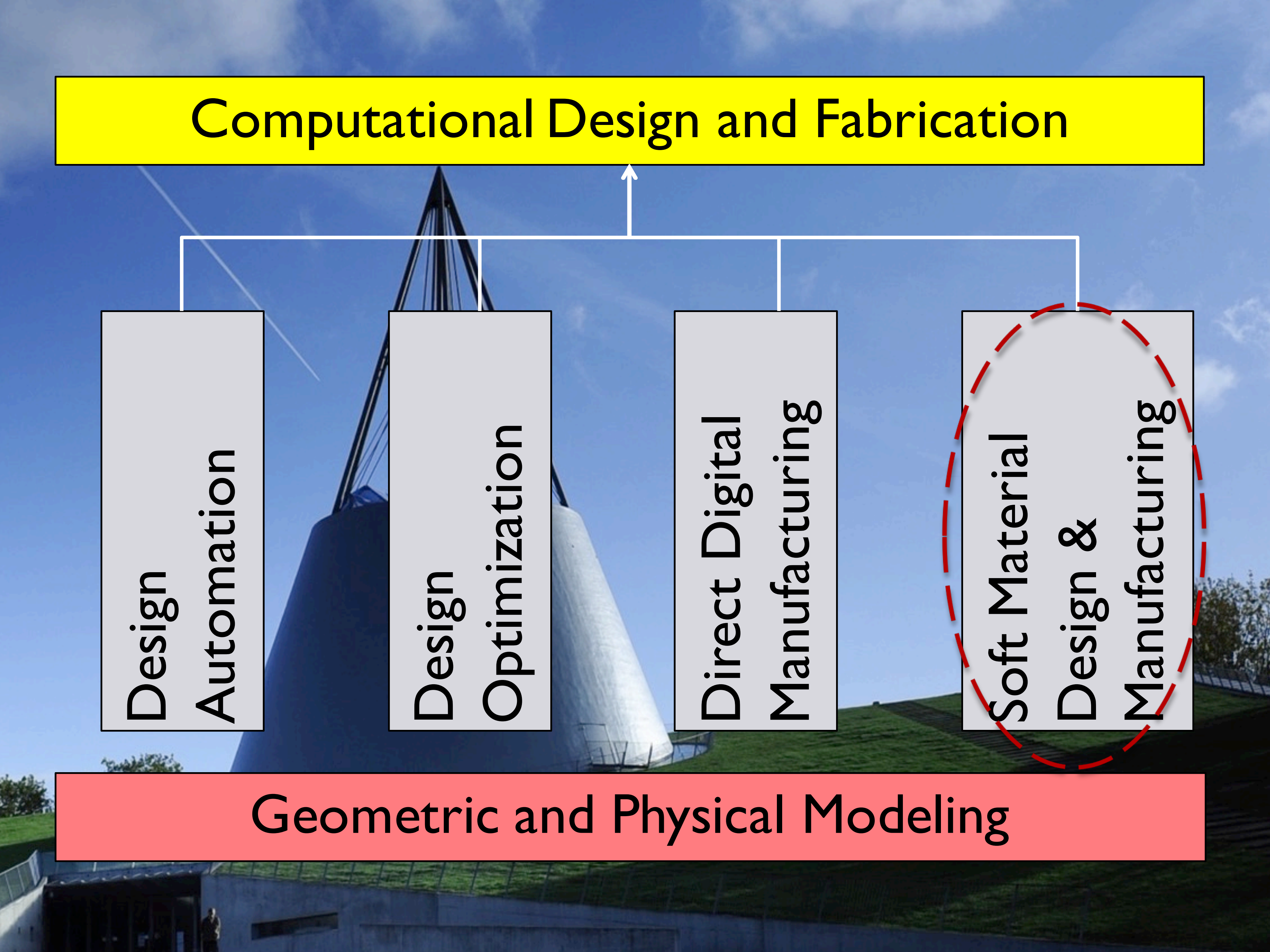


(f) Printing Electronics [8]

From 3D to 4D Printing

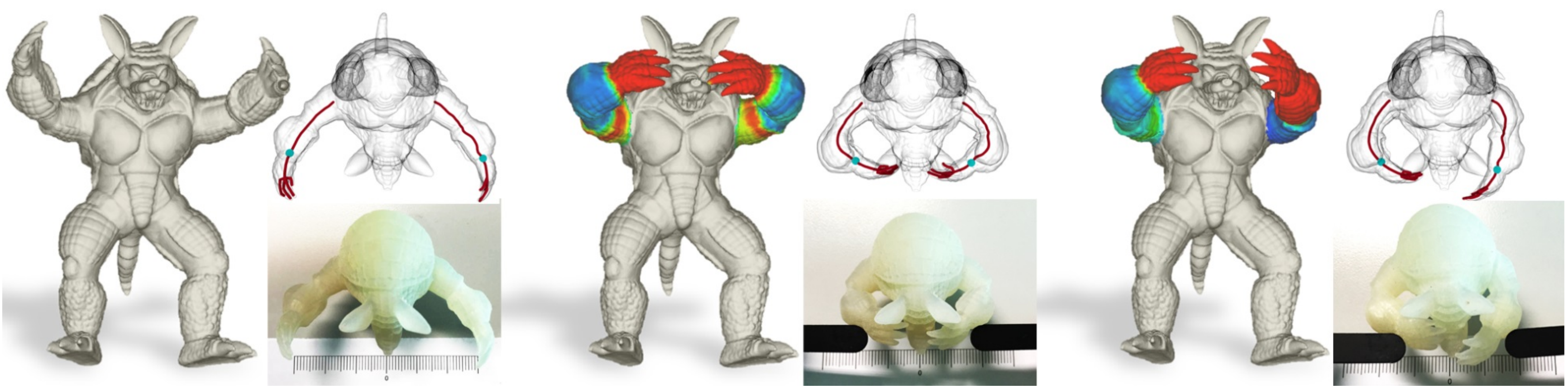
- 3D Printed Self-Assembly Structures
- How to predict the shape of fabricated model?
- Pattern Design / Process Optimization / New Triggers

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.


Computational Design and Fabrication
Design Automation
Design Optimization
Direct Digital Manufacturing
Soft Material Design & Manufacturing
Geometric and Physical Modeling

Deformation Behavior Design by Materials

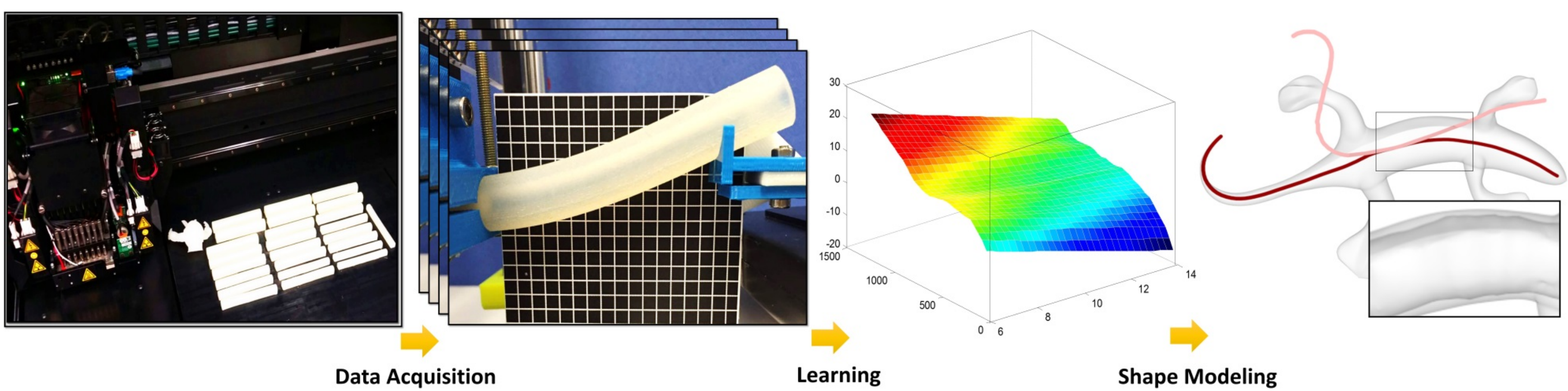
- 3D printing with elastomers => Deformation Behavior?
- Applications: personalized products, toys and soft robotics
- Different external forces lead to five different loads:
  - *Bending*, *Compression*, *Shear*, *Tension* and *Torsion*
  - Bending gives the most visible change to shapes
- We provide – an interactive tool to design bending behavior
  - Non-uniform hollowing on generalized cylindrical shapes



Xiaoting Zhang, Xinyi Le, Zhihao Wu, Emily Whiting, and **Charlie C.L. Wang**, "Data-driven bending elasticity design by shell thickness", *Computer Graphics Forum*, 2016.

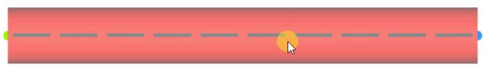
Data-Driven Approach – Learning Function of Local Bending w.r.t. Shell Thickness

- Variable for bending behavior design: thickness of hollowing
- An interface to design the bending behavior – 1D skeleton
- Offload time-consuming steps to the phase of learning
- Challenge:
  - To match the desired bending behavior
  - A function with elasticity, thickness & dimension of cross-section

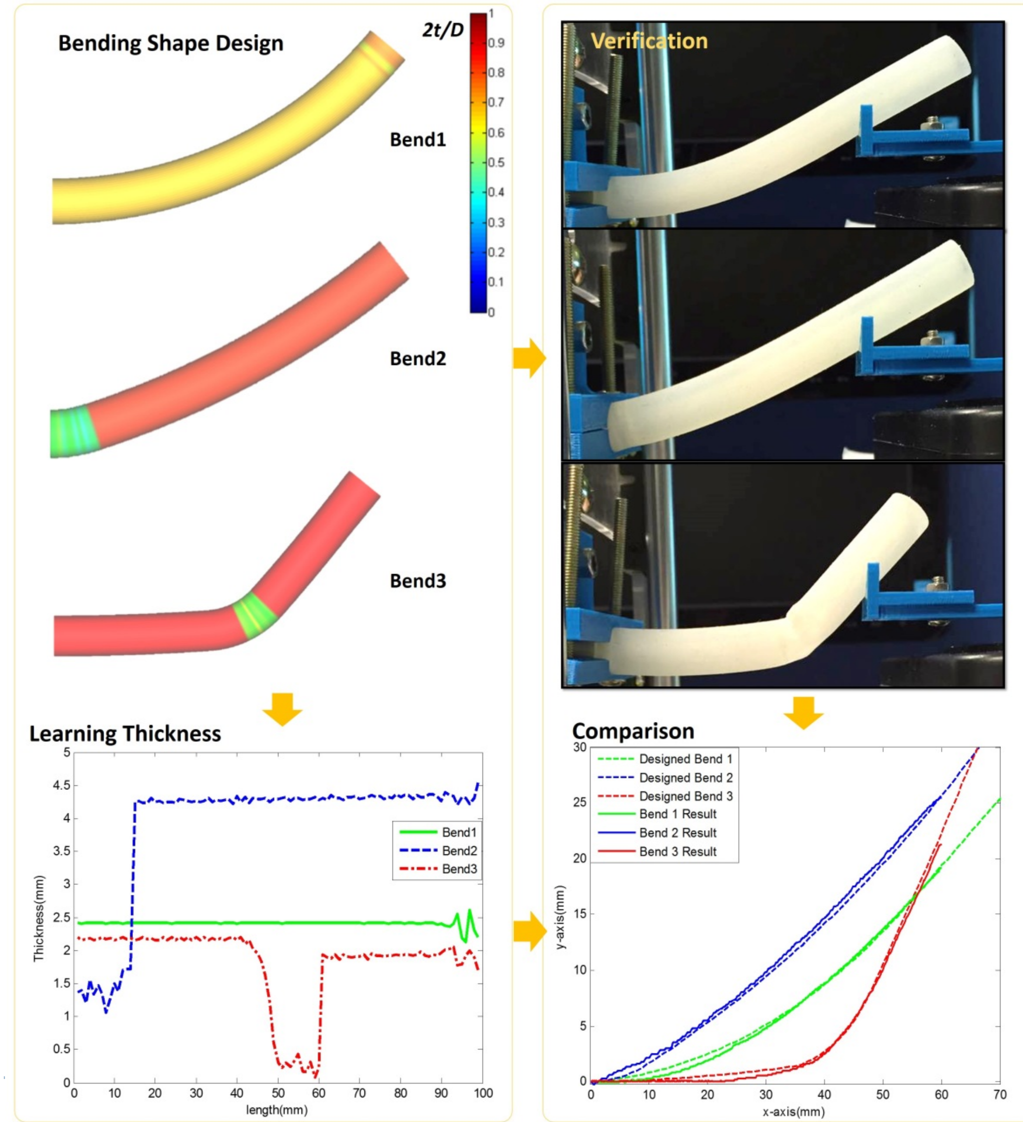


Result: Verification on Tubes

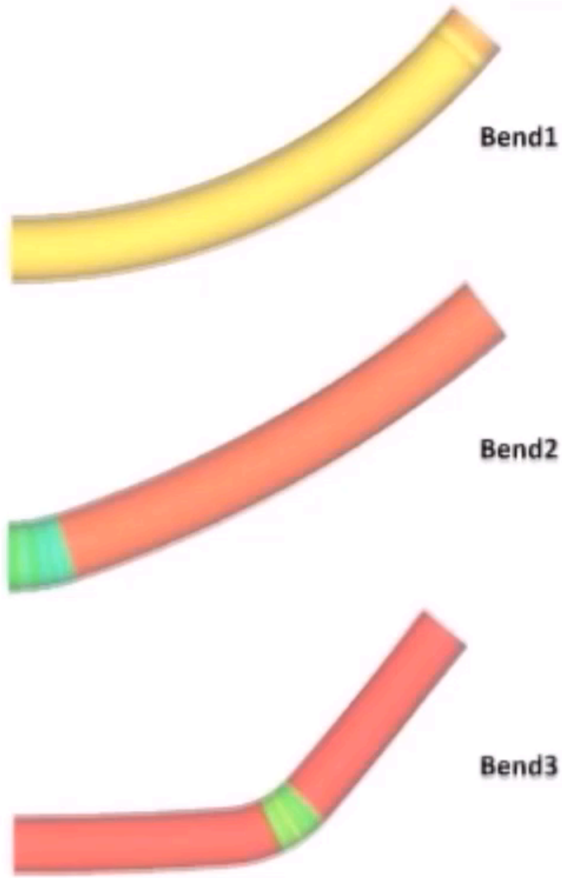
- Easy Interface



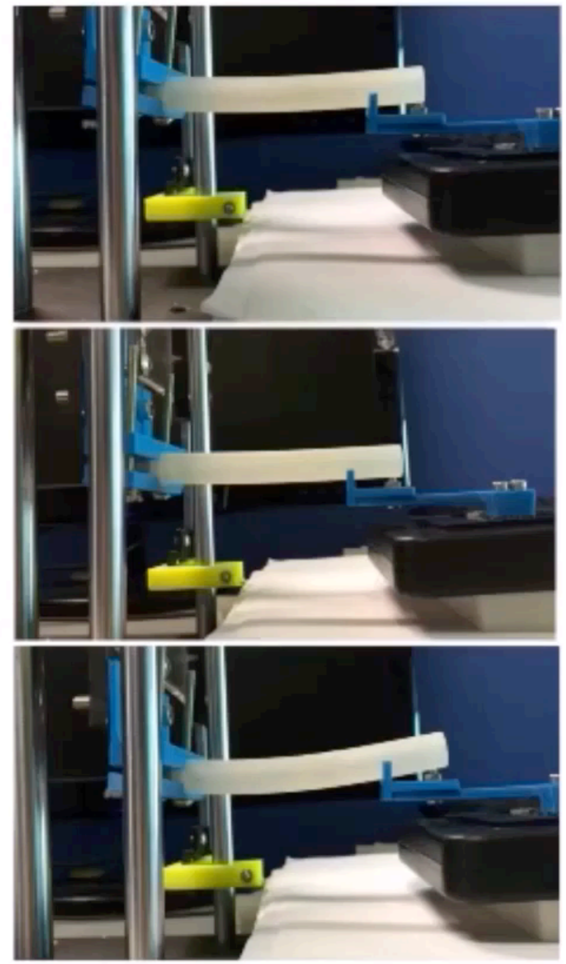
- Different behaviors
- Physical tests match designed behavior???



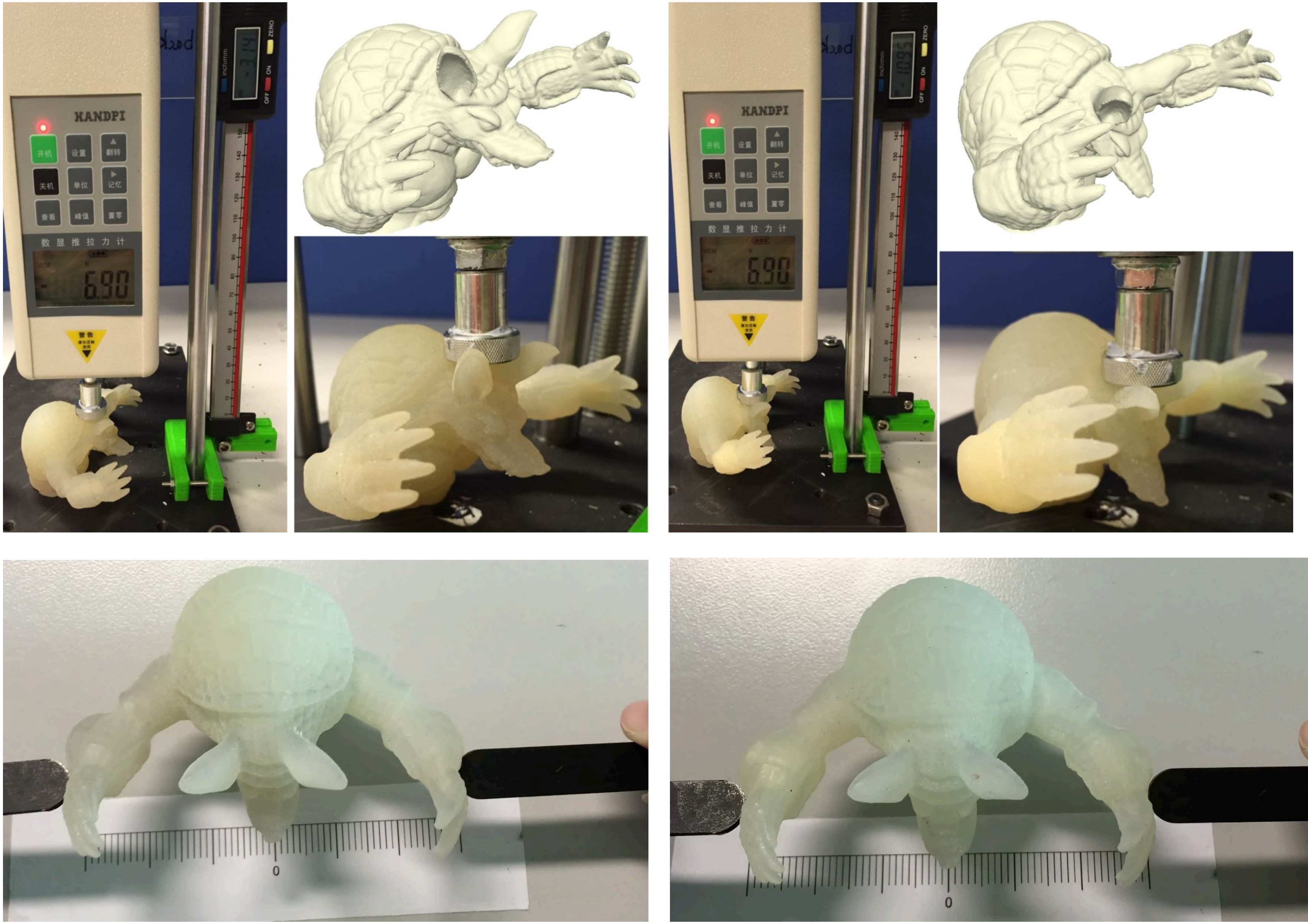
- Design



- Test

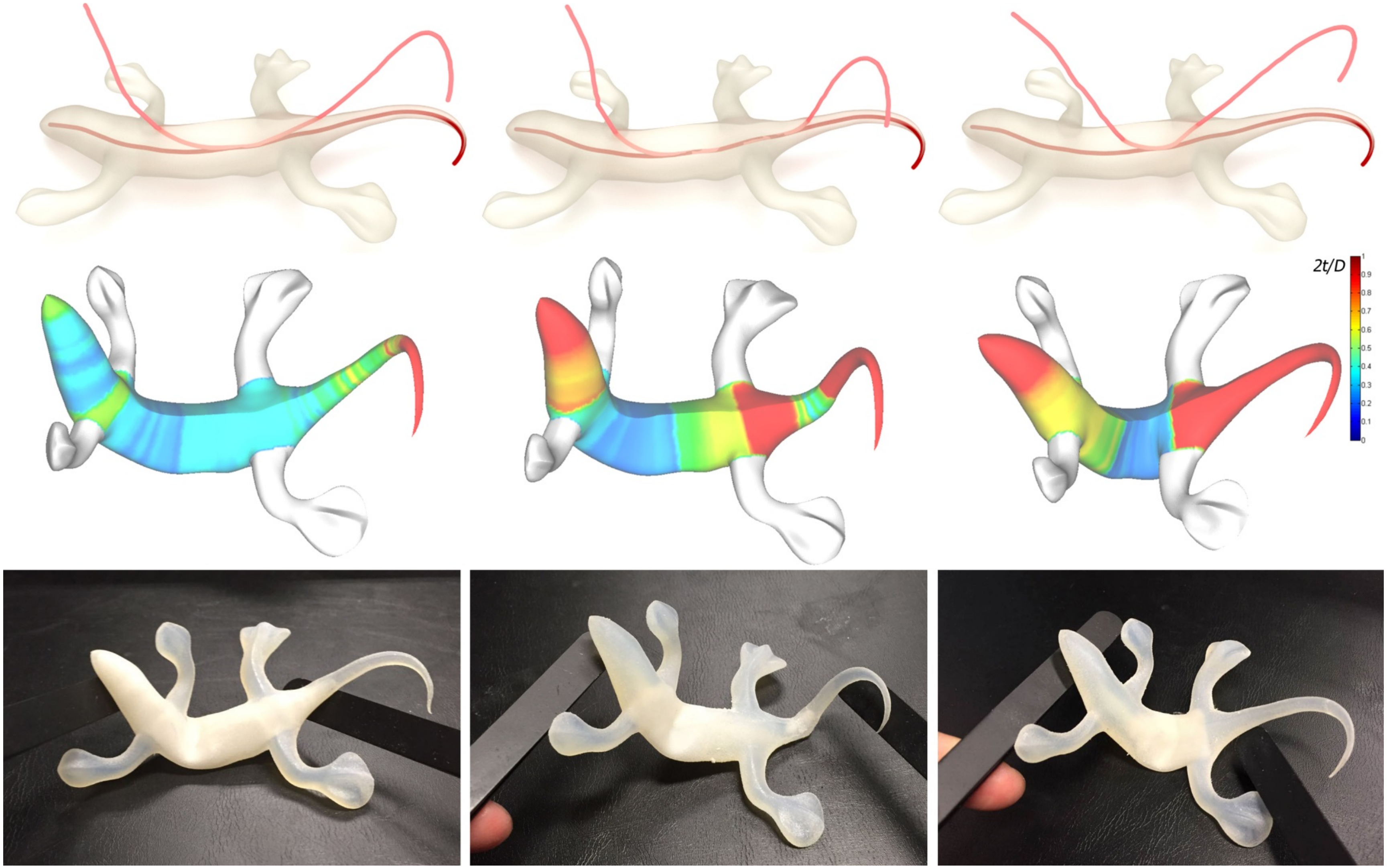


Xiaoting Zhang, Xinyi Le, Zhihao Wu, Emily Whiting, and Charlie C.L. Wang, "Data-driven bending elasticity design by shell thickness", *Computer Graphics Forum*, 2016.



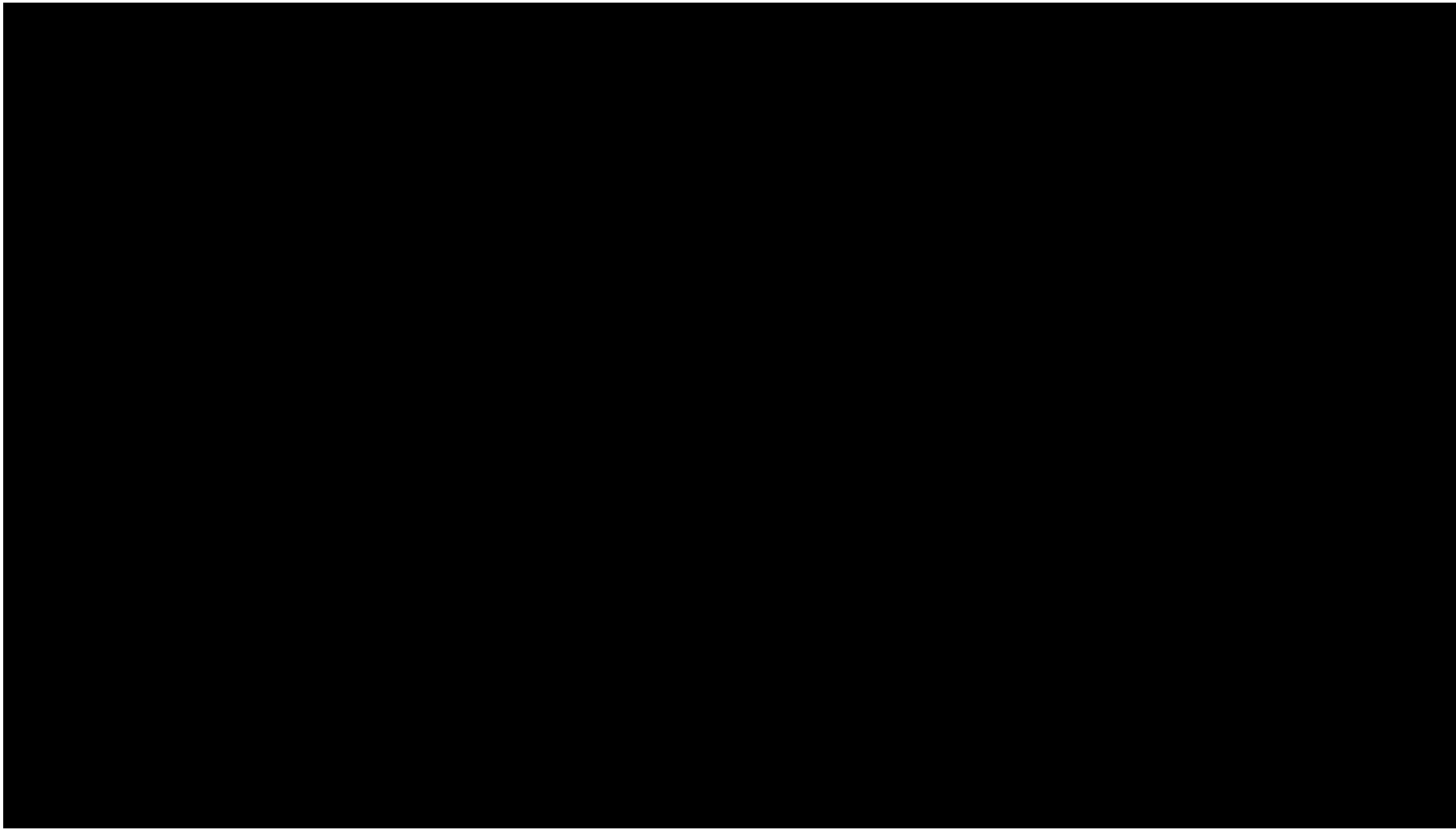
Xiaoting Zhang, Xinyi Le, Zhihao Wu, Emily Whiting, and Charlie C.L. Wang, "Data-driven bending elasticity design by shell thickness", *Computer Graphics Forum*, 2016.

Result: Models with Complex Shape



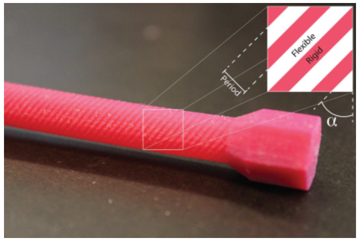
Xiaoting Zhang, Xinyi Le, Zhihao Wu, Emily Whiting, and Charlie C.L. Wang, "Data-driven bending elasticity design by shell thickness", *Computer Graphics Forum*, 2016.

Direct Digital Manufacturing for Soft Robotics



Designing Deformation Behaviors for Soft Grippers

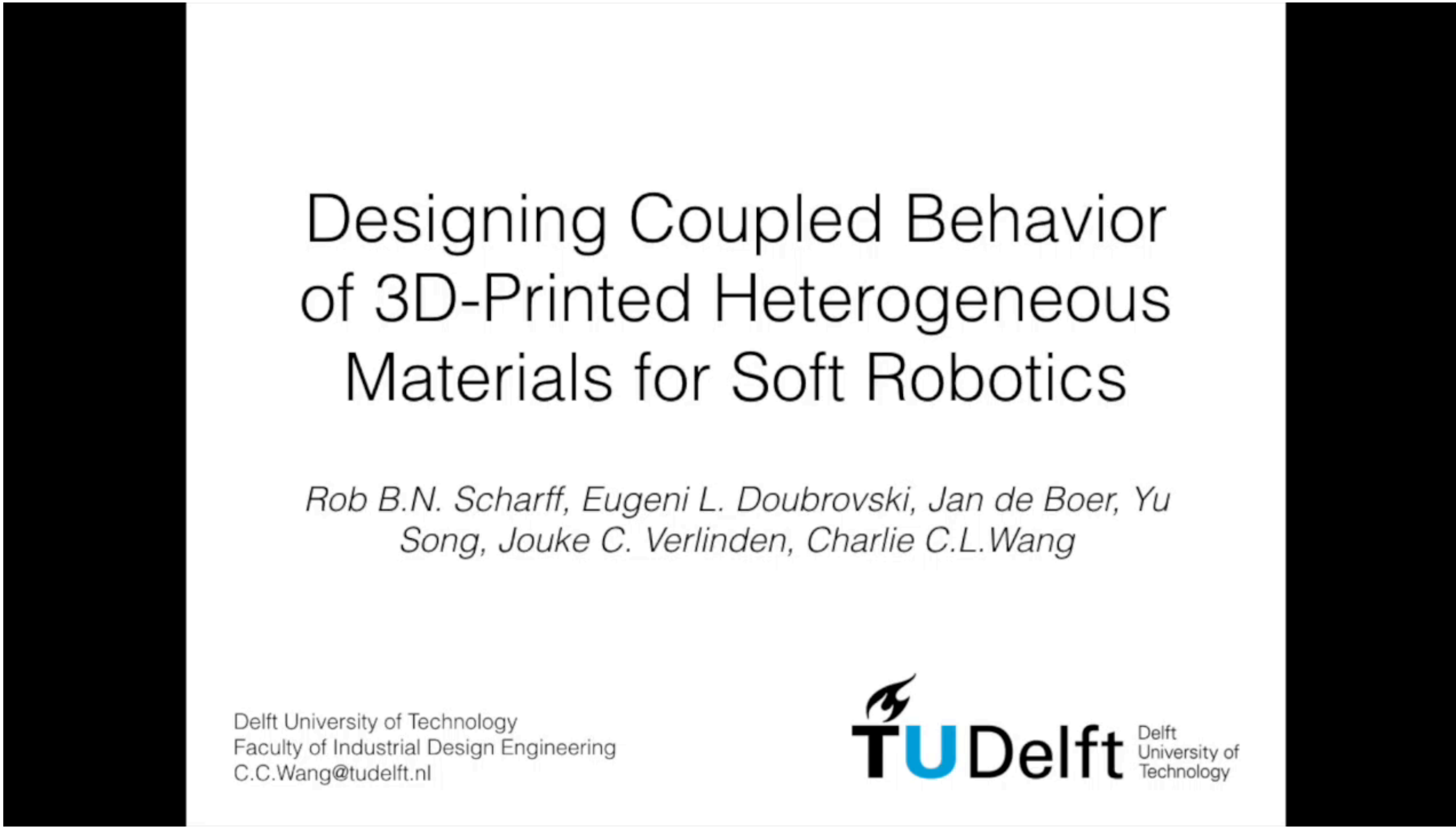
- Soft robotics application for better grippers
- Deformation behavior can also be influenced by the material distribution (Multi-Material Printing)



Parameterize Deformation Behavior under:

- Bending
- Twisting
- Stretching

Behavior Design by Multi-Material AM



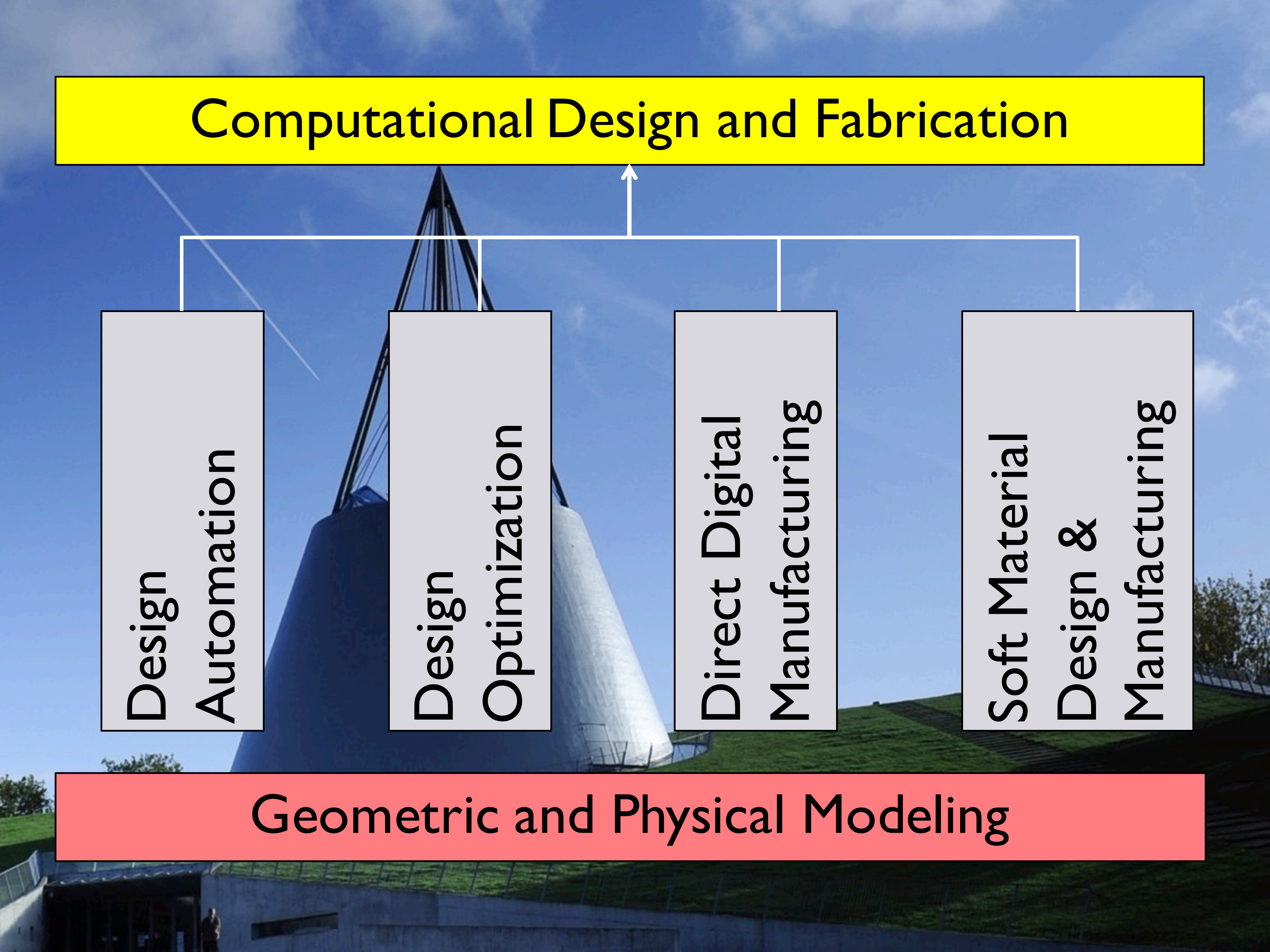
Sensing of Bending Deformation

Color-Based Sensing of Bending Deformation on Soft Robots

Scharff, R.B., Doornbusch, R.M., Klootwijk X.L., Doshi A.A., Doubrovski, E.L., Wu, J., Geraedts, J.M., Wang, C.C.*

*Corresponding author: C.C.Wang@tudelft.nl

TU Delft


Computational Design and Fabrication
Design Automation
Design Optimization
Direct Digital Manufacturing
Soft Material Design & Manufacturing
Geometric and Physical Modeling