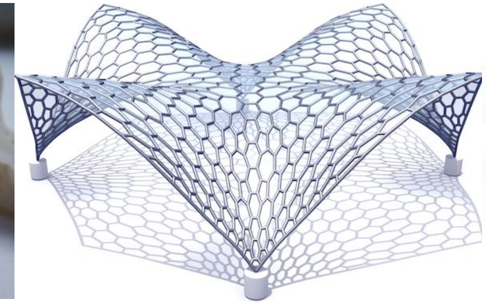
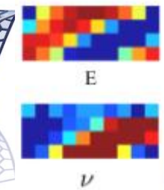
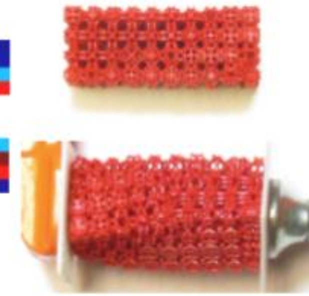


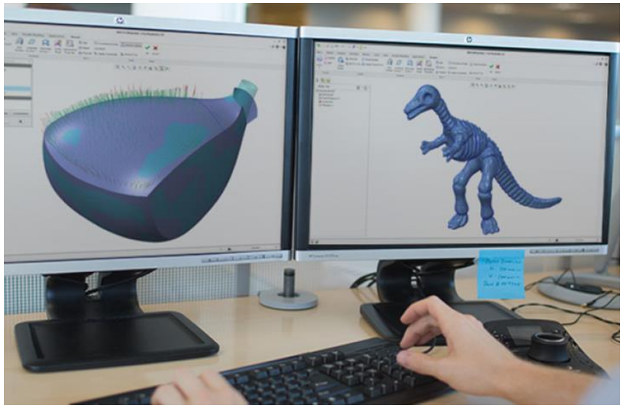



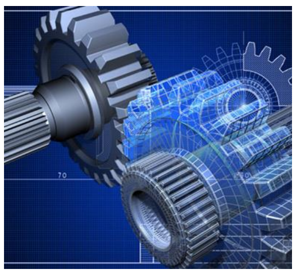


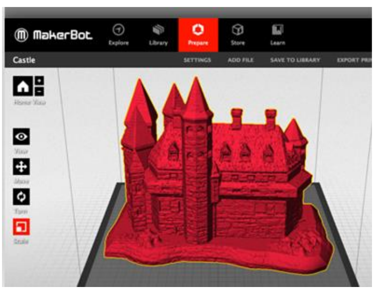
State Of The Art on Functional Fabrication

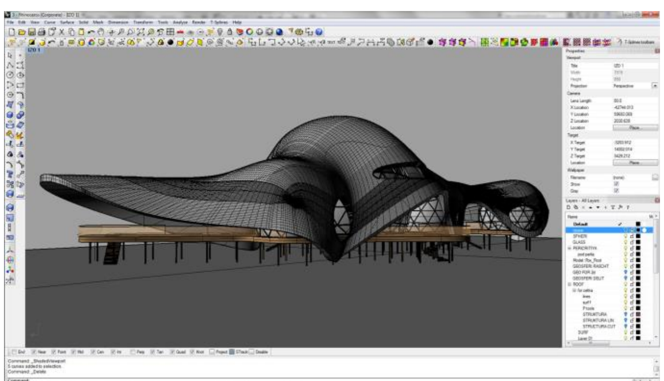
Asla Medeiros e Sa
Karina Rodriguez-Echavarria
Nico Pietroni
Paolo Cignoni

What is Digital Fabrication?

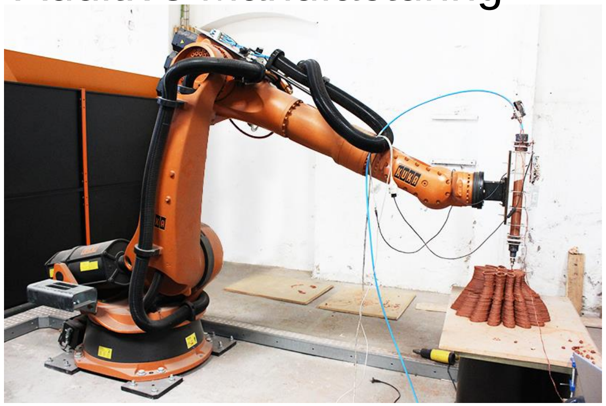




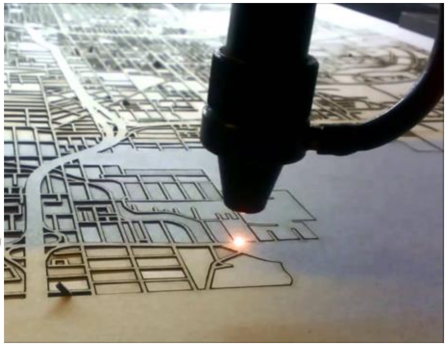




Additive Manufacturing



CNC Milling



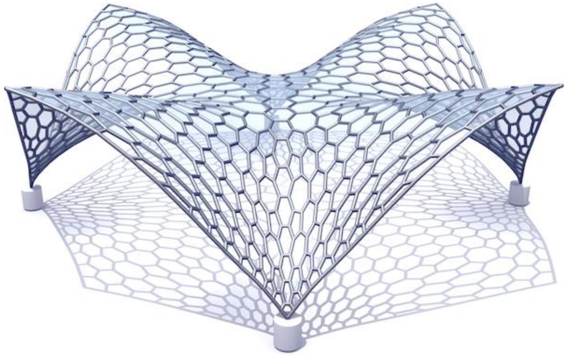
Laser Cutter

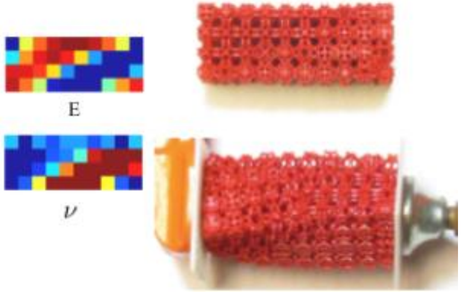
+ any computer assisted fabrication methodology ...

Why is Digital Fabrication relevant?

Additive Manufacturing (AM) technologies
are posing the question:
How design could take advantage of AM digital fabrication technology?

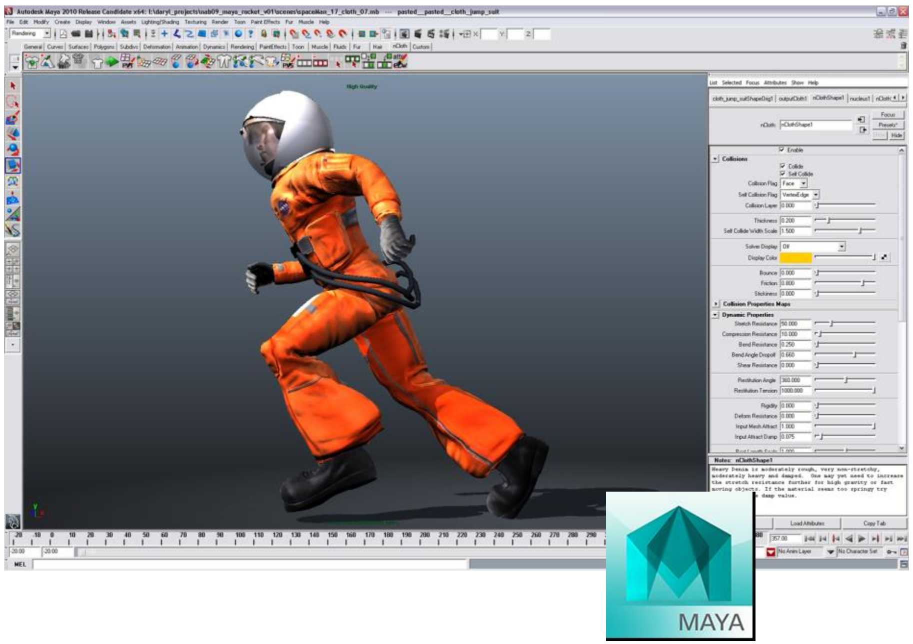
This is feeding the discussion in a broader sense:
How digital fabrication technology could impact on manufacturing processes and the exploration of the design space?

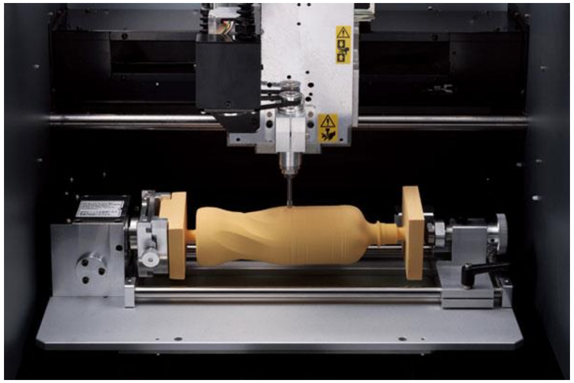




Why isn't Digital Fabrication plug-and-play?

MAIN GAP: Digital/Virtual worlds lack of physicality!





Roland®

Our work focus on this gap!!!

MAIN GAP: Technology limitations

What is Functional Fabrication?

Functional Fabrication comprises the design and manufacture of *physical* ***objects with functionalities*** by means of digital fabrication technologies. These functionalities include:

- Mechanically enhanced workpieces,
- Articulated physical models,
- Aerodynamic workpieces,
- Deformable workpieces and
- Object's with controlled appearance and acoustics.

Fabricating Articulated Characters from

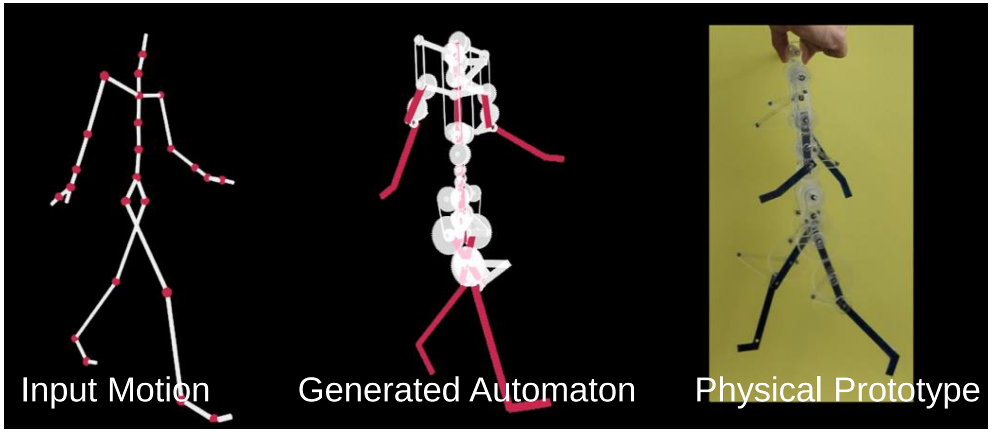
Spin-It: Optimizing Moment of Inertia for Spinnable Objects
Moritz Bächer, Emily Whiting, Bernd Bickel, Olga Sorkine-Hornung

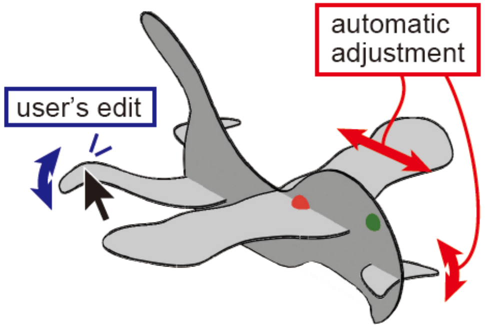
Color Enhancement for Rapid Prototyping
P. Cignoni, E. Gobbetti, R. Pintus and R. Scopigno

What role CG community plays?

Recent design tools are clearly taking advantage of relevant computer graphics techniques and extending these techniques to realise new physical forms as well as bringing innovation to feed into the design space.

That is: Guiding the **exploration of the feasible design space!**





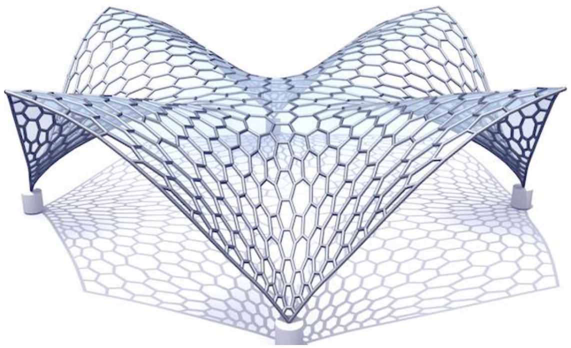
Designing and Fabricating Mechanical Automata from Mocap Sequences
Duygu Ceylan, Wilmot Li, Niloy J. Mitra, Maneesh Agrawala and Mark Pauly.

Pteromys: Interactive Design and Optimization of Free-formed Free-flight Model Airplanes

N. Umetani, Y. Koyama, R. Schmidt, T.Igarashi

Classification

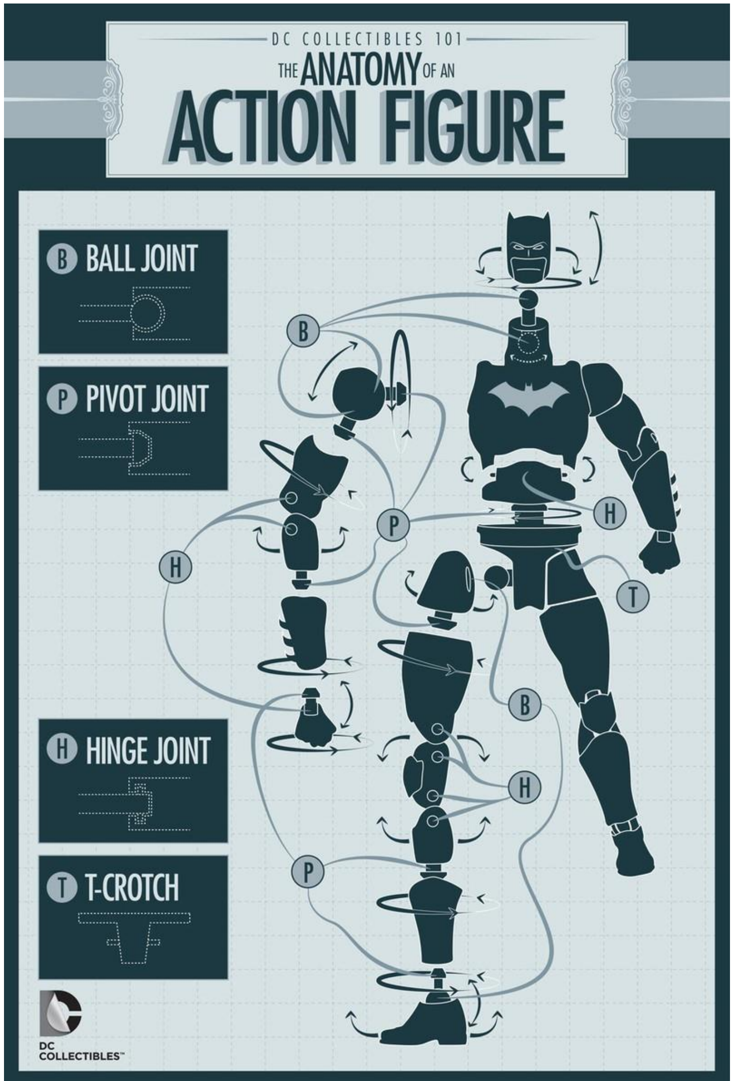
1. Articulating
2. Controlling deformability
3. Enhancing structural properties
4. Achieving balance
5. Aerodynamics
6. Appearance and Acoustics

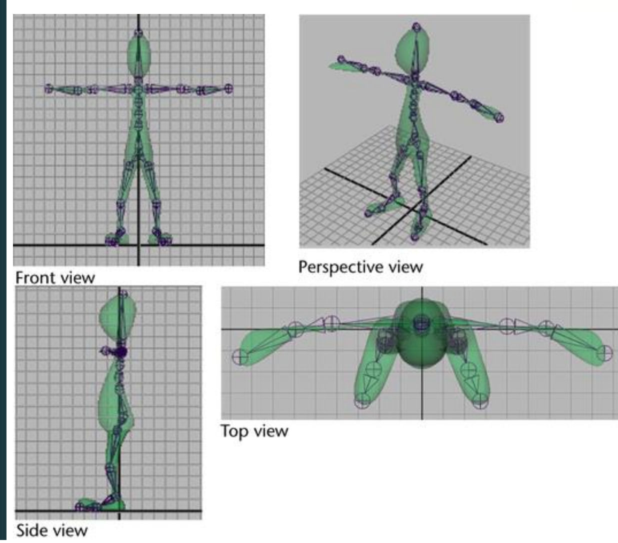


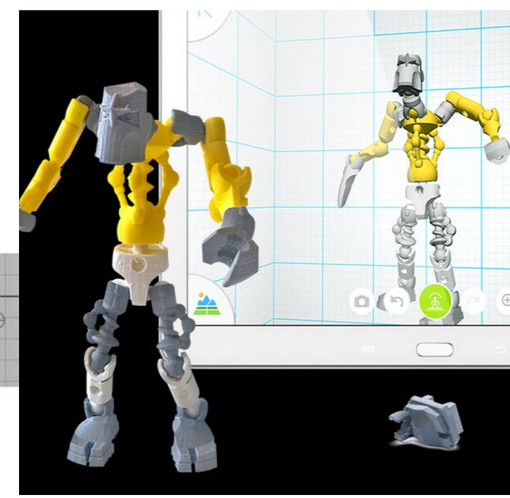




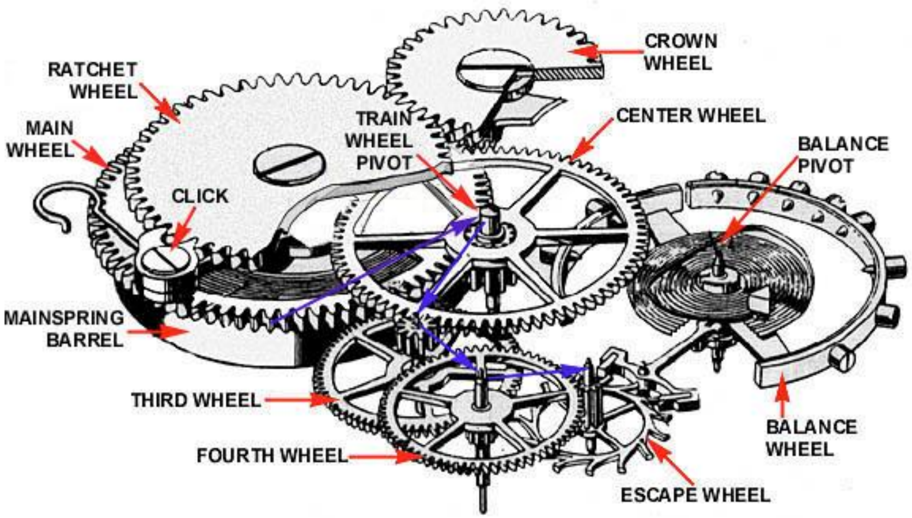
1. Articulating Workpieces







1. Articulating Workpieces



1. Articulating Workpieces

Computational Design of Twisty Joints and Puzzles

Timothy Sun Changxi Zheng
Columbia University *

Figure 1: Twisty Armadillo. *(left) A twisty puzzle in the shape of an* Armadillo *whose rotation axes are placed along a triangular prism. (right) The output of our algorithm was fabricated, assembled, and scrambled into contorted poses. The different parts of the model, such as the arms and legs, were deformed so that they do not collide with one other regardless of the configuration of the puzzle.*

1. Articulating Workpieces

3D-Printing of Non-Assembly, Articulated Models

Jacques Calì Dan A. Calian Cristina Amati Rebecca Kleinberger Anthony Steed Jan Kautz Tim Weyrich
University College London

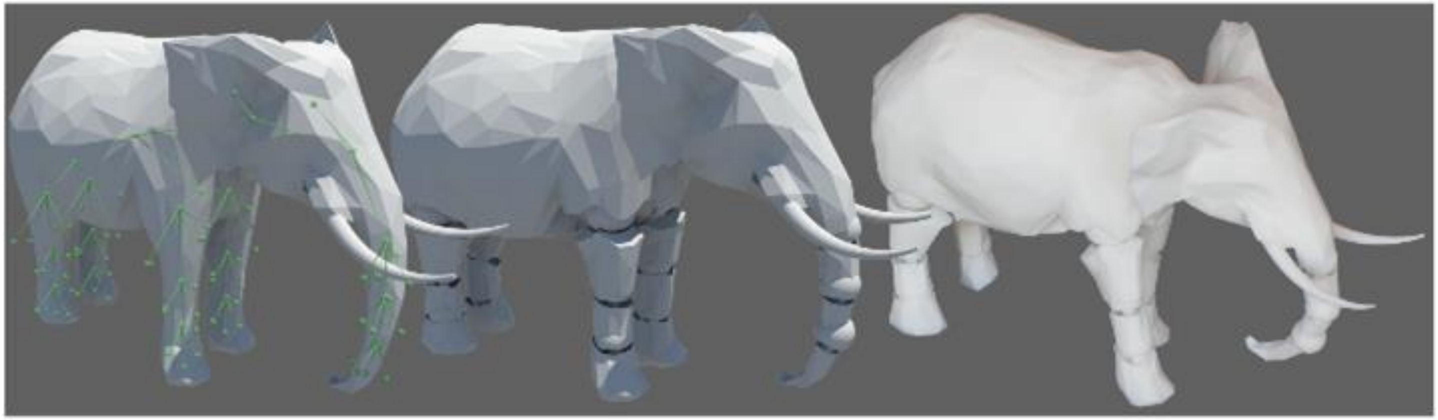


***Figure 1:** Starting from a 3D mesh (left), our system allows to intuitively add 3D-printable joints (center) that, when 3D-printed, create a functional, posable model with joints that exhibit internal friction. The model leaves the printer ready to use: no manual assembly is required.*

1. Articulating Workpieces

Boxelization: Folding 3D Objects into Boxes

Yahan Zhou[1] Shinjiro Sueda[1] Wojciech Matusik[2] Ariel Shamir[3,1]
[1]Disney Research Boston [2]MIT CSAIL [3]The Interdisciplinary Center

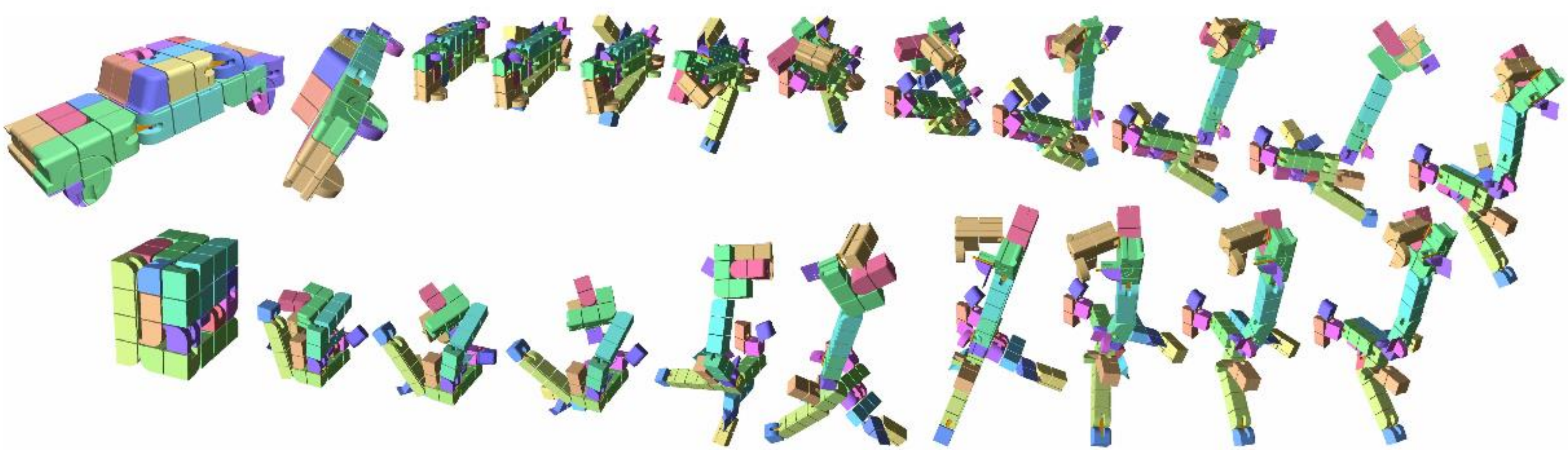


Figure 1: *Folding a car into a cube. Our system finds a collision-free folding sequence.*

1. Articulating Workpieces

Computational Design of Linkage-Based Characters

Bernhard Thomaszewski*[1] Stelian Coros*[1] Damien Gauge[2] Vittorio Megaro[2] Eitan Grinspun[3]
Markus Gross[1,2]

[1]Disney Research Zurich [2]ETH Zurich [3]Columbia University

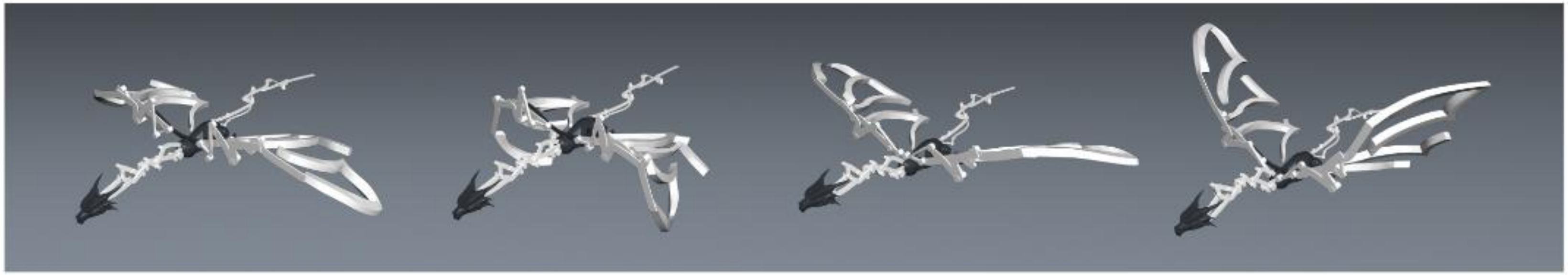


Figure 1: *Our design system allows the user to create linkage-based characters that are able to perform complex and compelling motions.*

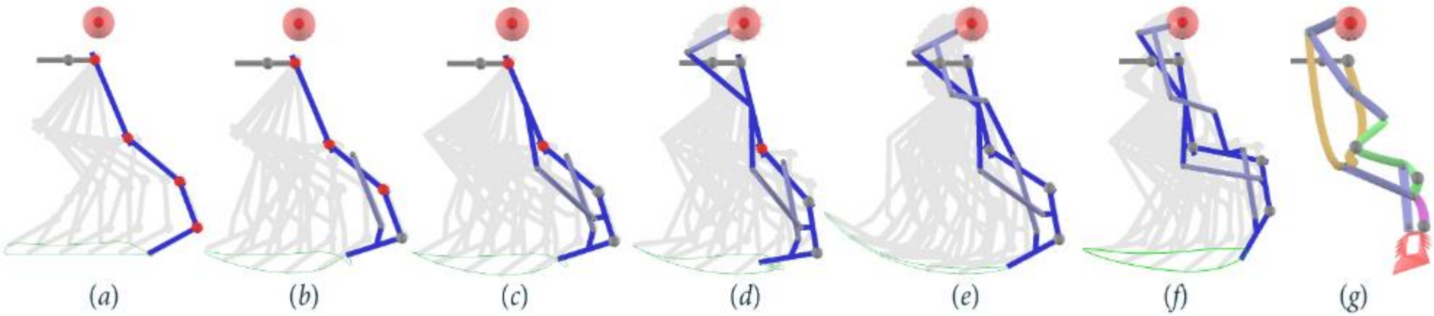


Figure 6: *The character design process illustrated on the Satyr's leg: input animation (a), interactive motor replacement (b-e), after global optimization (f) , and after linkage shaping (g).*

1. Articulating Workpieces

Designing and Fabricating Mechanical Automata from Mocap Sequences

Duygu Ceylan[1] Wilmot Li[2] Niloy J. Mitra[3] Maneesh Agrawala[4] Mark Pauly[1]
[1]EPFL [2]Adobe Research [3]University College London [4]University of California Berkeley

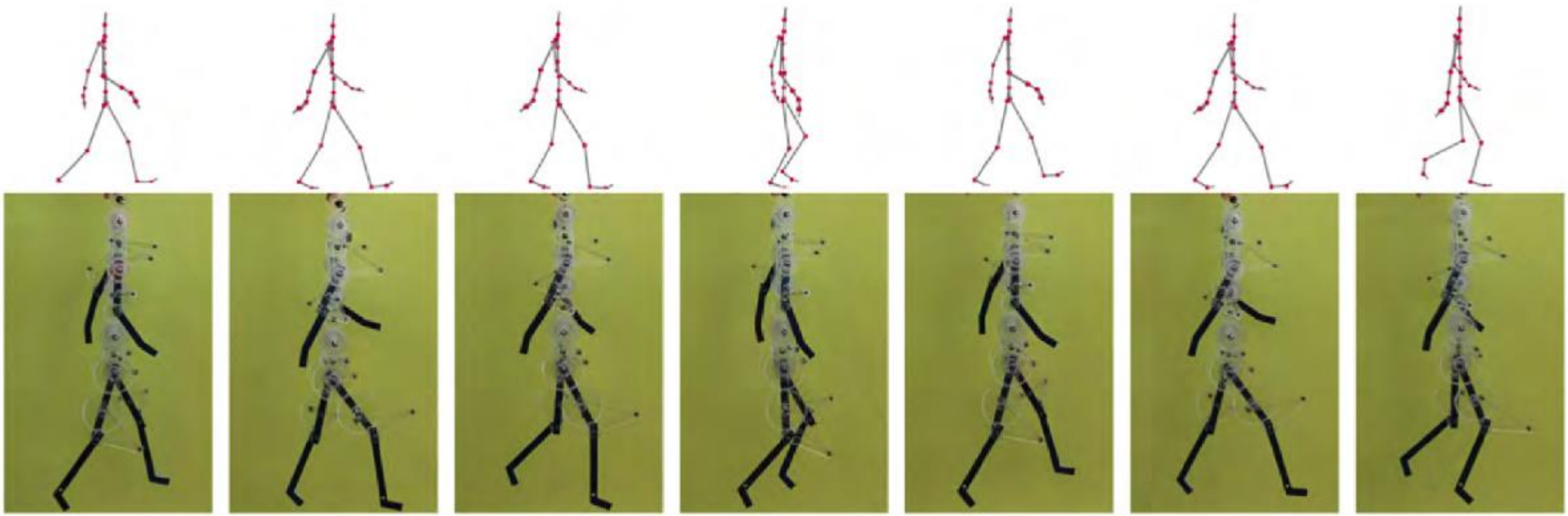


Figure 1: *We present a method for generating the design of a mechanical automaton (bottom row) that approximates an input motion sequence (top row). Our algorithm automatically determines the configuration, dimensions, and layout of all mechanical components.*

1. Articulating Workpieces

Computational Design of Mechanical Characters

Stelian Coros*[1] Bernhard Thomaszewski*[1] Gioacchino Noris[1] Shinjiro Sueda[2] Moira Forberg[2]
Robert W. Sumner[1] Wojciech Matusik[3] Bernd Bickel[1]

[1]Disney Research Zurich [2]Disney Research Boston [3]MIT CSAIL

Figure 1: *The interactive design system we introduce allows non-expert users to create complex, animated mechanical characters.*

1. Articulating Workpieces

Interactive Design of 3D-Printable Robotic Creatures

Vittorio Megaro[1] Bernhard Thomaszewski[2] Maurizio Nitti[2]
Otmar Hilliges[1] Markus Gross[1,2] Stelian Coros[3]

[1]ETH Zürich [2]Disney Research Zurich [3]Carnegie Mellon University

Abstract

We present an interactive design system that allows casual users to quickly create 3D-printable robotic creatures. Our approach automates the tedious parts of the design process while providing ample room for customization of morphology, proportions, gait and motion style. The technical core of our framework is an effi-

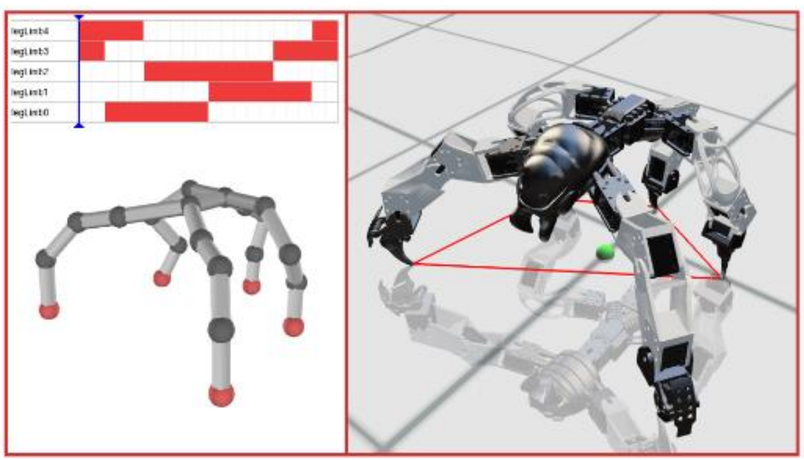


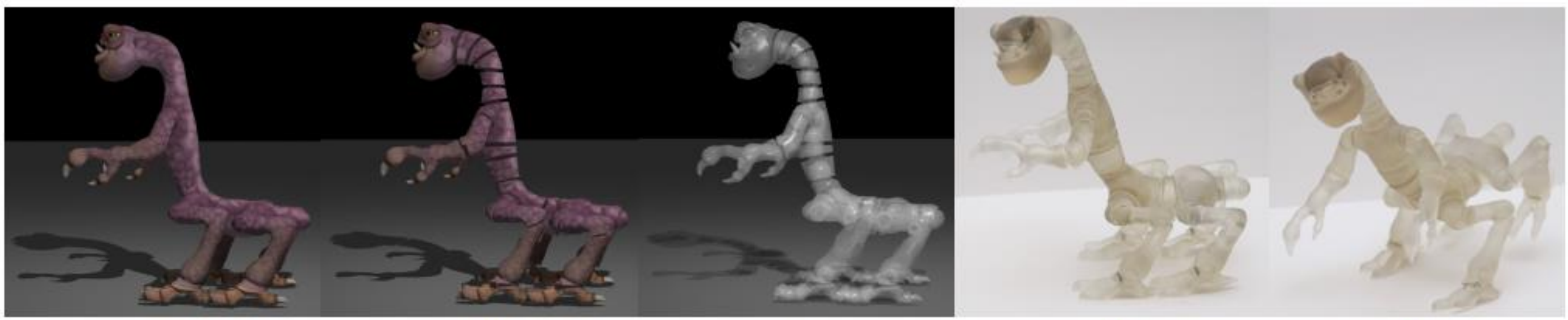
Figure 3: *Snapshot of the design interface.* Left*: the design viewport with the footfall pattern graph.* Right*: the preview window showing the center of pressure of the robot (green) and the support polygon (red).*

Figure 1: *Digital designs (left) and physical prototypes (right) for our* Ranger *(top),* Bobby *(middle) and* Predator *(bottom) designs, fabricated using 3D-printing and off-the-shelf servo motors.*

1. Articulating Workpieces

Fabricating Articulated Characters from Skinned Meshes

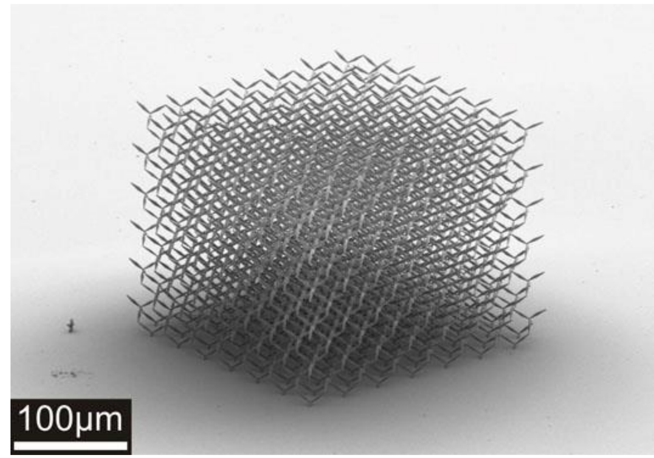
Moritz Bächer, Harvard University
Bernd Bickel, TU Berlin
Doug L. James, Cornell University
Hanspeter Pfister, Harvard University

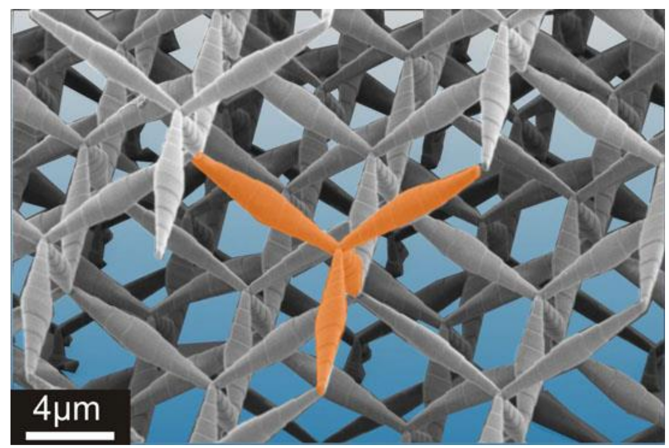


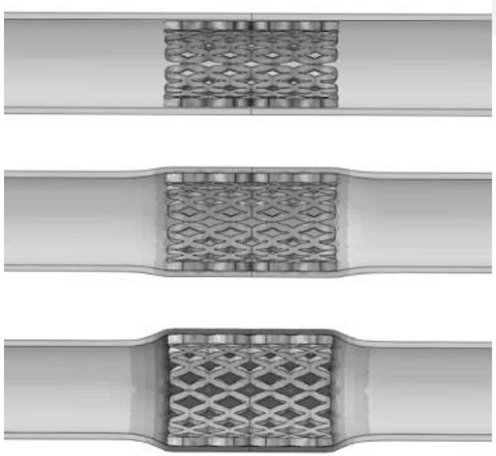
(a) (b) (c) (d) (e)

Figure 1: *Given a skinned mesh (a), we estimate (b) a fabricatable articulated character with (c) internal joints of hinge and ball-and-socket type. (d,e) Final 3D printed characters (transparent material) have durable joints with a frictional design for character posing.*

2.Controlling Deformability







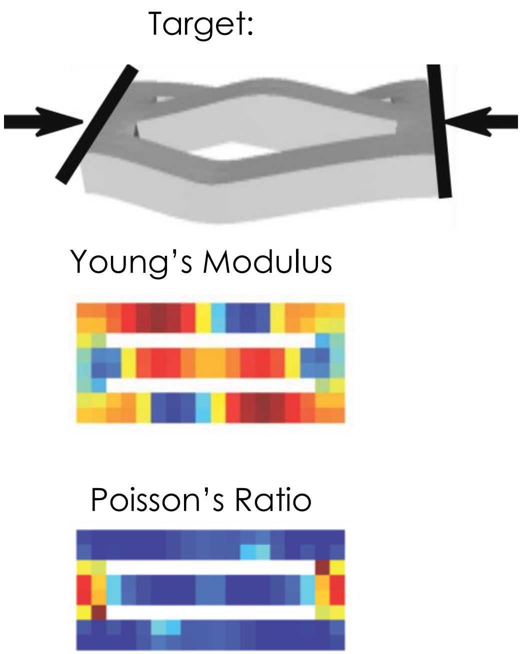
Small-scale microstructure “looks” homogenous

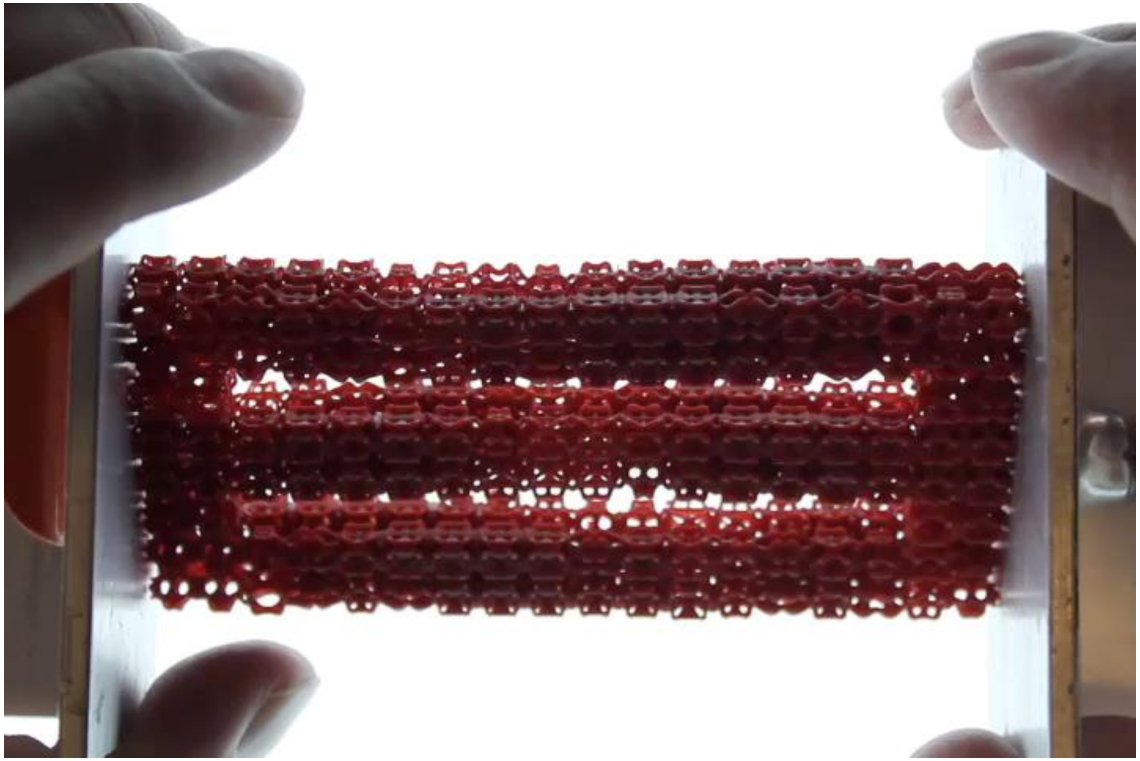
A lot of different patterns…

Goal: design microstructures for widest range of elastic behaviors …A library of Elastic Tensors

Elastic Textures for Additive Fabrication
Julian Panetta, Qingnan Zhou, Luigi Malomo, Nico Pietroni, Paolo Cignoni, Denis Zorin
Siggraph 2015,

2.Controlling Deformability





Elastic Textures for Additive Fabrication
Julian Panetta, Qingnan Zhou, Luigi Malomo, Nico Pietroni, Paolo Cignoni, Denis Zorin
Siggraph 2015

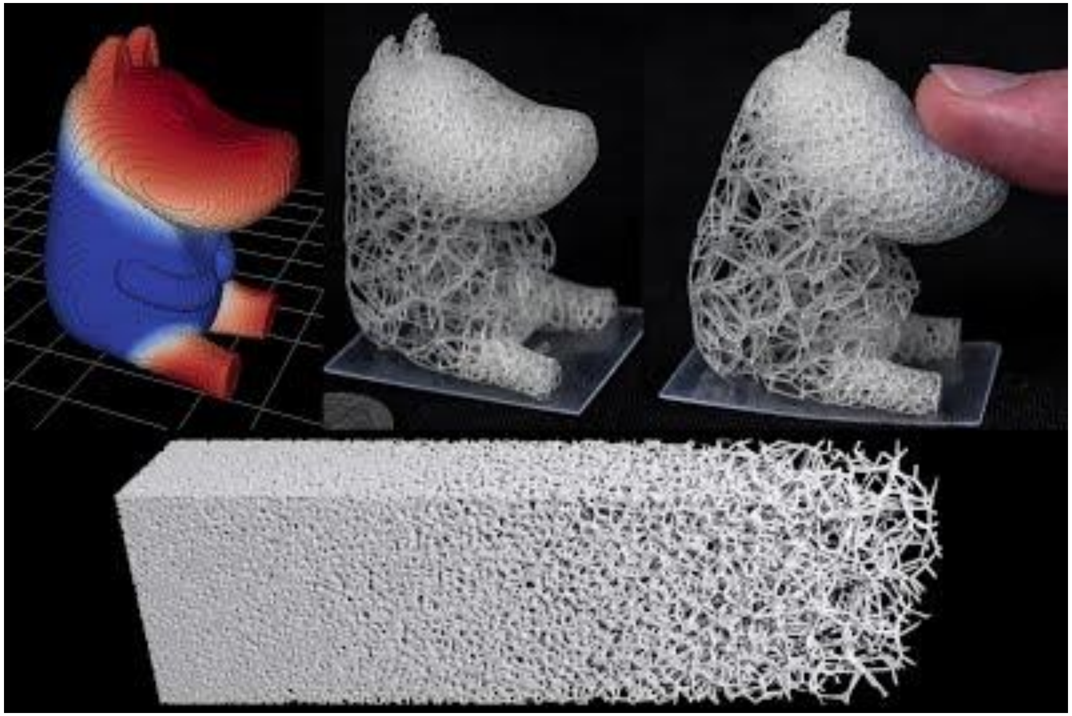
2.Controlling Deformability

Microstructures to Control Elasticity in 3D Printing

Christian Schumacher[1,2] Bernd Bickel[1,3] Jan Rys[2] Steve Marschner[4] Chiara Daraio[2] Markus Gross[1,2]
[1]Disney Research Zurich [2]ETH Zurich [3]IST Austria [4]Cornell University

Figure 1: *Given a virtual object with specified elasticity material parameters (blue=soft, red=stiff), our method computes an assemblage of small-scale structures that approximates the desired elastic behavior and requires only a single material for fabrication.*

2.Controlling Deformability



Procedural Voronoi Foams for Additive Manufacturing
Jonàs Martínez, Jérémie Dumas, Sylvain Lefebvre
SIGGRAPH 2016

2.Controlling Deformability

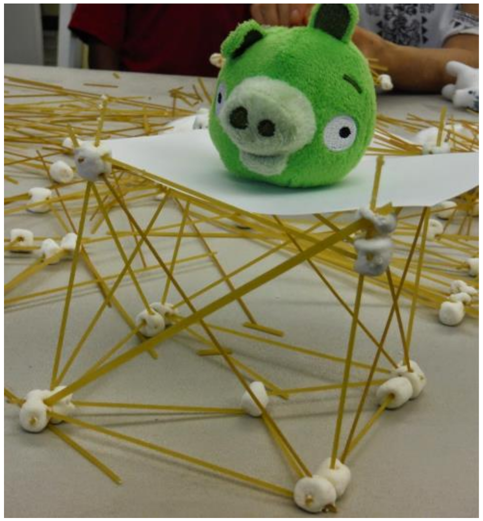
Microstructures to Control Elasticity in 3D Printing

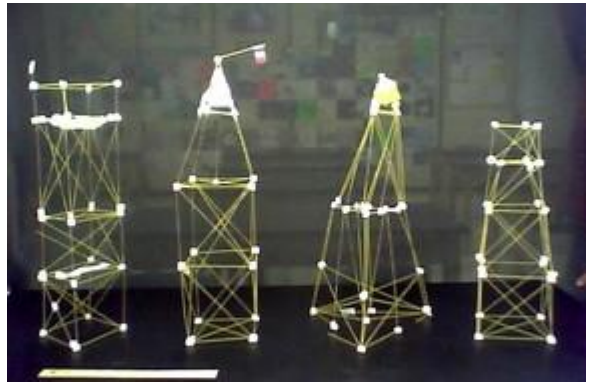
Christian Schumacher[1,2] Bernd Bickel[1,3] Jan Rys[2] Steve Marschner[4] Chiara Daraio[2] Markus Gross[1,2]

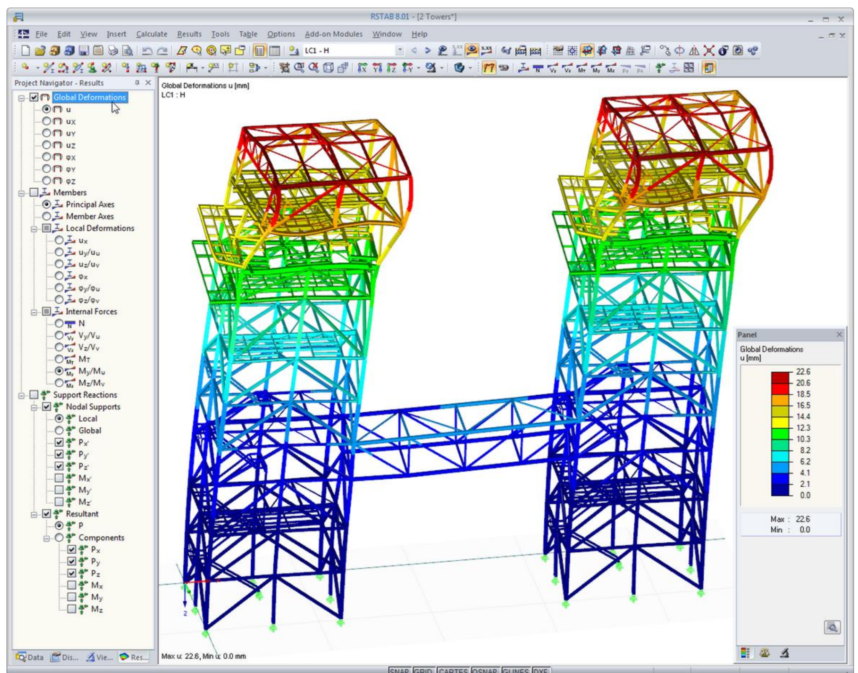
[1]Disney Research Zurich [2]ETH Zurich [3]IST Austria [4]Cornell University

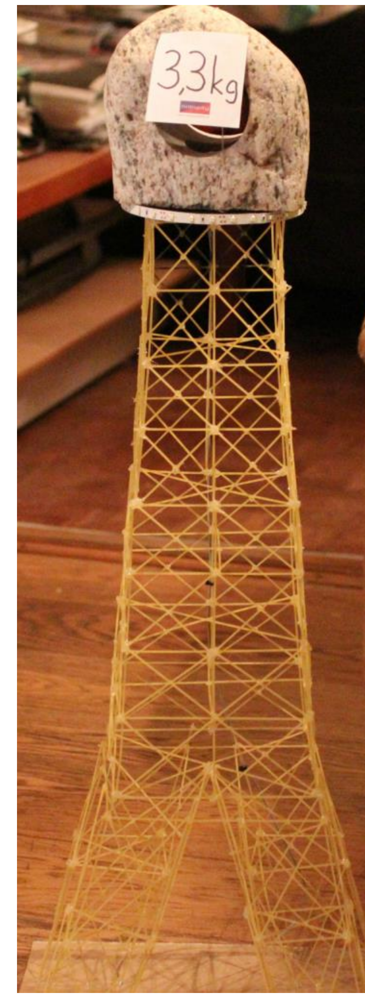
Figure 1: *Given a virtual object with specified elasticity material parameters (blue=soft, red=stiff), our method computes an assemblage of small-scale structures that approximates the desired elastic behavior and requires only a single material for fabrication.*

3.Structurally Functional Shapes

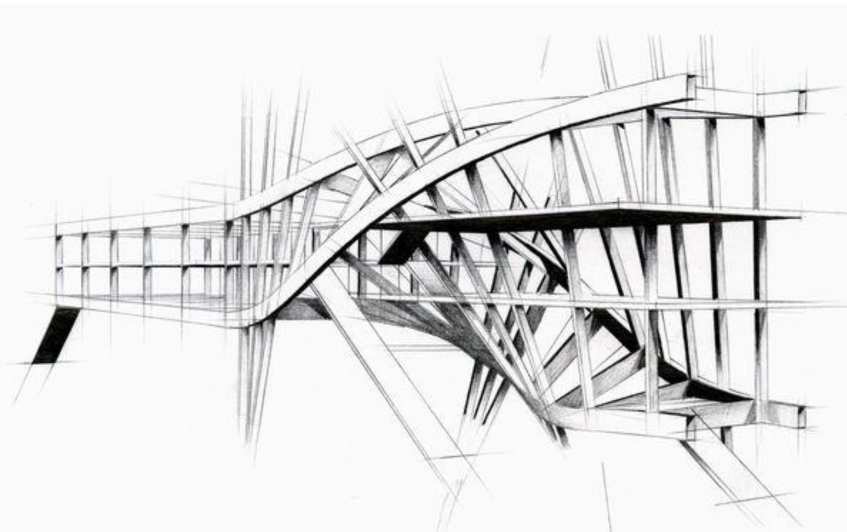


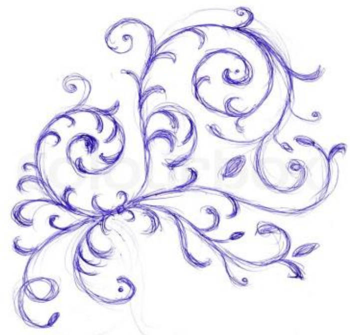


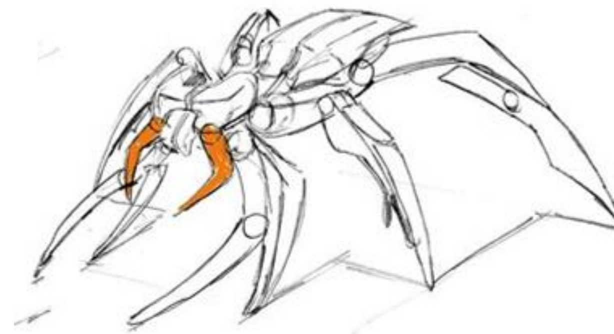


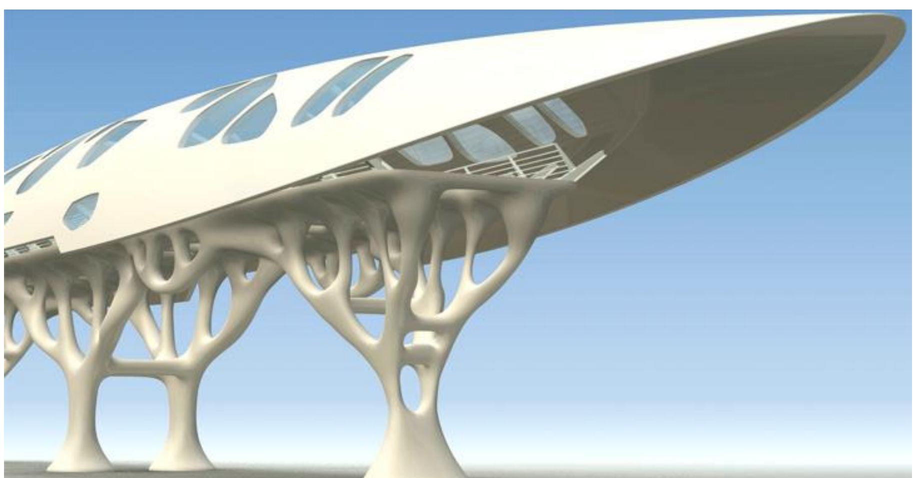


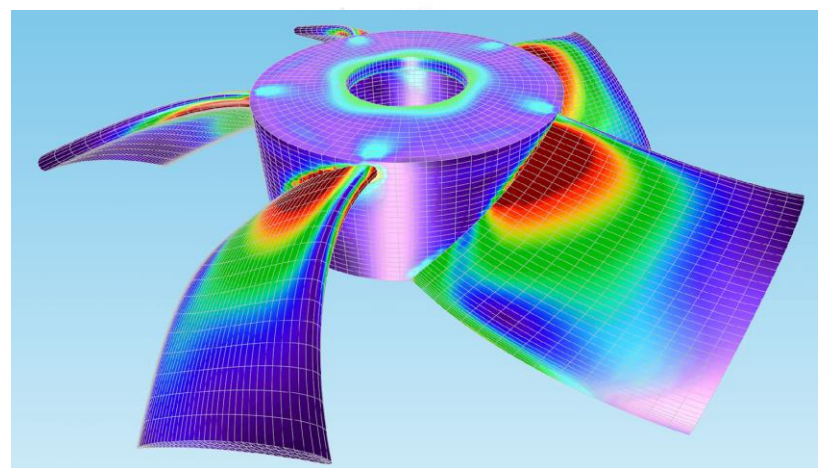
3.Structurally Functional Shapes











3.Structurally Functional Shapes

Stress Relief: Improving Structural Strength of 3D Printable Objects

Ondrej Stava[1] Juraj Vanek[1] Bedrich Benes[1] Nathan Carr[2] Radomír Měch[2]

[1] Purdue University [2] Adobe Systems Incorporated

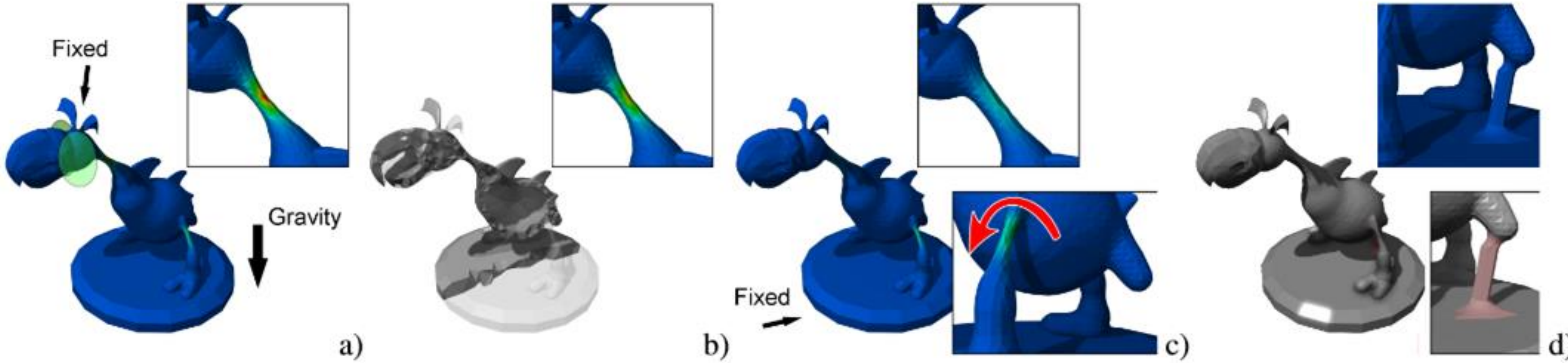


Figure 1: *A model of a dragon was first hollowed to reduce stress caused by its weight if held by the head (a). The stress decreased, but the neck had to be still thickened (b,c). The object was still too front heavy causing a twist deformation on the legs (c), that was eliminated by fixing the model to the pedestal by a strut (red) (d). These steps were done automatically by our system.*

3.Structurally Functional Shapes

Worst-case Structural Analysis

Qingnan Zhou,* Julian Panetta,† and Denis Zorin‡
New York University

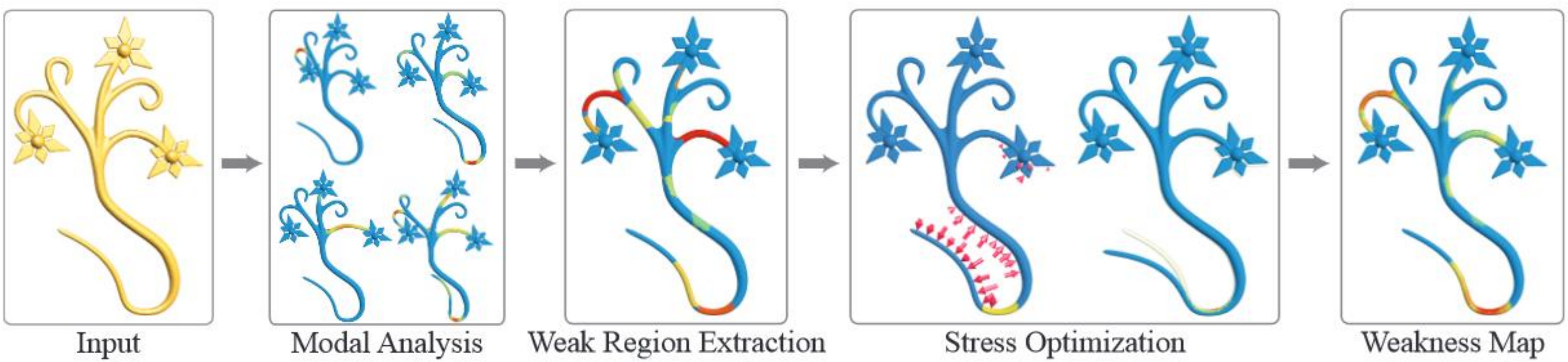


Figure 1: *Algorithm overview*

3.Structurally Functional Shapes

Cross-sectional Structural Analysis for 3D Printing Optimization

Nobuyuki Umetani,* Ryan Schmidt†
Autodesk Research

Abstract

We propose a novel *cross-sectional structural analysis* technique that efficiently detects critical stress inside a 3D object. We slice the object into cross-sections and compute stress based on bending momentum equilibrium. Unlike traditional approaches based on finite element methods, our method does not require a volumetric mesh or solution of linear systems, enabling interactive analysis speed. Based on the stress analysis, the orientation of an object is optimized to increase mechanical strength when manufactured with 3D printing.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling;

Keywords: structural analysis, optimization, 3D printing

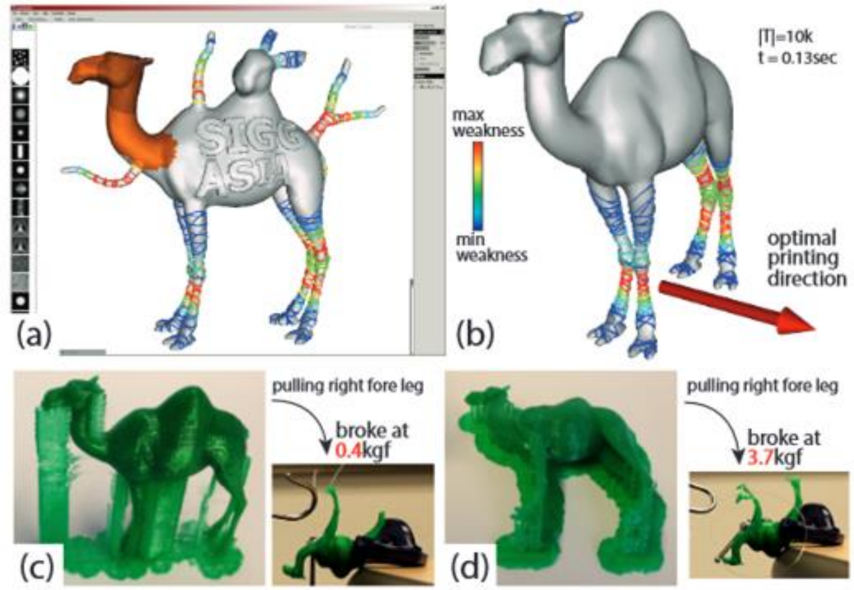


Figure 1: *(a) our system visualizes structural weakness at interactive rates during mesh editing. (b) A computed optimal printing direction. (c) A naïve printed model easily fractures under external force, while (d) the optimized print bears much larger forces.*

1 Introduction

Democratized digital manufacturing devices such as desktop 3D printers enable non-professionals to casually create physical ob-

3.Structurally Functional Shapes

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

Lin Lu[1]* Andrei Sharf[2] Haisen Zhao[1] Yuan Wei[1] Qingnan Fan[1] Xuelin Chen[1]
Yann Savoye[2] Changhe Tu[1] Daniel Cohen-Or[3] Baoquan Chen[1]†

[1] Shandong University [2] Ben-Gurion University [3] Tel Aviv University

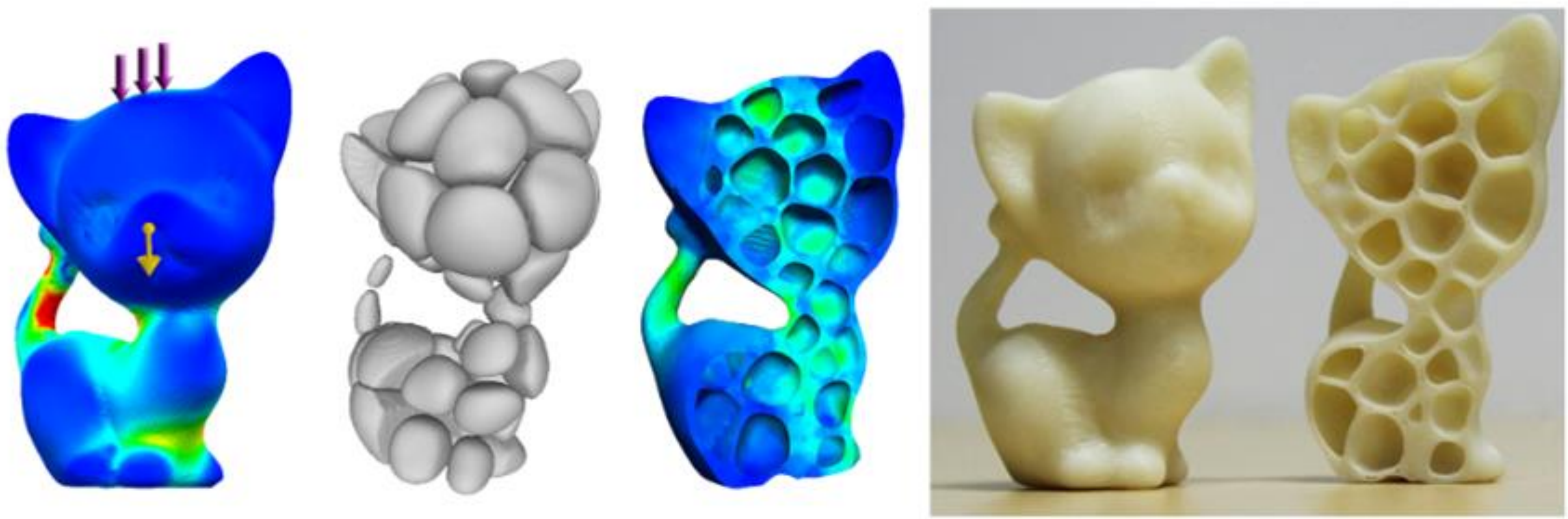


Figure 1: *We reduce the material of a 3D kitten (left), by carving porous in the solid (mid-left), to yield a honeycomb-like interior structure which provides an optimal strength-to-weight ratio, and relieves the overall stress illustrated on a cross-section (mid-right). The 3D printed hollowed solid is built-to-last using our interior structure (right).*

3.Structurally Functional Shapes

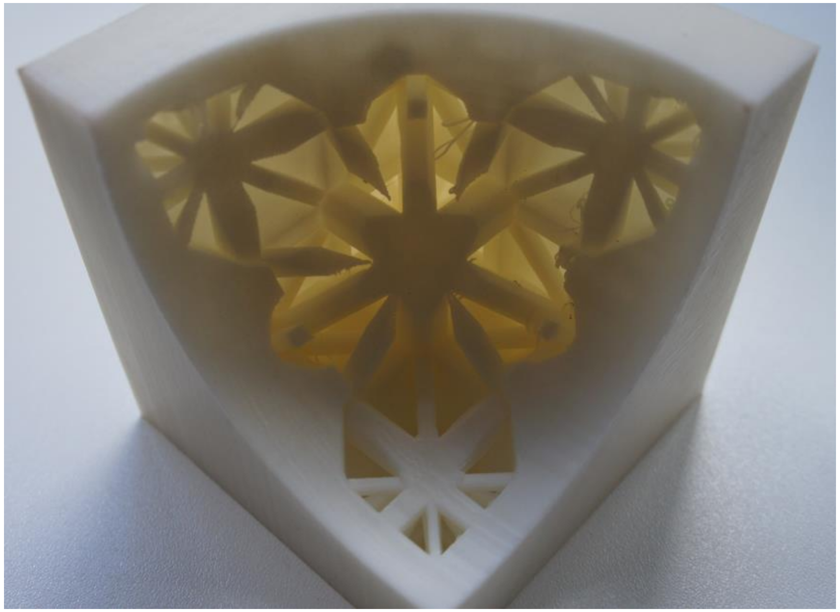
Cost-effective Printing of 3D Objects with Skin-Frame Structures

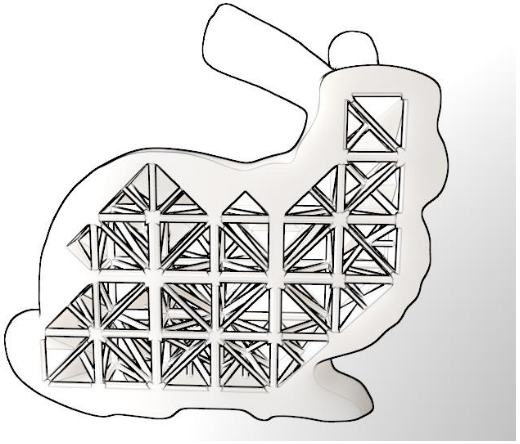
Weiming Wang[†,‡] Tuanfeng Y. Wang[†] Zhouwang Yang[†*] Ligang Liu[†] Xin Tong[§]
Weihua Tong[†] Jiansong Deng[†] Falai Chen[†] Xiuping Liu[‡]
[†]University of Science and Technology of China [‡]Dalian University of Technology [§]Microsoft Research Asia

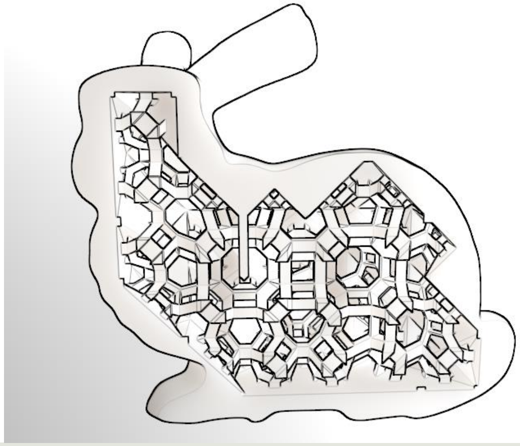
(a) (b) (c) (d)

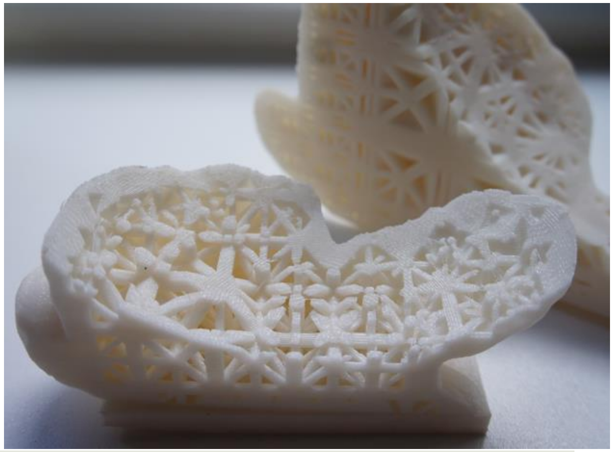
Figure 1: *Given an input Horse model (a), our method generates a skin-frame structure (b), which is approximate to the model, to minimize the cost of material used in printing it. The frame structure is designed to meet various constraints by an optimization scheme. In (b) we remove the front part of the skin in order to show the internal structure of frame. (c) is the photo of an printed model by removing part of its skin to see the internal struts. (d) is the photo of the printed model generated by our method. A small red drawing pin is put under the object as a size reference in (c) and (d) respectively. The material usage in (d) is only 15.0% of that of a solid object.*

3.Structurally Functional Shapes



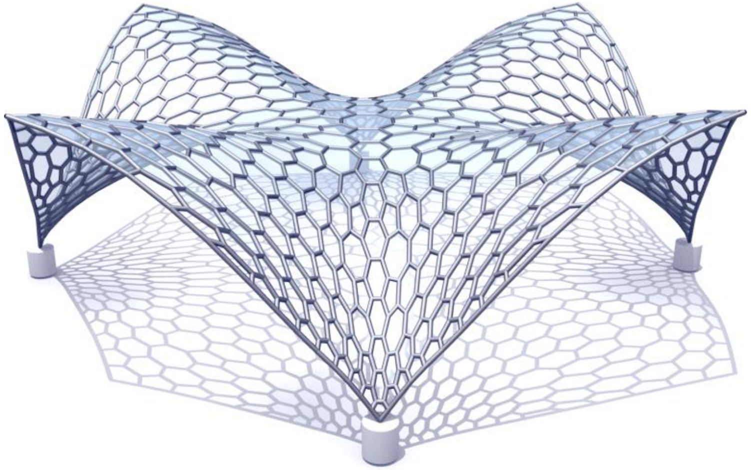


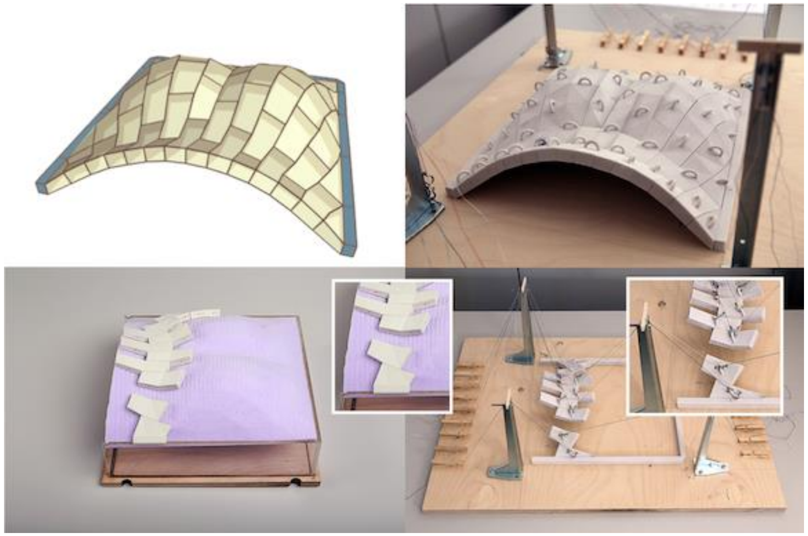




3.Structurally Functional Shapes: Architecture

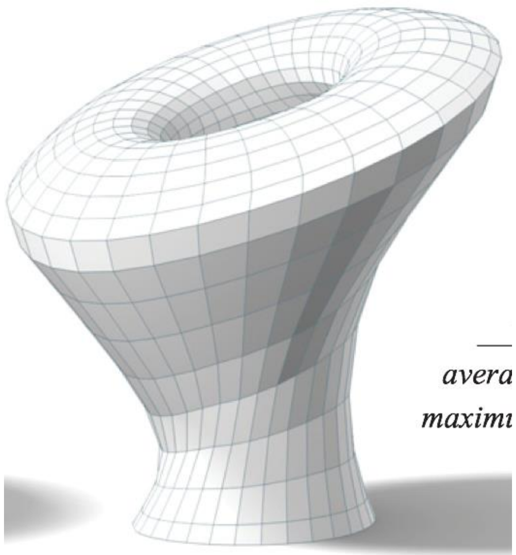
- Paneling
- Improving Performance
- Construction Plan



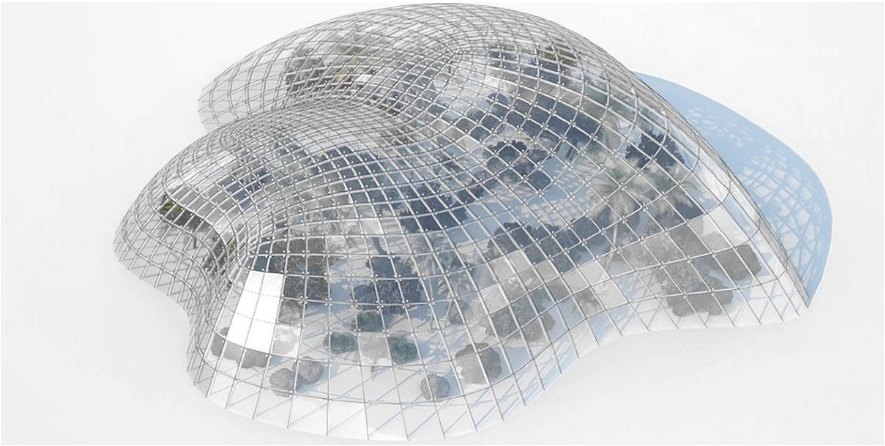


3. Architecture Paneling

- Planar faces are highly desirable
- Bending glass panel may be an expensive operation



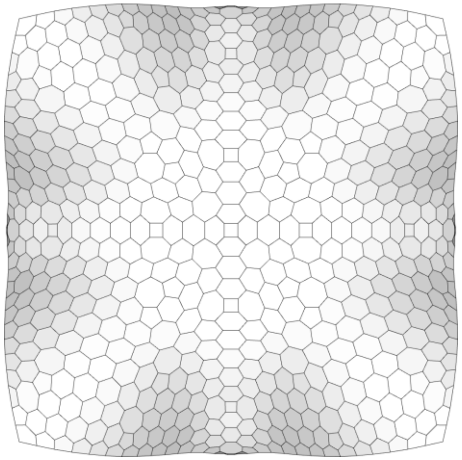
Shape-Up: Shaping Discrete Geometry with Projections

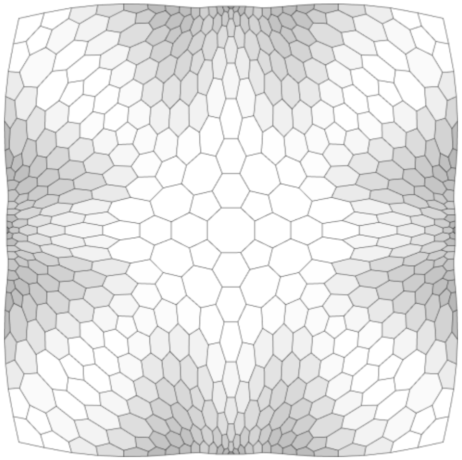


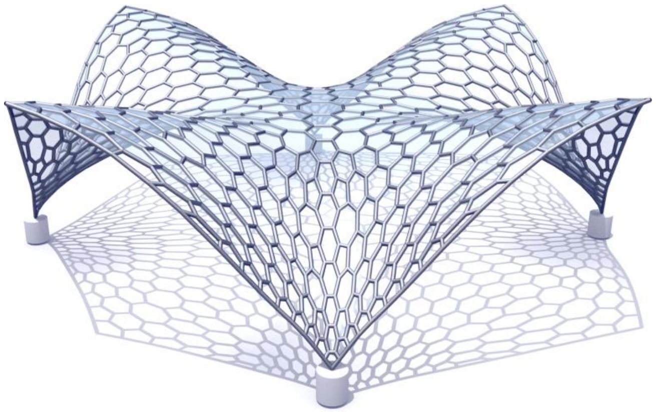
Form-finding with Polyhedral Meshes Made Simple

3. Architecture: Static performance

- **Optimize performances by changing the meshing**
- Keeping the overall weight constant
- Concentrate cells in region with higher stress
- Elongate cells along stress directions

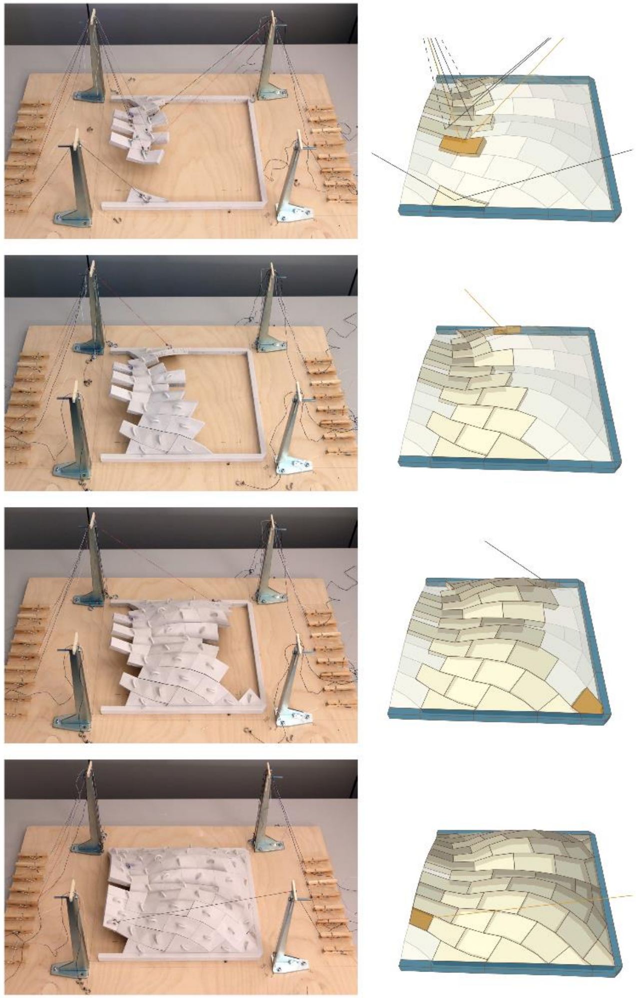


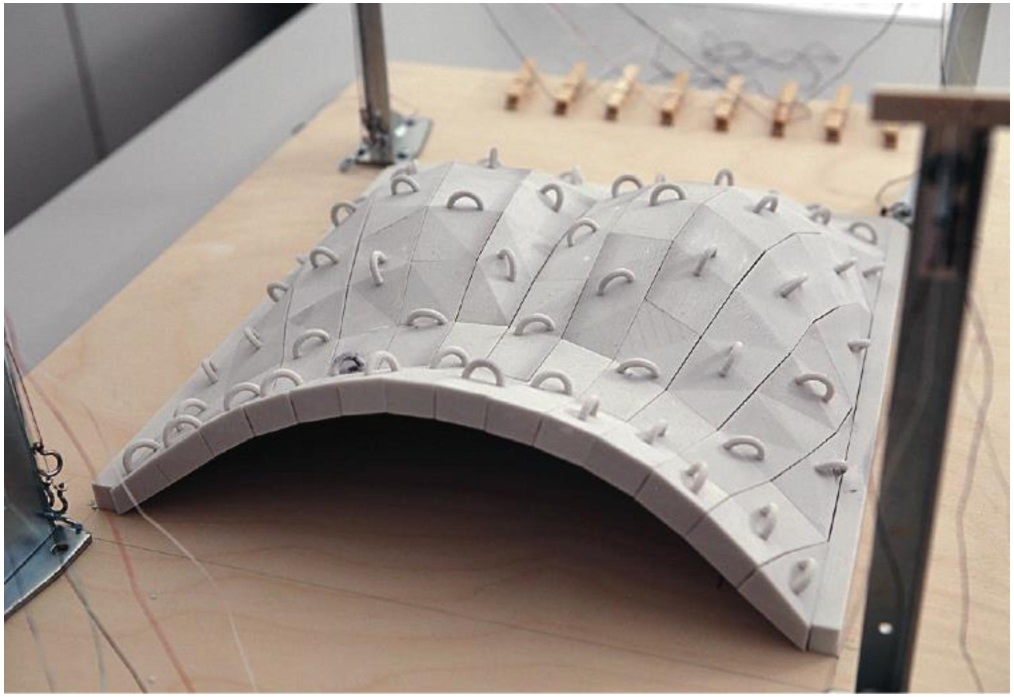




Statics Aware Grid Shells

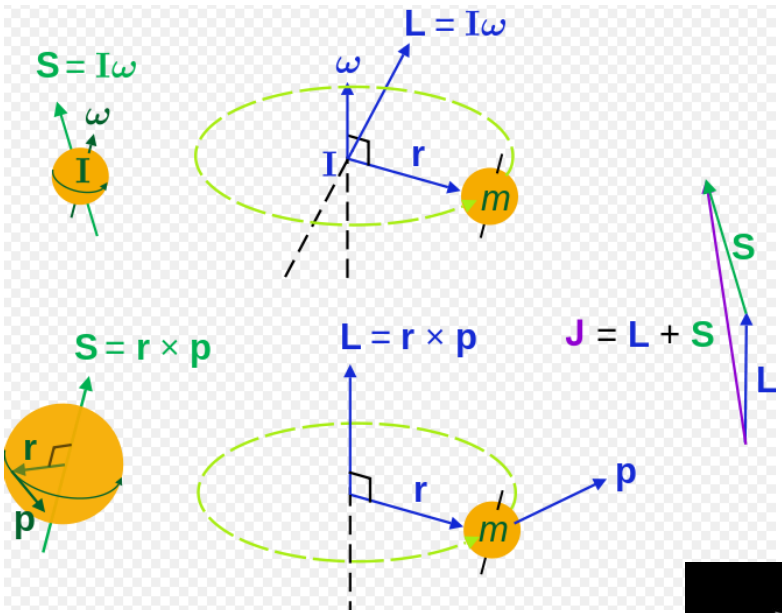
3. Architecture: Construction Plan

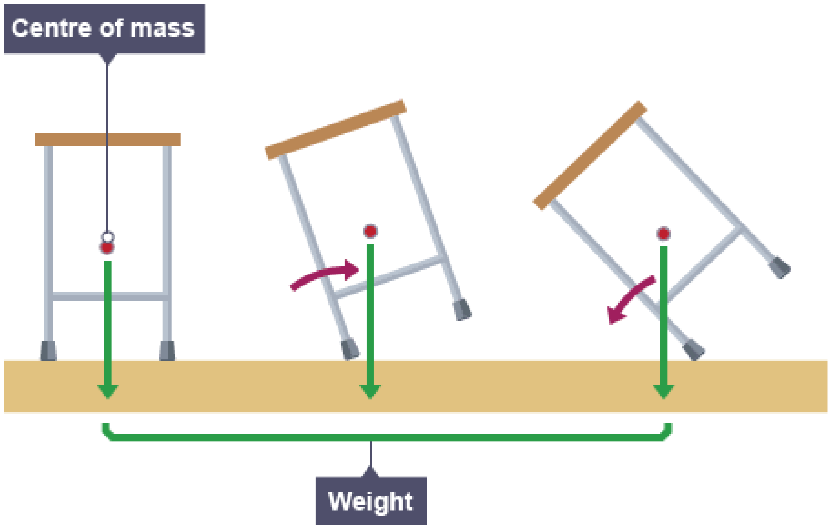


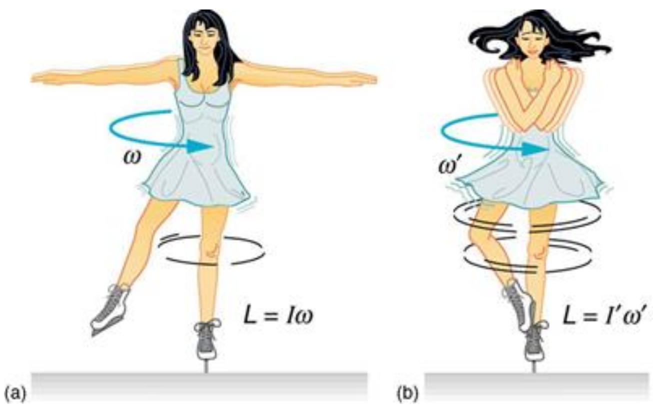


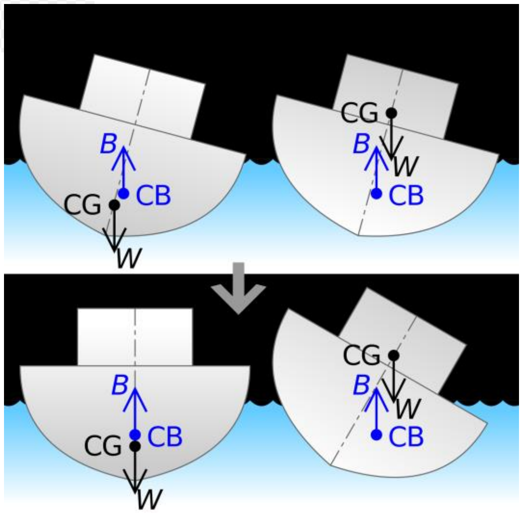
Assembling Self-Support Structures

4. Achieving Balance









4. Achieving Balance

Make It Stand: Balancing Shapes for 3D Fabrication

Romain Prévost[1] Emily Whiting[1] Sylvain Lefebvre[2] Olga Sorkine-Hornung[1]

[1]ETH Zurich [2]INRIA

(a) (b) (c) (d)

Figure 1: *Our algorithm iterates between carving and deformation to reach the final, balanced result. (a) The original horse model does not stand on its hind legs and requires using the tail as a third support. (b) Our approach deforms the horse to make it stand on a* single hind *leg. (c,d) The user scaled up the head of the T-Rex. Our optimizer succeeds in finding the delicate balance of a massive head and body on a tiny base of support. It deforms and carves the model (yellow region visible by transparency) to precisely position the center of mass.*

4. Achieving Balance

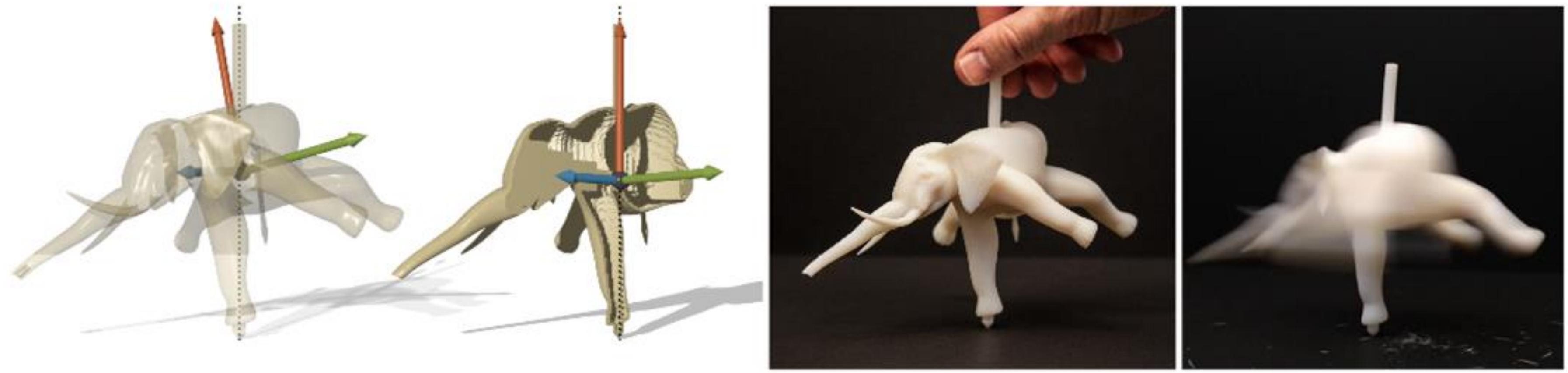
Spin-It: Optimizing Moment of Inertia for Spinnable Objects

Moritz Bächer
Disney Research Zurich

Emily Whiting
ETH Zurich

Bernd Bickel
Disney Research Zurich

Olga Sorkine-Hornung
ETH Zurich



(a) unstable input (b) hollowed, optimized model (c) our spinning top design (d) elephant in motion

Figure 1: *We introduce an algorithm for the design of spinning tops and yo-yos. Our method optimizes the inertia tensor of an input model by changing its mass distribution, allowing long and stable spins even for complex, asymmetric shapes.*

4. Achieving Balance

Guided Exploration of Physically Valid Shapes for Furniture Design

Nobuyuki Umetani
University of Tokyo

Takeo Igarashi
Univ. of Tokyo / JST Erato

Niloy J. Mitra
University College London

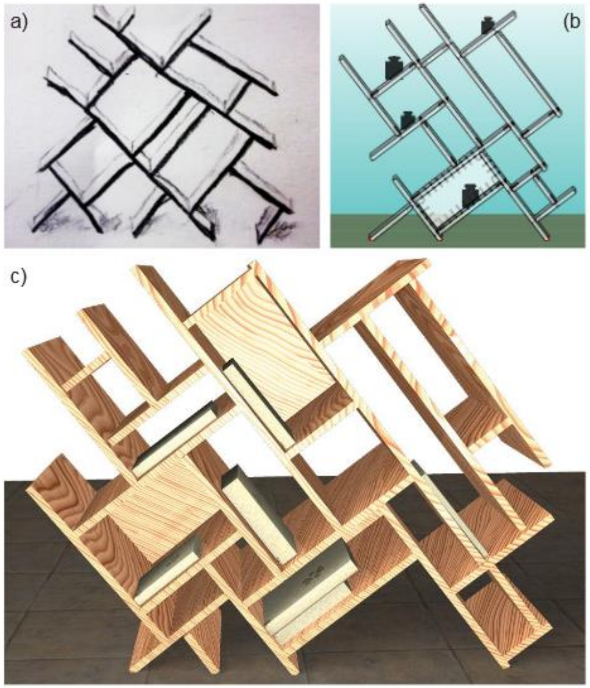


Figure 1: Modeling a design concept (a) often produces invalid 3D realizations (b) due to model instability (i.e., toppling) or non-durability (i.e., excessive joint force) under target loads. Our interactive computational design framework supports guided shape exploration to help the user reach a valid configuration, which can then be readily manufactured (c).

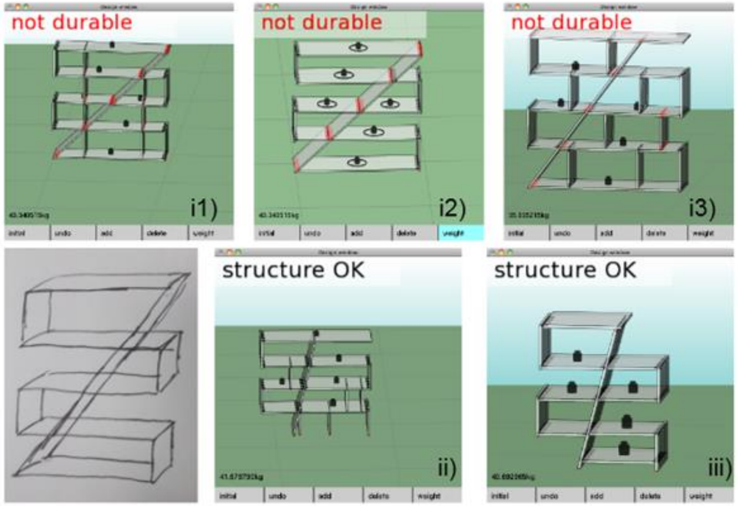


Figure 19: Starting from a design concept (bottom-left), three failed attempts with no feedback or suggestions (i1-3), using only feedback without suggestions (ii), and results using our system (iii).

4. Achieving Balance

Buoyancy Optimization for Computational Fabrication

L. Wang and E. Whiting

Dartmouth College, USA

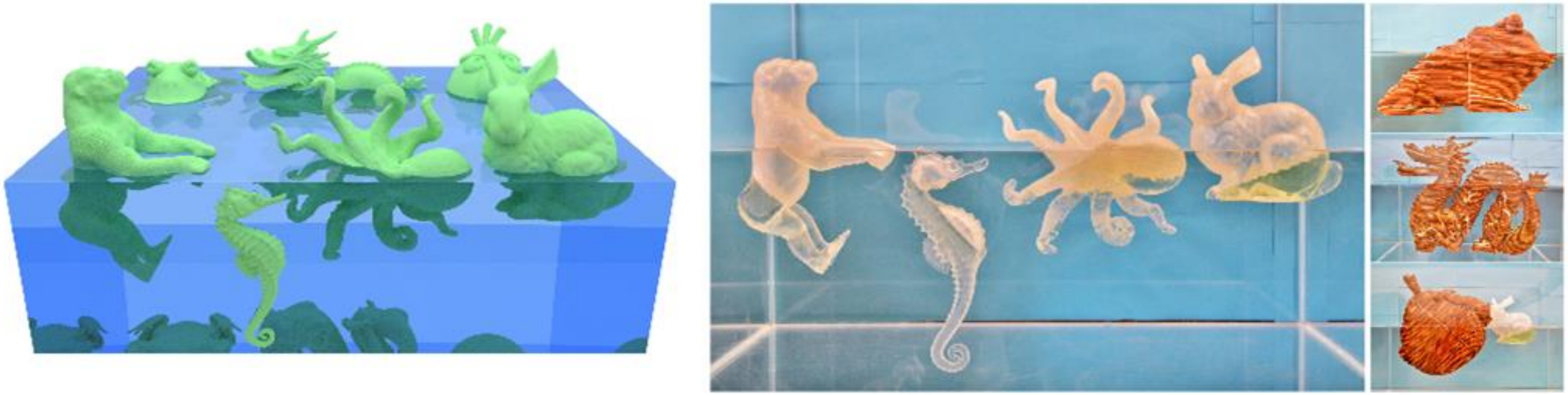
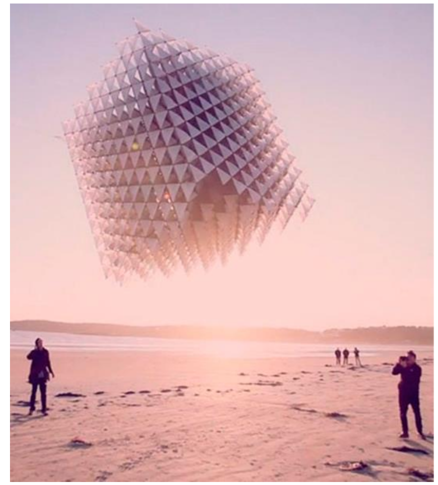
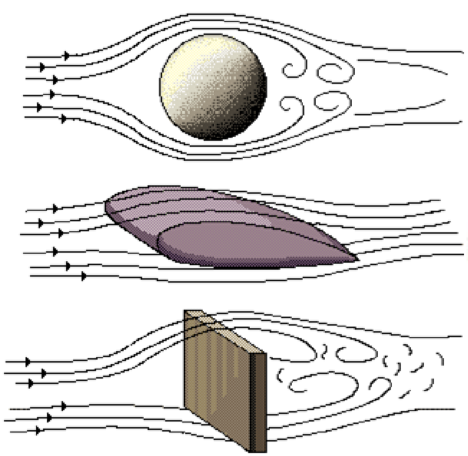
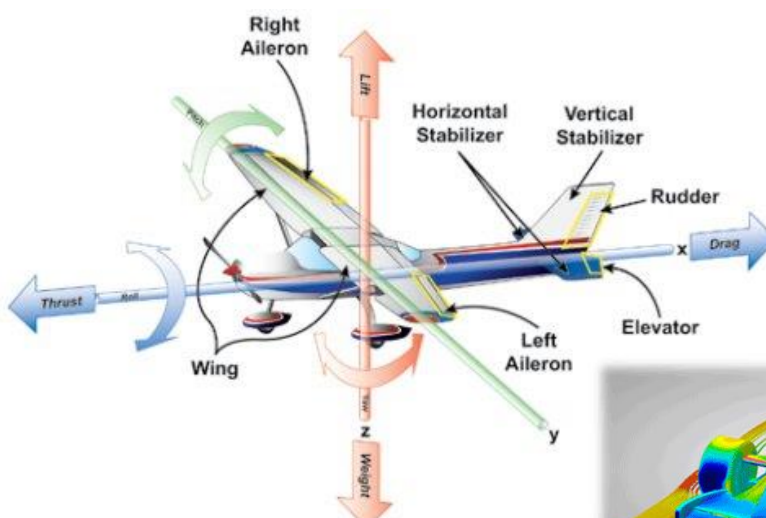


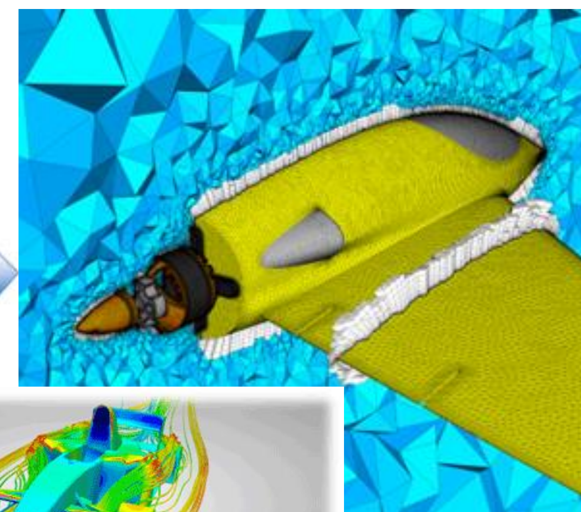
Figure 1: We introduce a novel design objective for 3D objects that float in user-specified ways. The user chooses the desired orientation and waterline (left). An optimization determines the internal configurations necessary for the shapes to float in the desired positions. The shapes can then be 3D printed and dropped in a water tank (right). For shapes too large to be efficiently 3D printed, we introduce a construction method using laser-cut, plywood slices (far right).

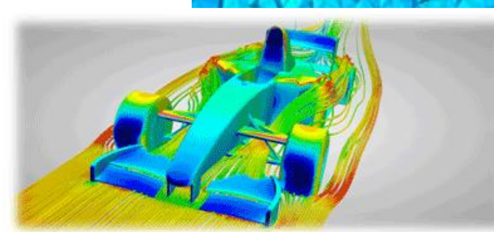
5. Capturing Aereodynamics











5. Capturing Aereodynamics

Pteromys: Interactive Design and Optimization of Free-formed Free-flight Model Airplanes

Nobuyuki Umetani[1,2]* Yuki Koyama[1] Ryan Schmidt[2] Takeo Igarashi[1]
[1]The University of Tokyo / JST ERATO [2]Autodesk Research

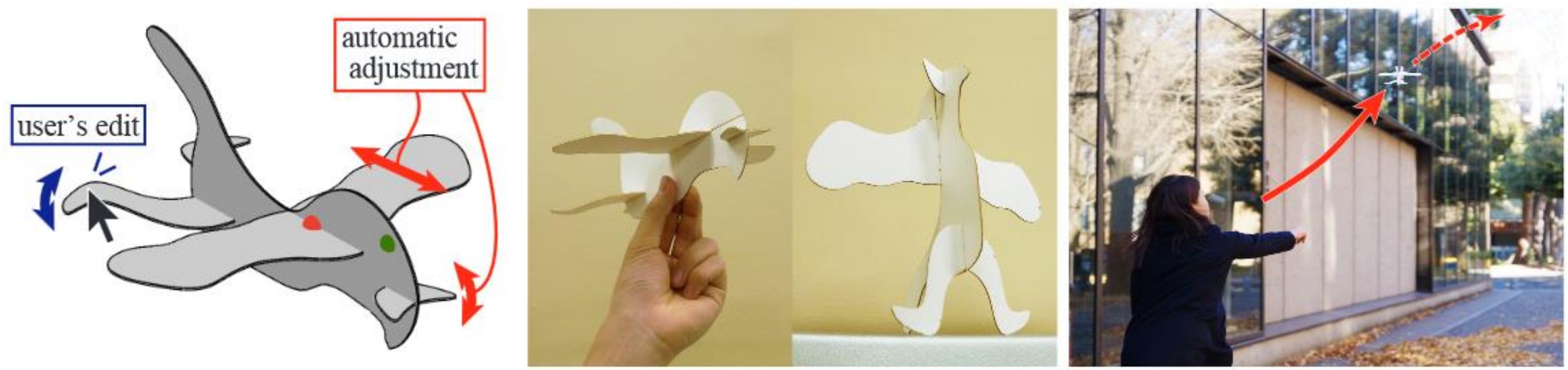


Figure 1: *(Left) Our model airplane design tool analyzes the aerodynamic properties of a glider and optimizes while the user interactively designs the plane. (Center) The user fabricates the airplane. (Right) The airplane actually flies.*

5. Capturing Aereodynamics

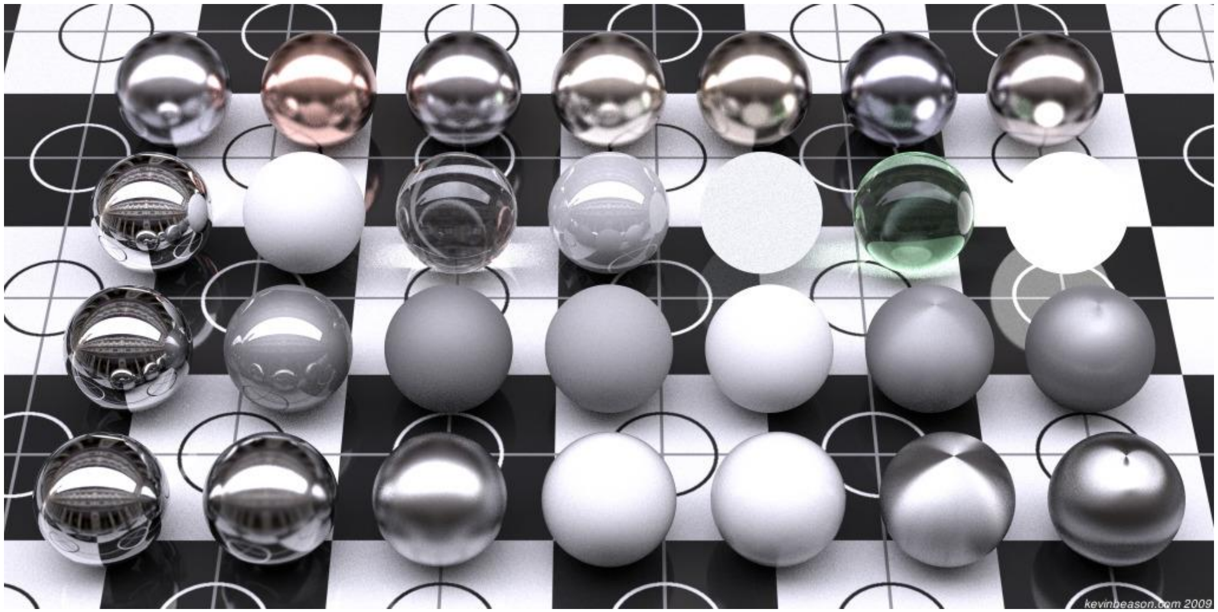
OmniAD: Data-driven Omni-directional Aerodynamics

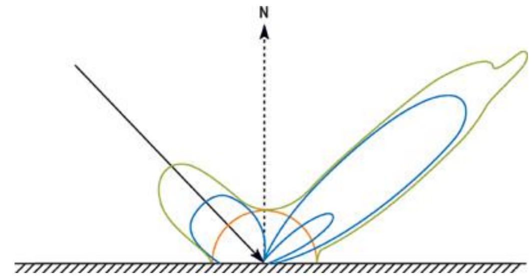
Tobias Martin* — ETH Zürich
Nobuyuki Umetani* — Disney Research Zürich
Bernd Bickel — IST Austria

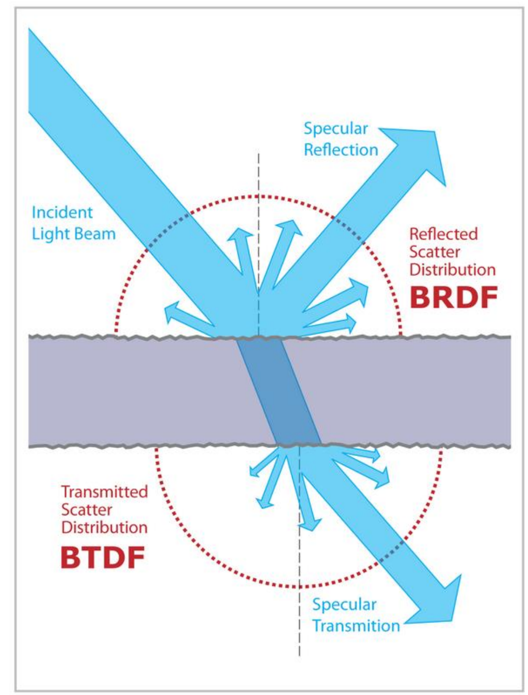
(a) example falling motion
(b) omni-directional aerodynamics model
(c) real-time simulation
(d) flyable kite design

Figure 1: *(a) Example sequence of a falling heart-shaped foam object. (b) Acquired omni-directional aerodynamic property for force and torque generated by air. (c) Real-time simulation of many hearts. (d) Flyable design of a kite carrying the heart inside.*

6. Appearance





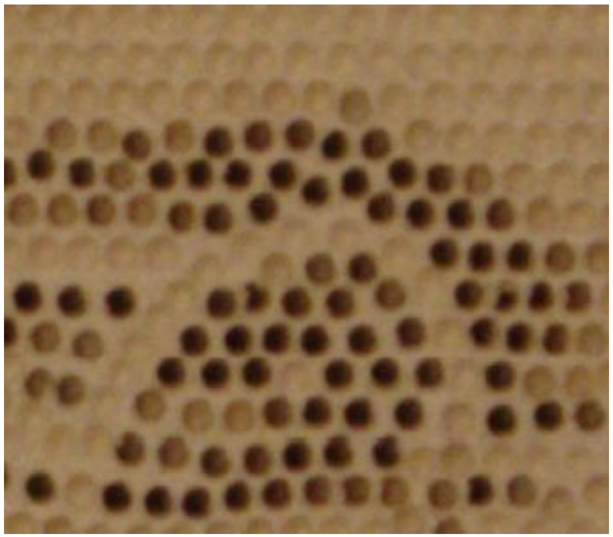


6. Appearance

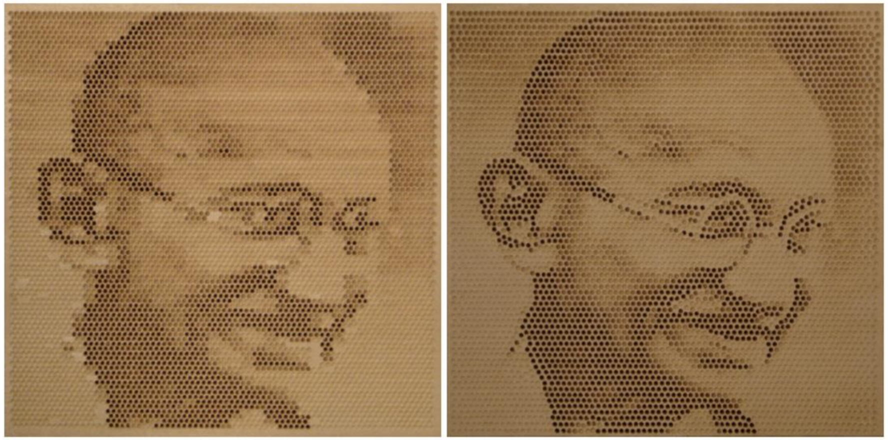
[Cignoni(2008]

6. Appearance

Multi material 3D-prints [Hasan et al. 2010]

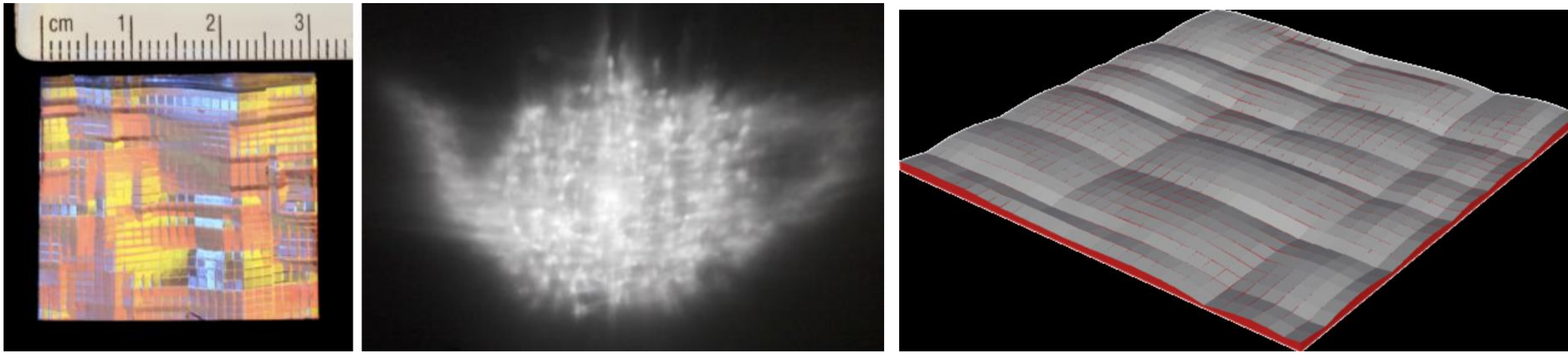


3D Printing svBRDF [2013]
O. Rouiller, B. Bickel, J. Kautz, W. Matusik and M. Alexa



Alexa and Matusik [2011]

6. Appearance



Milling a BRDF [Weyrich et al. 2007]

Kiser et al. [2013]

Conclusions and Future Work