Interactive Design and Simulation of Material and Damping

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USC

Dynamics in the Real World

muscle

cloth

hair

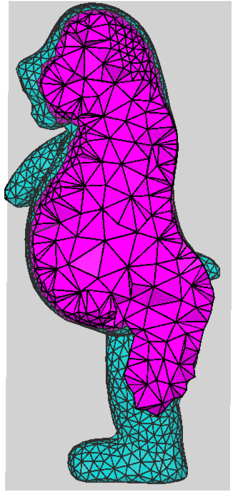
tree

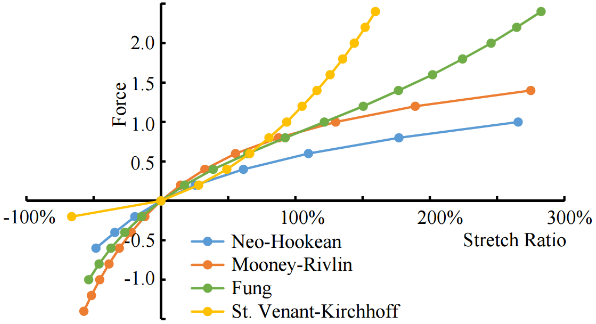
rigid bodies

fluid

Physically-Based Simulation

Geometric modeling ⇨ Material modeling ⇨ Simulation ⇨ 3D fabrication





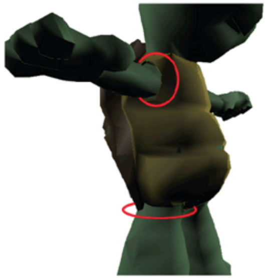
(src: [Wang & Yang 2016])

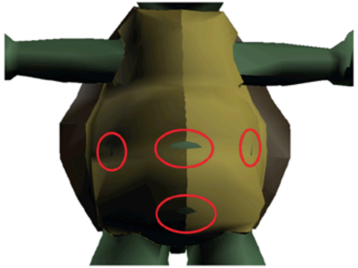
My PhD Research Work Overview

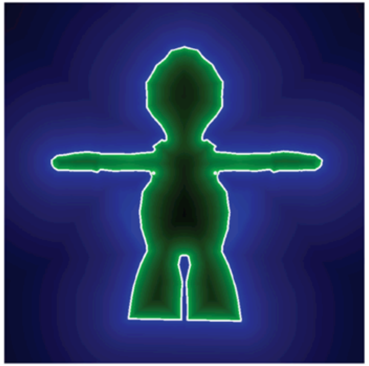
Geometric modeling ⇨ Material modeling ⇨ Simulation ⇨ 3D fabrication

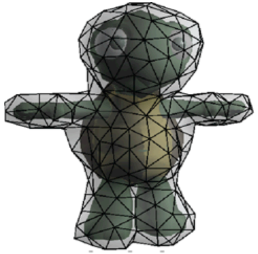

components of turtle


overlapping and colliding geometry


self-intersection


non-manifold geometry


signed distance field


coarse tetrahedral mesh

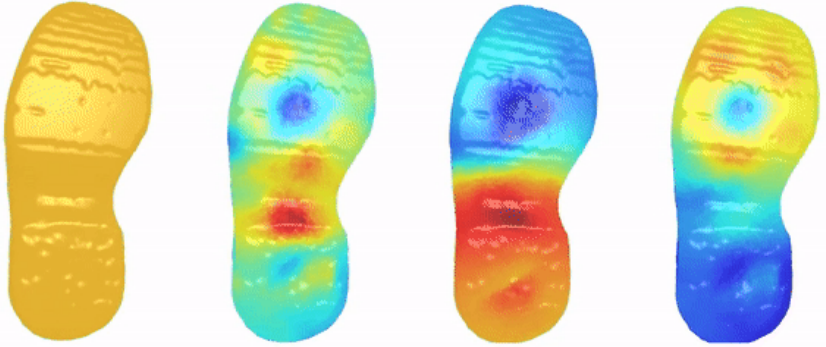

fine tetrahedral mesh

Signed distance fields for polygon-soup geometries [Xu & Barbič 2014]

My PhD Research Work Overview

Geometric modeling ⇨ Material modeling ⇨ Simulation ⇨ 3D fabrication

Nonlinear material
[Xu et al SIGGRAPH 2015]



Heterogeneous material
[Xu et al TOG 2015]

Anisotropic nonlinear damping
[Xu & Barbič SIGGRAPH 2017]

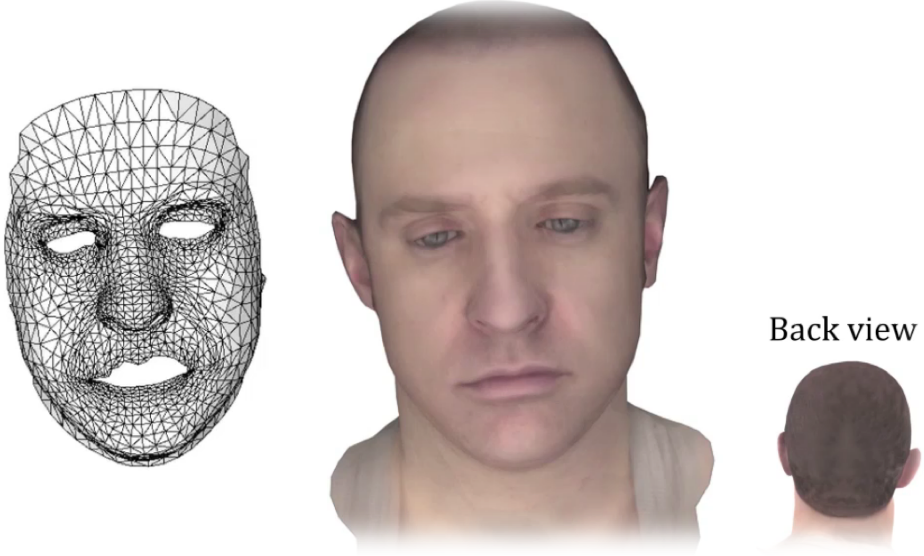
My PhD Research Work Overview

Geometric modeling

Material modeling

Simulation

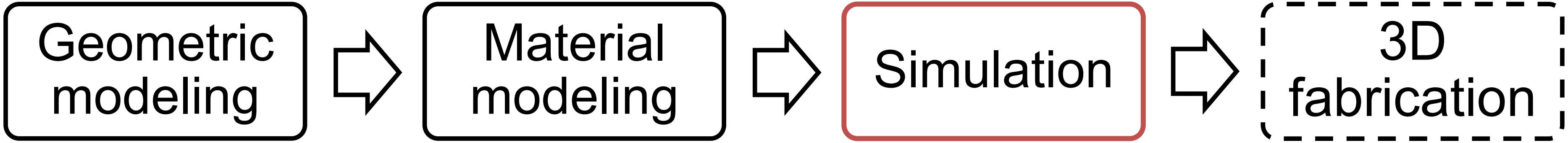
3D fabrication

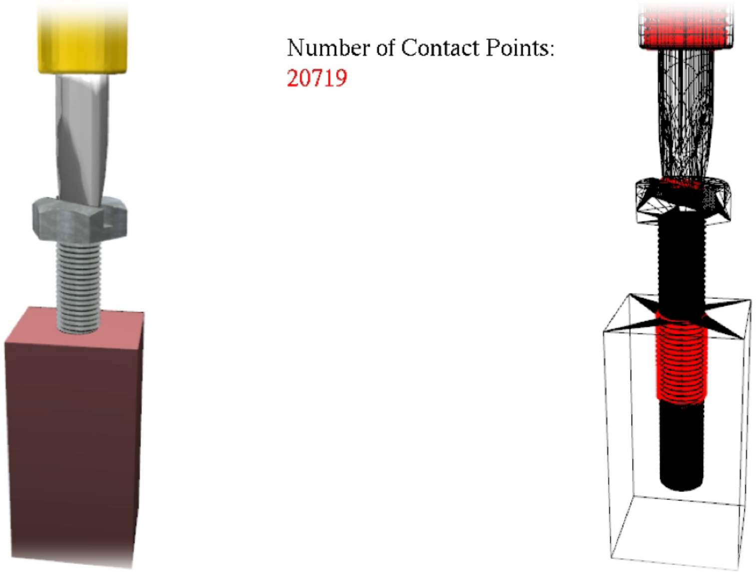


Animation with secondary dynamics

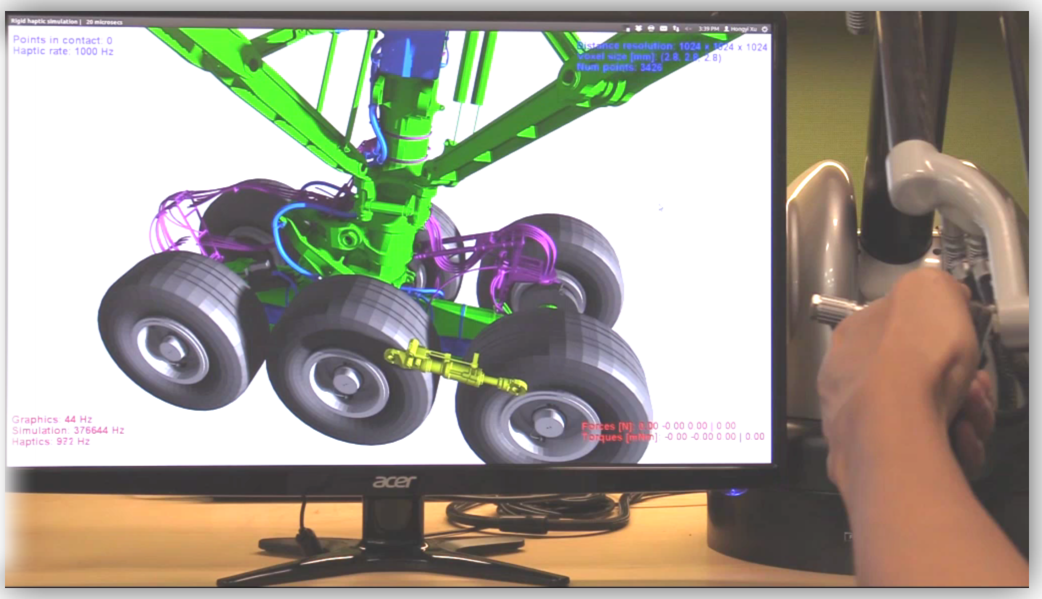
[Li et al 2016] [Xu & Barbič SIGGRAPH 2016]

My PhD Research Work Overview





Implicit penalty contact
[Xu et al 2014]



Adaptive stiffness scaling & continuous collision detection
[Xu & Barbič 2016] [Xu & Barbič 2016]

My PhD Research Work Overview

Performance + Realism + Controllability

Geometric modeling → Material modeling → Simulation → 3D fabrication

Geometric modeling:

[Xu & Barbič 2014]

Material modeling:

[Xu et al 2015]
[Xu et al 2015]
[Xu & Barbič 2017]

Simulation:

[Li et al 2016]
[Xu & Barbič 2016]

[Xu et al 2014]
[Xu & Barbič 2016]
[Xu & Barbič 2016]

3D fabrication:

[Xu et al 2015]

Outline

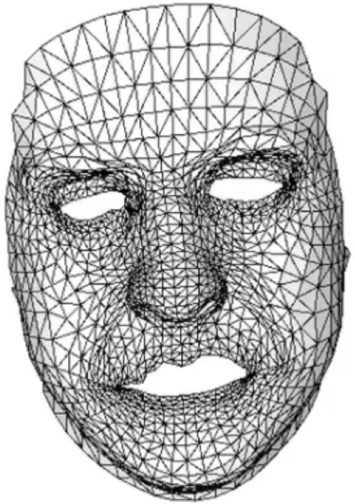
- Adding Physics to Character Animation in *Real-Time*
- *Interactive* and *Intuitive* Design of *Elastic Materials* and *Damping*

Adding Physics to Character Animation in *Real-Time*

Animation techniques:

keyframing

rigging

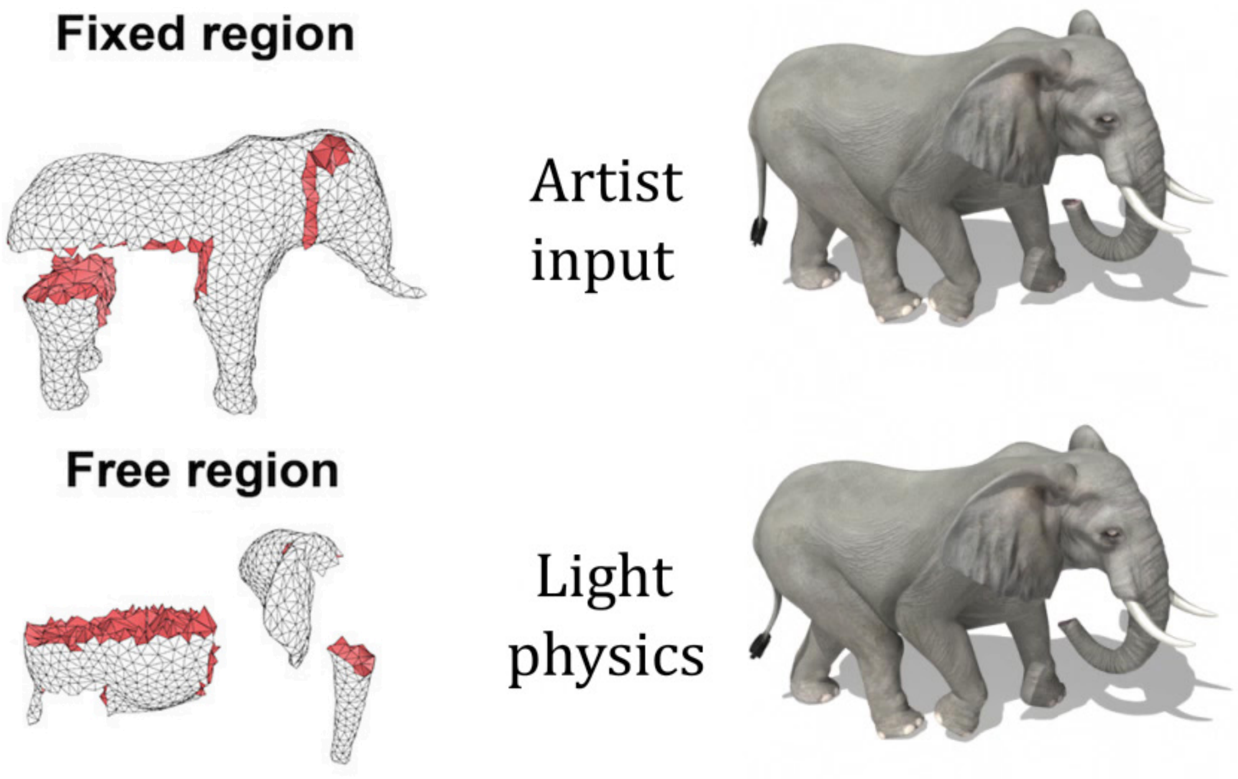


performance capture

Enriching Triangle Mesh Animations With Physically Based Simulation

IEEE TRANSACTIONS ON
VISUALIZATION AND COMPUTER GRAPHICS
A PUBLICATION OF THE IEEE COMPUTER SOCIETY

Yijing Li, Hongyi Xu, Jernej Barbič



Pose-Space Subspace Dynamics

Hongyi Xu, Jernej Barbič

Standard rigging

No dynamics

Our method: real-time FEM dynamics

1800 FPS

Our Solution: Pose-Space Model Reduction

Character Rigging + Pose-Space Deformation
(standard animation pipeline)

+

Finite Element Method
(physically-based simulation)

+

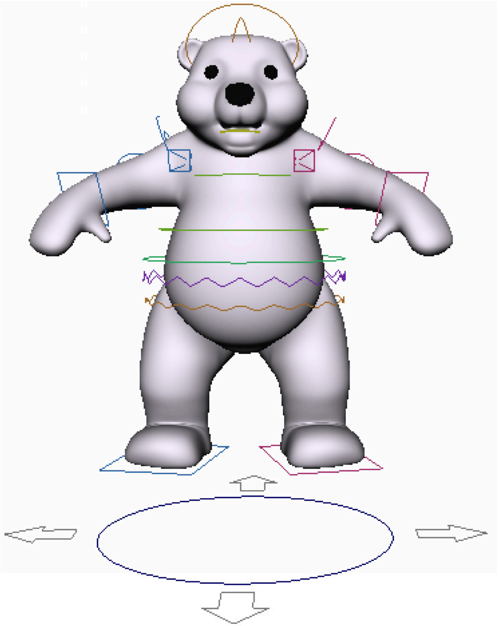
Pose-Space Model Reduction
(real-time performance)

Animation Rig

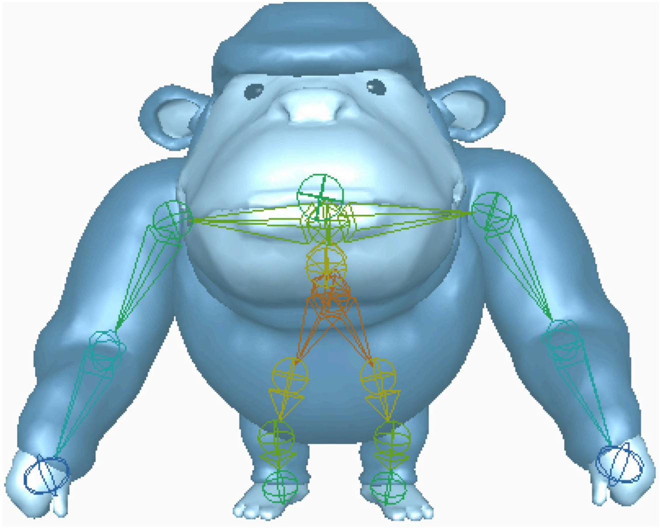
$$p \rightarrow \bar{\Phi}(p, \bar{X})$$

rig control parameters

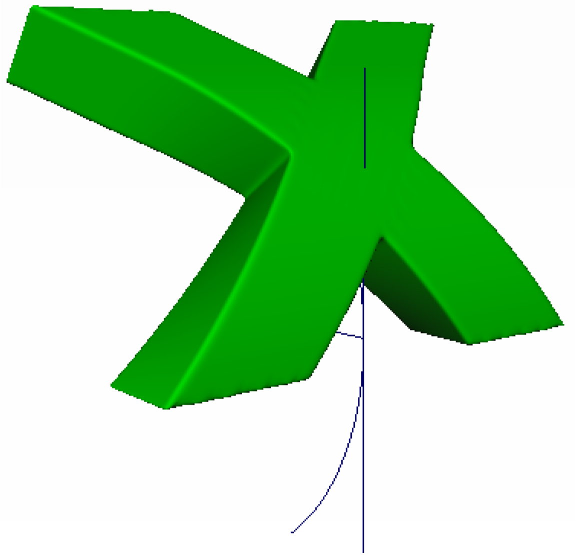
mesh vertices positions



Wire Deformer



Skeleton



Nonlinear Deformer

Pose-Space Deformation

$$p \rightarrow \bar{\Phi}(p, \bar{X}) + \bar{\delta}(p)$$

$$\bar{\delta}(p) = \sum_{i=1}^{m} w_i(p)\, \bar{\delta}_i$$

interpolated
pose correction

normalized
RBF weights

corrections on
example poses

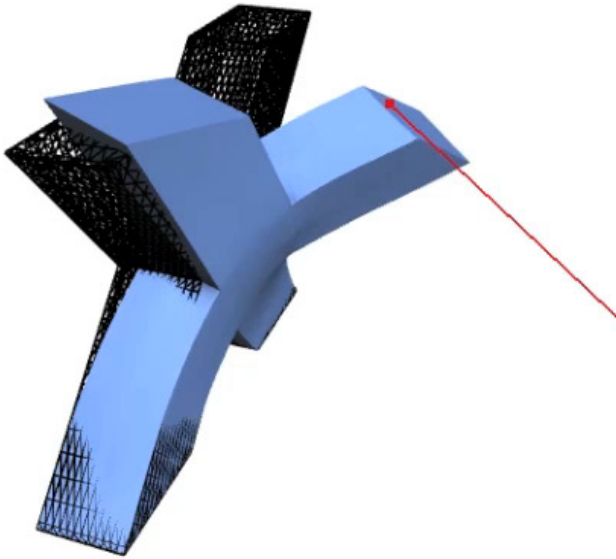
[Lewis et al 2000]

Adding FEM Physics to Pose-Space Deformation

$$M\ddot{u} + D\dot{u} + f_{\text{int}}(\boxed{\Phi(p)}, u) = f_{\text{ext}} \boxed{+ f_{\text{inert}}}$$

Treat each rigged shape $\Phi(p)$
as ***a new rest shape***

Add ***inertial forces*** due to the rig motion

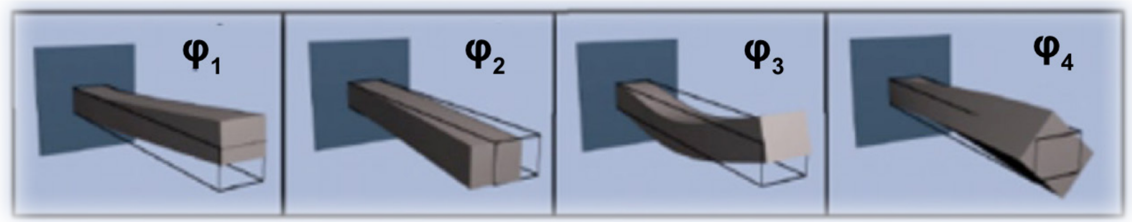


Use Model Reduction for Speed

$$M\ddot{u} + D\dot{u} + f_{\text{int}}(\Phi(p), u) = f_{ext} + f_{inert}$$

- Subspace approximation:

$$u = Uq$$



Reduced equation:

[Barbič and James 2005]

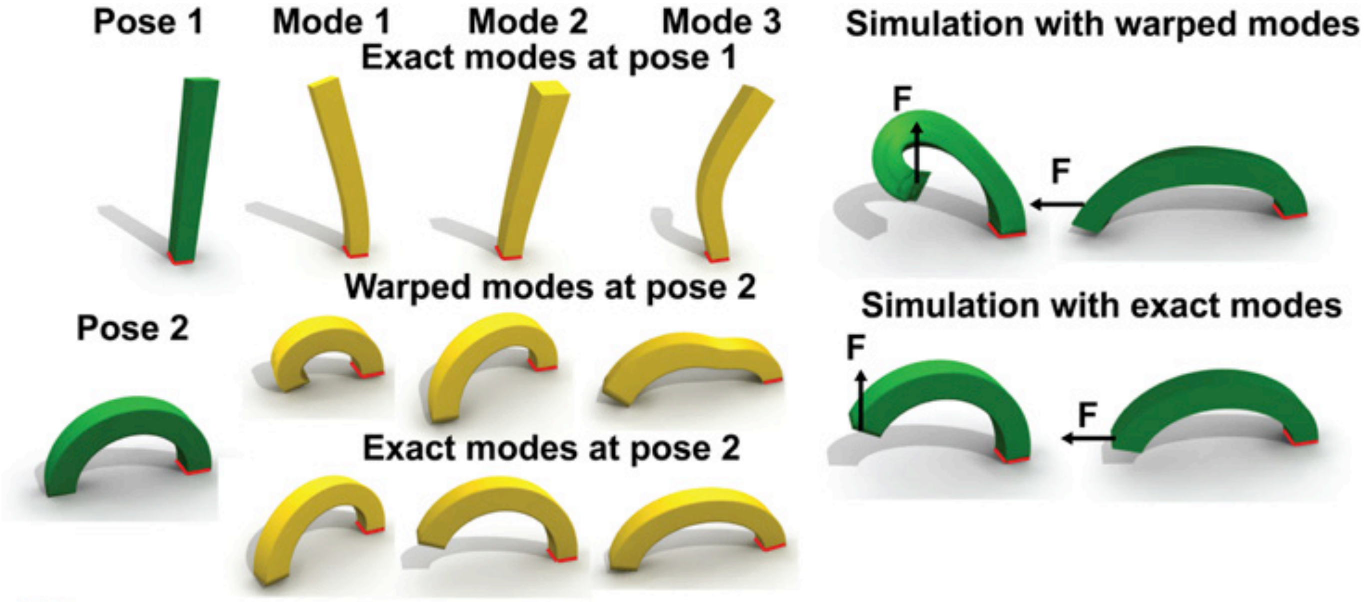
$$U^T MU\ddot{q} + U^T DU\dot{q} + U^T f_{\text{int}}(\Phi(p), Uq) = U^T(f_{ext} + f_{inert})$$

Multi-model Model Reduction: a basis at each pose!

$$p \rightarrow U(p)$$

Basis affected by:

- geometry



Multi-model Model Reduction: A basis at each pose!

$$p \rightarrow U(p)$$

Basis affected by:

- geometry
- contact configuration

No contact

Contact with the ground

Multi-model Model Reduction: A basis at each pose!

$$p \rightarrow U(p)$$

Basis affected by:

- geometry
- contact configuration
- material properties

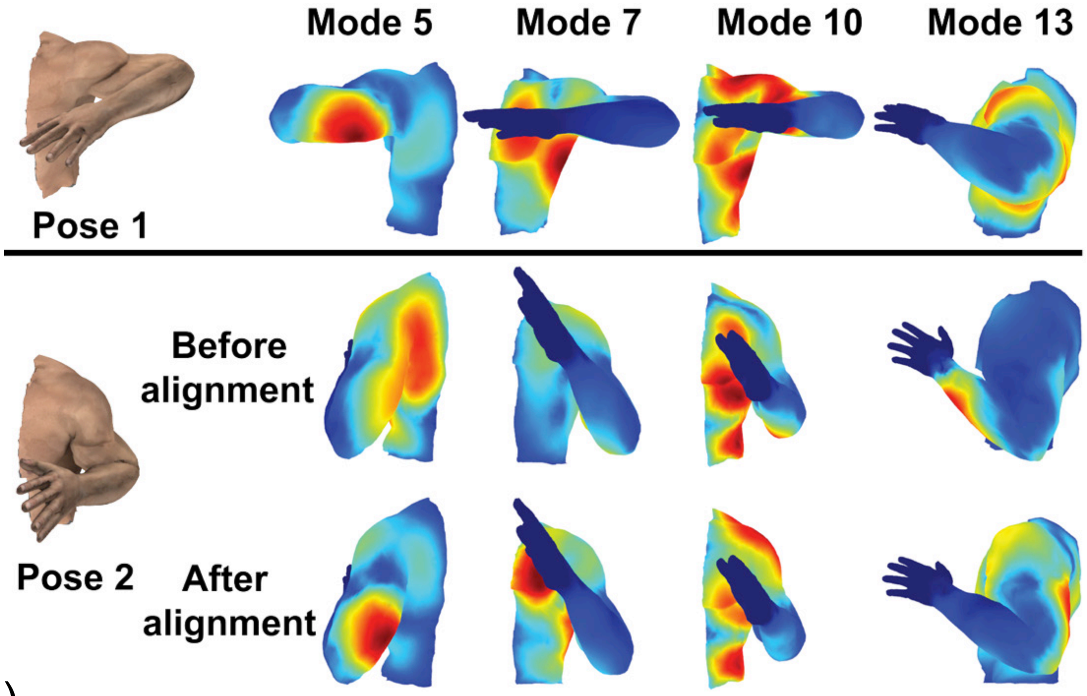
Material stiffness weights

Multi-model Model Reduction

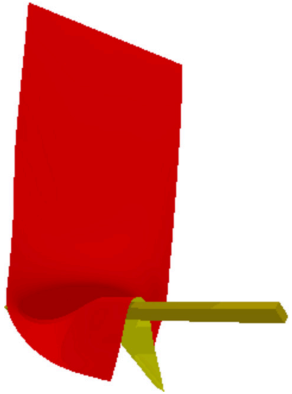
- Construct basis at ***example poses***

- ***Interpolate*** in pose-space at run-time

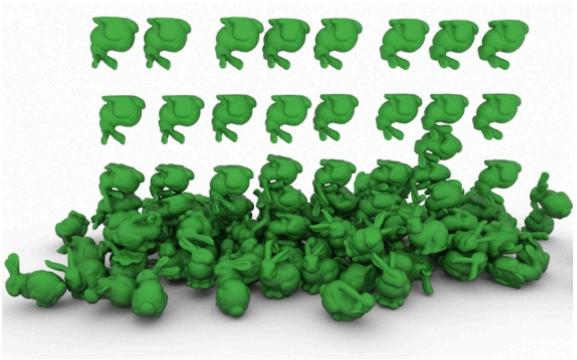
- We ***pre-aligned*** the bases for optimal interpolation (orthogonal Procrustes problem)



Self-Contact in Reduced Simulations



[Schvartzman et al. 2009]



[Barbič & James 2010]

[Teng et al. 2014]

[Teng et al. 2015]

- Expensive
- Must avoid locking artifacts

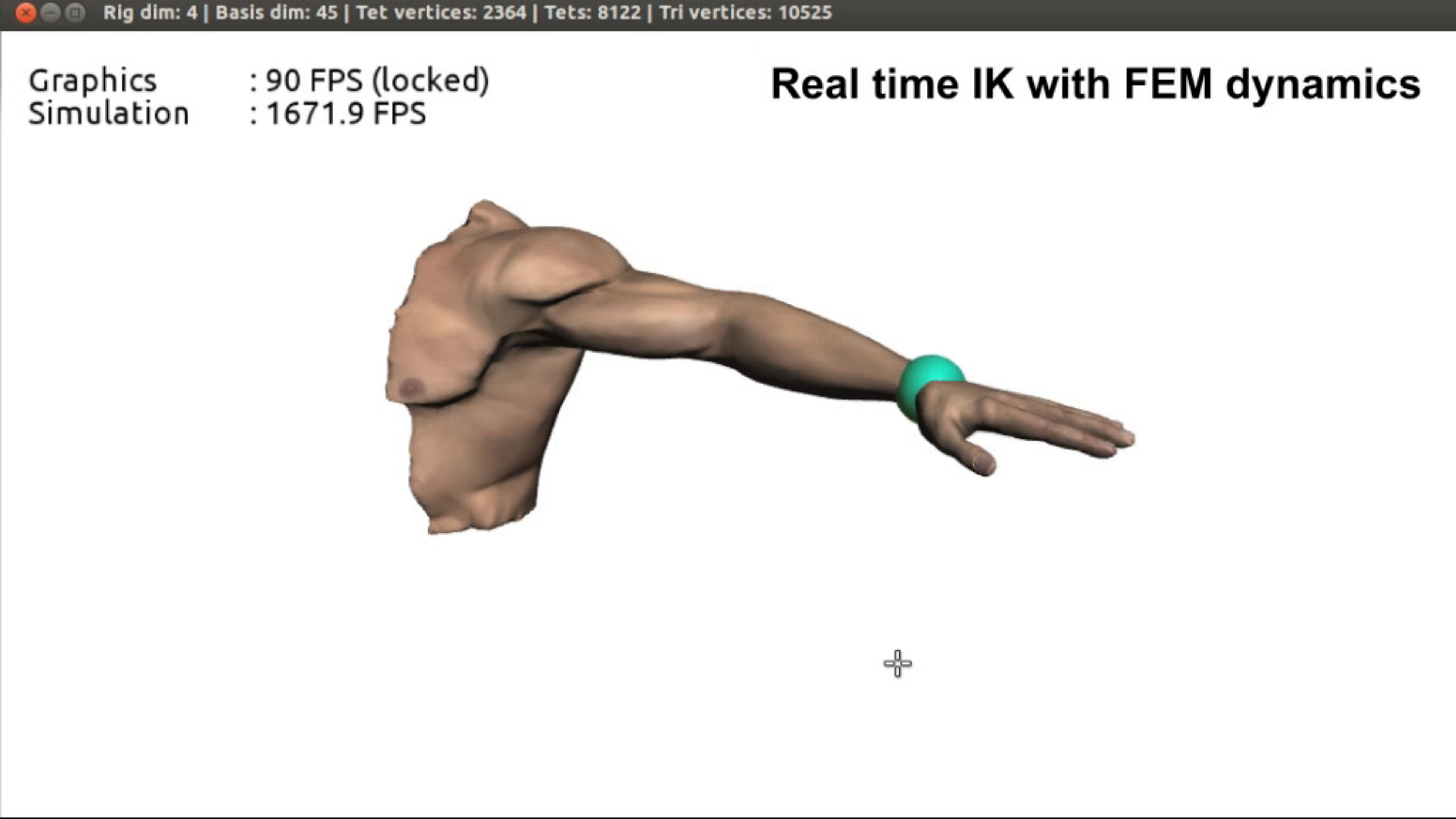
Self-Contact-Aware Basis at Example Poses

Model contacts as bilateral constraints:

$$K\varphi_i = \lambda_i M\varphi_i,$$
$$\text{s.t. } C\varphi_i = 0$$

Basis without constraints

Basis with constraints



```
Rig dim: 4 | Basis dim: 45 | Tet vertices: 2364 | Tets: 8122 | Tri vertices: 10525
```

```
Graphics        : 90 FPS (locked)
Simulation      : 1671.9 FPS
```

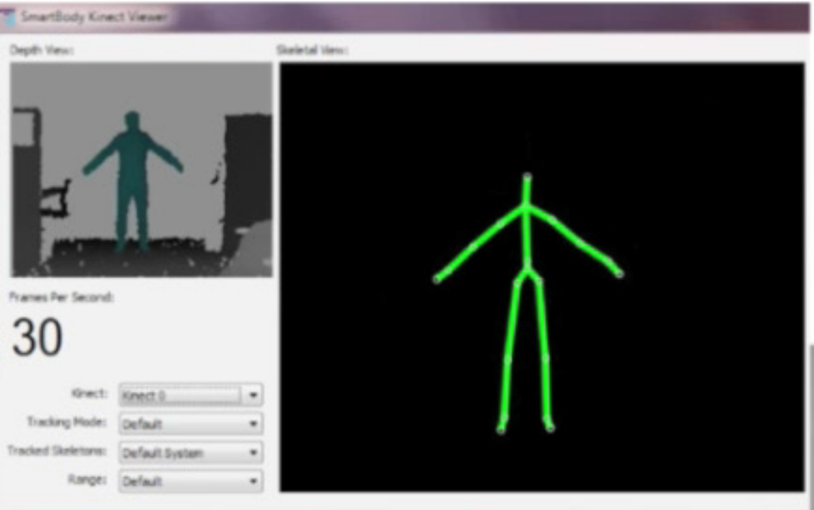
Real time IK with FEM dynamics

Rig dim: 60 | Basis dim: 100 | Tet vertices: 3771 | Tets: 16297 | Tri vertices: 15774

```
Graphics        : 90 FPS (locked)
Simulation      : 735.7 FPS
```

Output: real time soft tissue FEM dynamics

Input: real time skeleton tracking



Frames Per Second:
30

Kinect: Kinect 0
Tracking Mode: Default
Tracked Skeletons: Default System
Range: Default

Future Work – Digital Characters

Done

- A real-time solid simulator for character
- Predictable self-contact in subspace

To be done

- Real-time simulate internal anatomical structures & high-frequency deformations

- Real-time hair and cloth simulation, two-way interacting with body motion

- Interaction with virtual environments

Ziva Dynamics

Outline

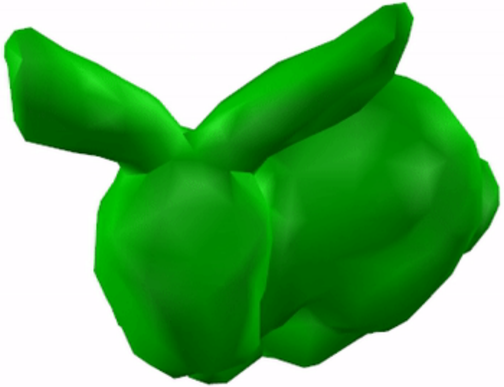
- Adding Physics to Character Animation in *Real-Time*

- ***Interactive*** **and** ***Intuitive*** **Design of** ***Elastic Materials*** **and** ***Damping***

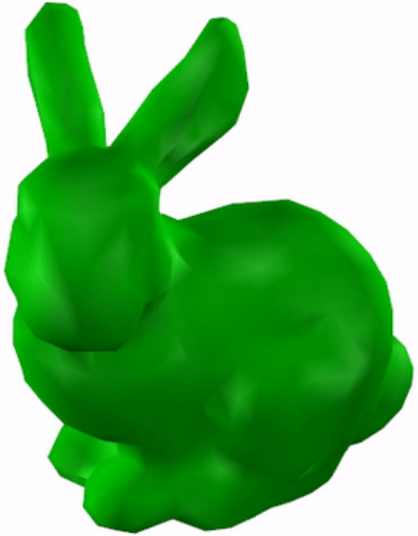
Material is important

Dynamic behavior is determined by the

- ***strain-stress material law***



soft material



stiff material

Damping is important

Dynamic behavior is determined by the

- strain-stress material law
- ***damping model***

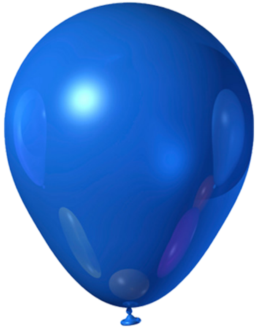
small damping

large damping

Nonlinear Elastic Materials

Infinite-dimensional

muscle



balloon

cushion

rubber

jello

SIGGRAPH2015

Nonlinear Material Design Using Principal Stretches

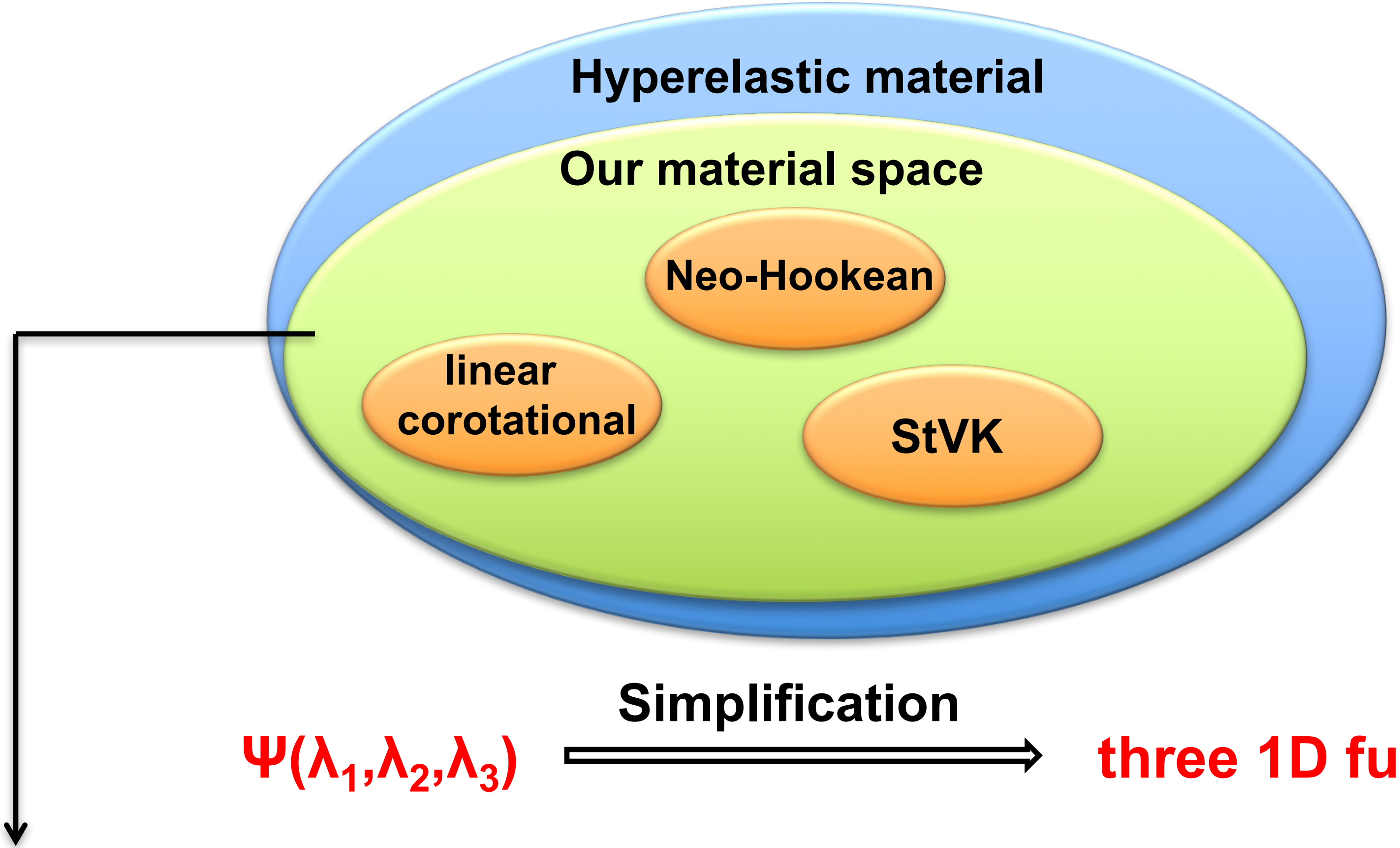
Hongyi Xu, Funshing Sin,
Yufeng Zhu, Jernej Barbič

Make the elastic strain energy separable

$$\Psi(\lambda_1,\lambda_2,\lambda_3) = f(\lambda_1) + f(\lambda_2) + f(\lambda_3) + \\ + g(\lambda_1\lambda_2) + g(\lambda_2\lambda_3) + g(\lambda_3\lambda_1) + h(\lambda_1\lambda_2\lambda_3)$$

$f(x),\ g(x),\ h(x)$: 1D scalar functions for uniaxial (length), biaxial (area) and triaxial (volume) strain.

- An extension of the Valanis-Landel hypothesis [Valansis and Landel 1967]

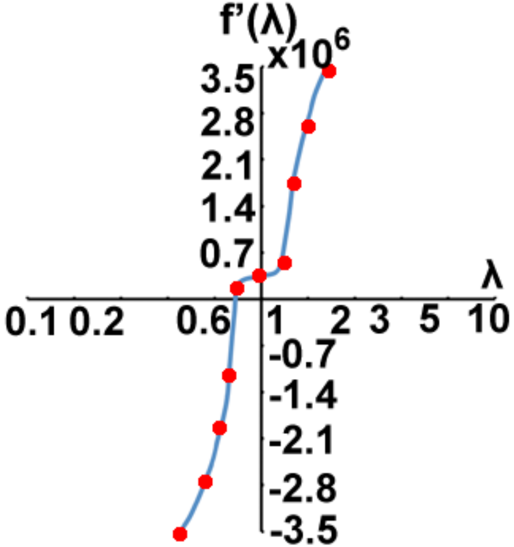


Venn diagram

$\Psi(\lambda_1,\lambda_2,\lambda_3) \xrightarrow{\text{Simplification}}$ three 1D functions

This material space is still expressible.
But material design becomes much easier and more intuitive!

Reduce the nonlinear material space into 1-D strain-stress spline functions.



Heterogeneous Elastic Materials

High-dimensional

steak

muscle

flip-flop

skin

tree

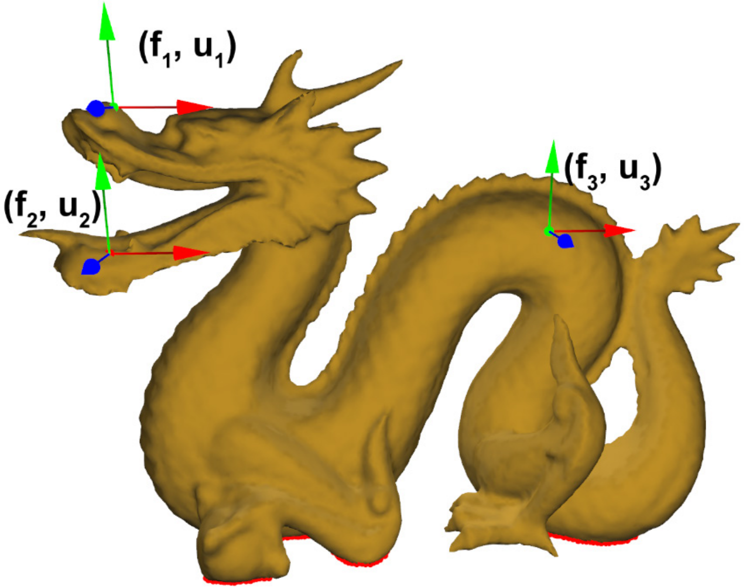
SIGGRAPH2015

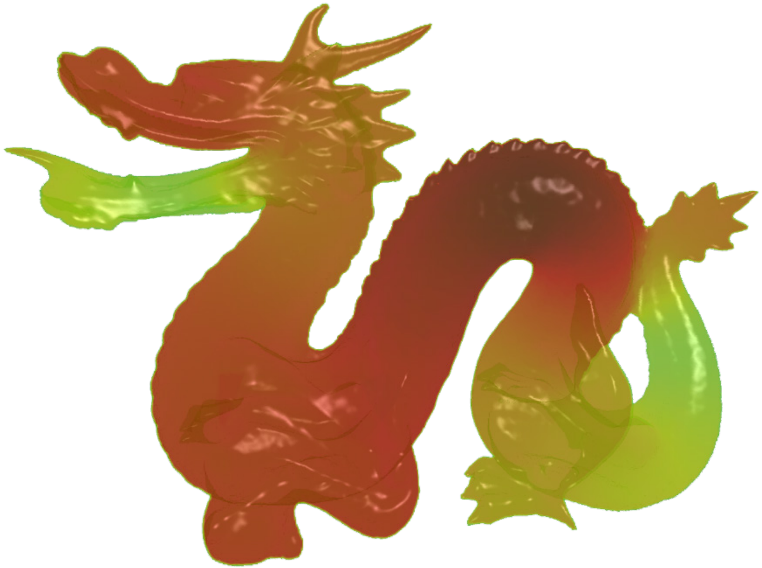
Interactive Material Design Using Model Reduction

Hongyi Xu, Yijing Li, Yong Chen, Jernej Barbič

Inverse Design of Heterogeneous Material

- An intuitive user-interface.





Young’s modulus

Input: Forces and displacements

Output: Heterogeneous material

Optimization

E = vector of tet Young's moduli

$\tilde{u}$ = modified handle displacements

$$\min_{E,\,\tilde{u}} \boxed{\frac{\alpha}{2}\left\|\tilde{K}(E)\tilde{u} + K_{21}(E)K_{11}^{-1}(E)\hat{f} - \bar{f}\right\|_W^2} + \frac{\alpha\beta}{2}\left\|\tilde{u} - \bar{u}\right\|^2 + \frac{1}{2}E^T L E$$

soft constraints on forces

Optimization

E = vector of tet Young's moduli

$\tilde{u}$ = modified handle displacements

$$\min_{E,\,\tilde{u}} \; \frac{\alpha}{2}\left\|\tilde{K}(E)\tilde{u} + K_{21}(E)K_{11}^{-1}(E)\hat{f} - \bar{f}\right\|_W^2 + \boxed{\frac{\alpha\beta}{2}\left\|\tilde{u} - \bar{u}\right\|^2} + $$

$$+\frac{1}{2}E^T L E$$

soft constraints on displacements

Optimization

E = vector of tet Young's moduli

$\tilde{u}$ = modified handle displacements

$$\min_{E,\,\tilde{u}} \frac{\alpha}{2}\left\|\tilde{K}(E)\tilde{u} + K_{21}(E)K_{11}^{-1}(E)\hat{f} - \overline{f}\right\|_W^2 + \frac{\alpha\beta}{2}\left\|\tilde{u} - \overline{u}\right\|^2 +$$

$$+\boxed{\frac{1}{2}E^T L E}$$

material smoothness

Material modes: Use eigenvectors of the Laplace operator

$$Ly_j = \lambda_j V y_j$$

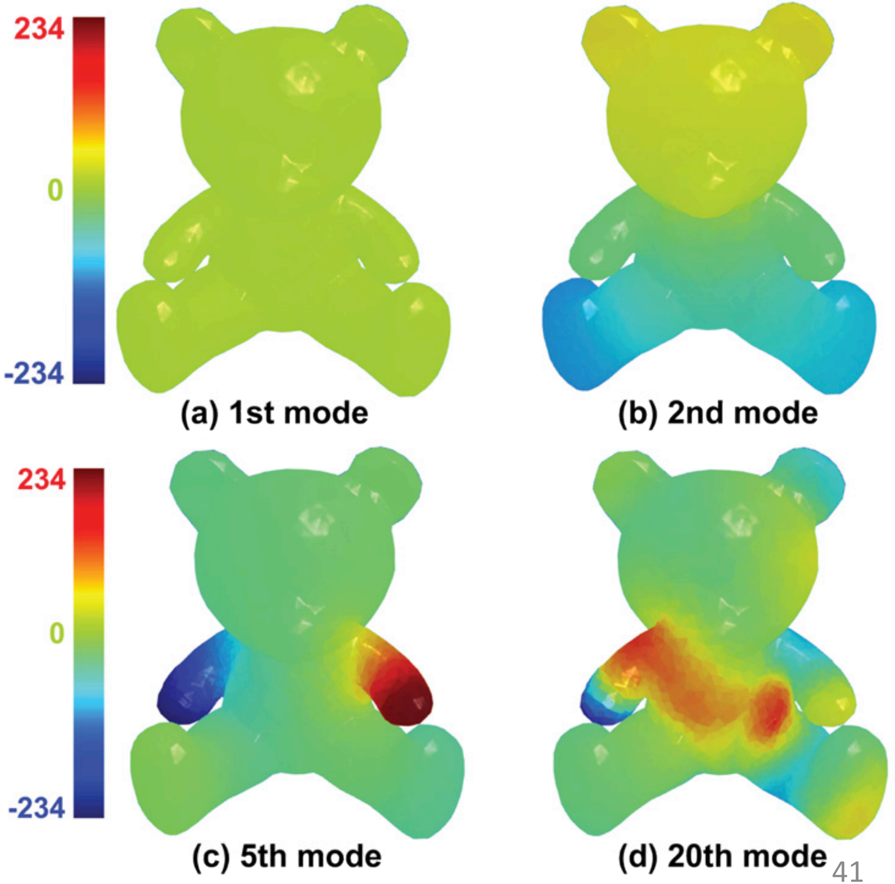
$$E = \Phi z$$

- material basis matrix:

$$\Phi = \begin{bmatrix} y_1 & y_2 & \cdots & y_r \end{bmatrix} \in R^{m,r}$$

- reduced material vector:

$$z \in R^r \quad r << m$$

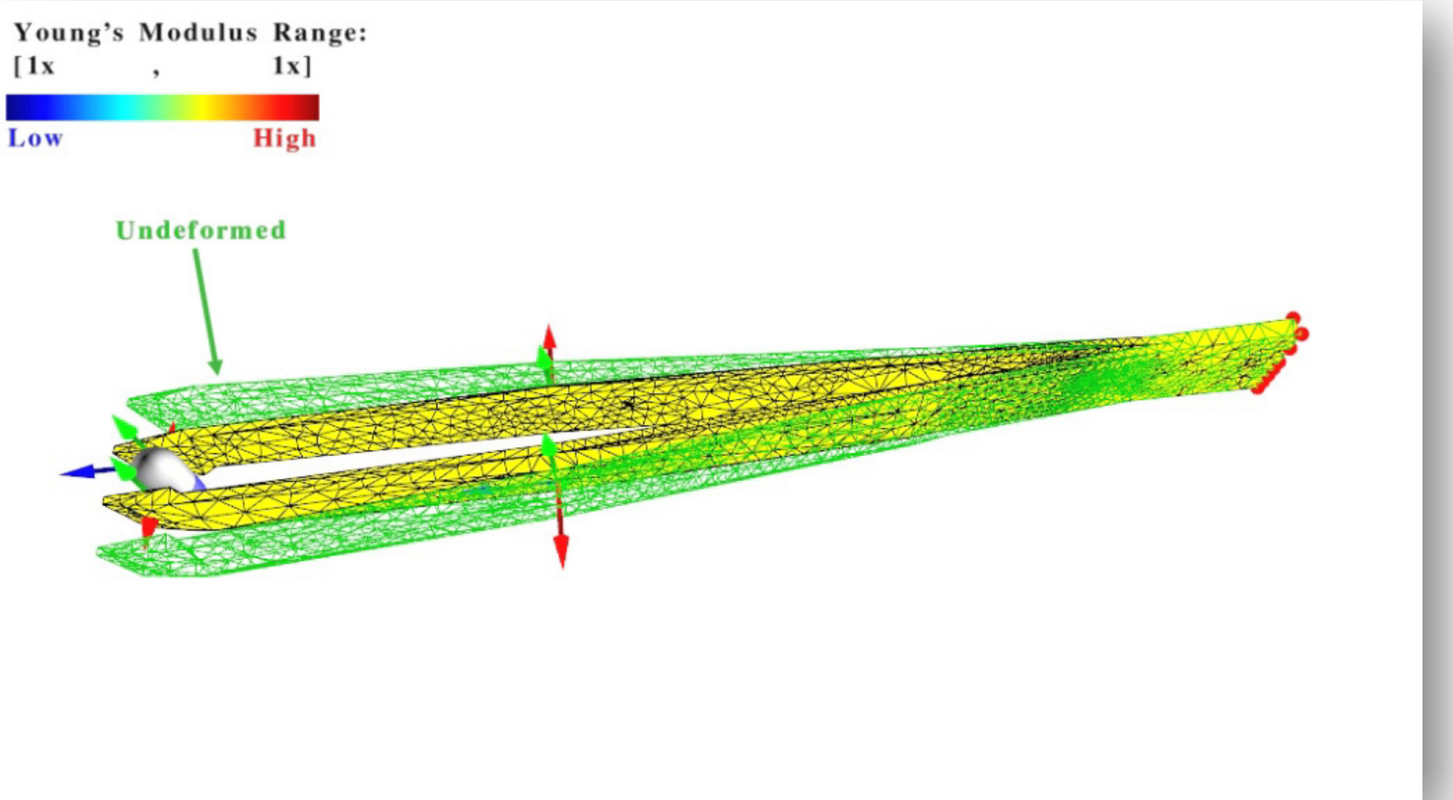


(a) 1st mode (b) 2nd mode

(c) 5th mode (d) 20th mode

Reduced optimization

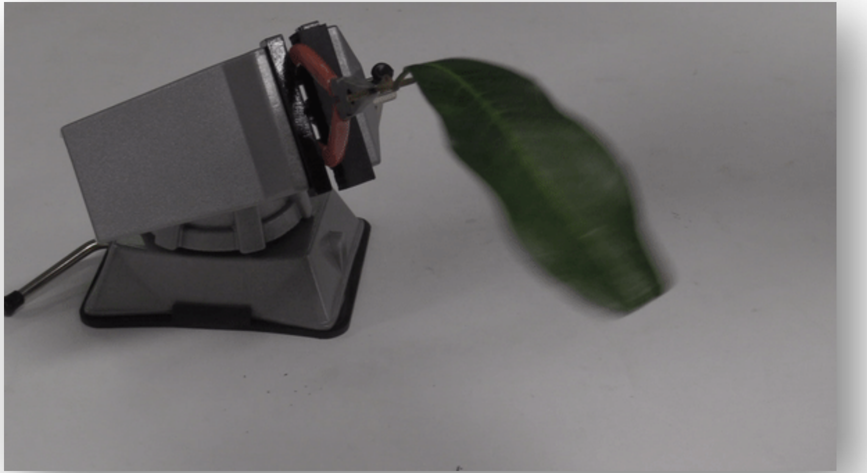
- Two orders of magnitude speedup
- Faster convergence and avoid local minimal



Anisotropic Nonlinear Damping

No universally accepted damping model; Infinite-dimensional

string



tree leaf

SIGGRAPH2017

Example-Based Damping Design

Hongyi Xu, Jernej Barbič

Problem: Damping design is globally coupled

- Rayleigh damping:

$$C = \alpha M + \beta K$$

Hard to control damping independently for different motions

Tuning Rayleigh α and β affect dynamics globally

Our solution:

Decouple damping in the space of example deformation

$$f_d = C\dot{u}$$

example deformation 1

example deformation 2

Our solution:

Decouple damping in the space of example deformation

$$f_d = f_d^1(\dot{u}) + f_d^2(\dot{u}) + (C\dot{u} - f_d^1(\dot{u}) - f_d^2(\dot{u}))$$

$f_d^1(\dot{u})$: damping force along example deformation 1

$f_d^2(\dot{u})$: damping force along example deformation 2

Our solution:

Decouple damping in the space of example deformation

Scale damping force along example deformation by

$$\hat{f}_d = \gamma_1 f_d^1(\dot{u}) + \gamma_2 f_d^2(\dot{u}) + (C\dot{u} - f_d^1(\dot{u}) - f_d^2(\dot{u}))$$

$$\hat{f}_d^1(\dot{u}) = \gamma_1 f_d^1(\dot{u})$$

$$\hat{f}_d^2(\dot{u}) = \gamma_2 f_d^2(\dot{u})$$

Example shapes

Damping

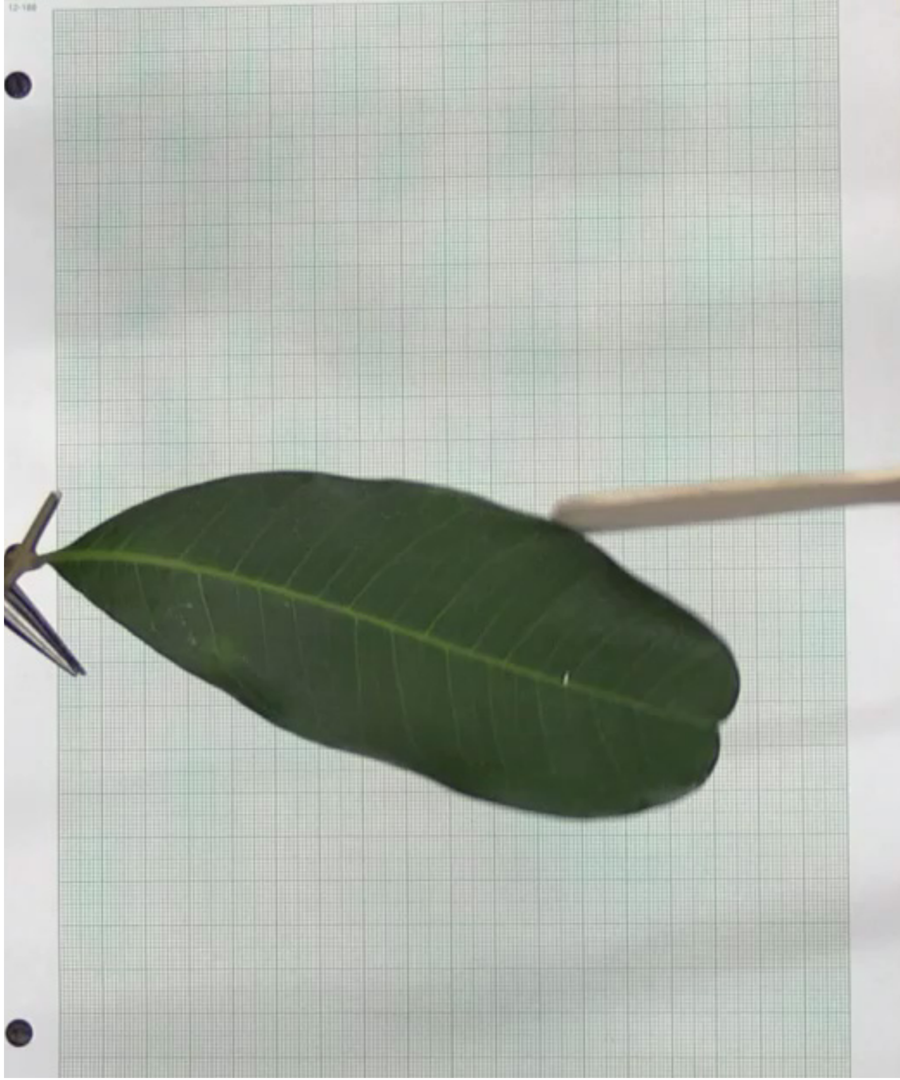
made 10X weaker

made 3X stronger

Nonlinear Damping

"In many cases, it is the damping that is the dominant source of nonlinearity."

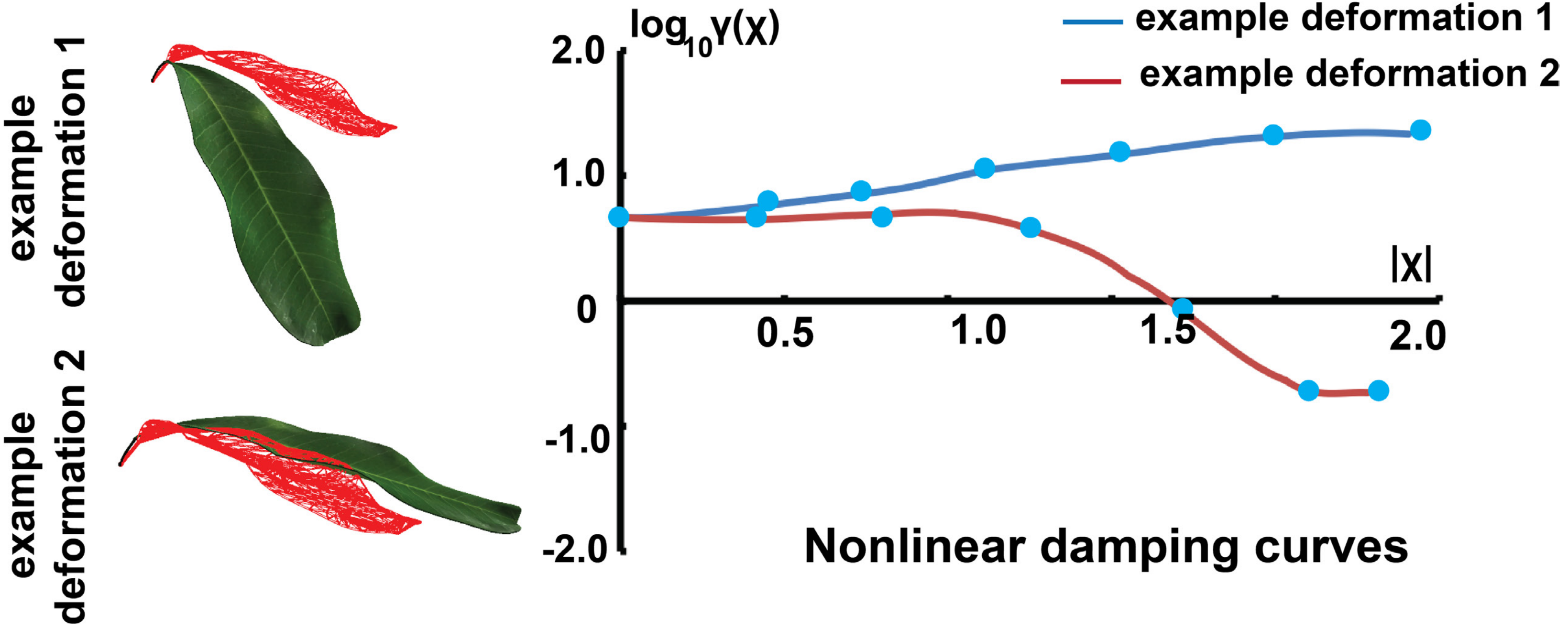
--- [Elliott et al. 2015]



Our solution:

Make damping scaling nonlinearly depend on deformation

- $\gamma_i(\chi_i)$: 1-D spline curve (damping scaling vs deformation magnitude)



Nonlinear damping curves

Recorded leaf vibration

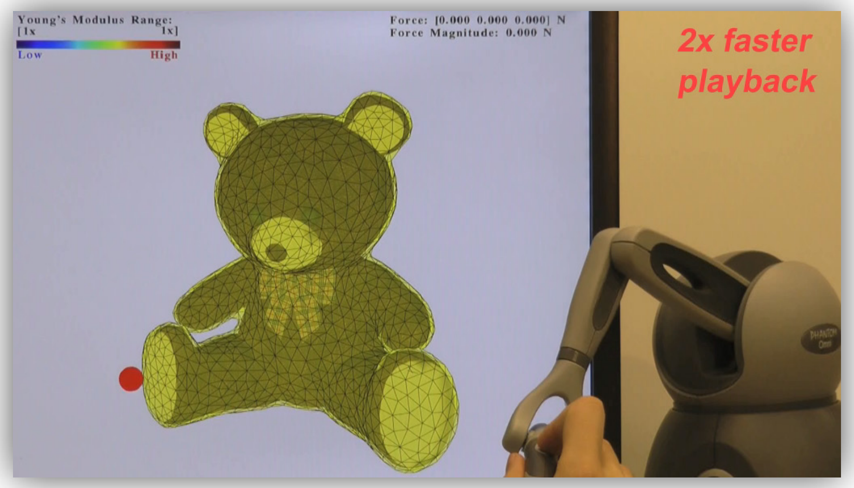
Future Work

Done

- Material and damping models with good modeling power/versatility/expressiveness

To be done

- High-level material design
- Material capture
- Computational fabrication



[Xu et al TOG 2015]

3D printing

[Schumacher et al 2015]

Thank you! 谢谢！

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