SIGGRAPH2015
Xroads of Discovery

Deformation Capture and Modeling of Soft Objects

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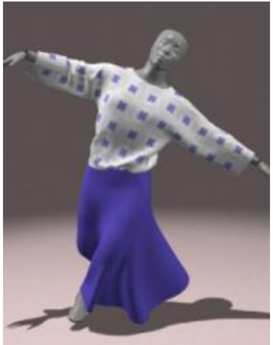
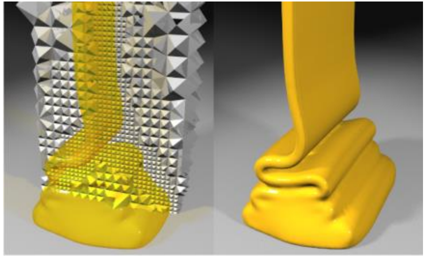
Deformation Models



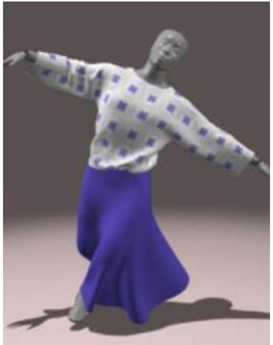
Mass Spring [Baraff et. al 98]

Thin Shell [Pfaff et. al 14]



Finite Element [Batty et. al 11]

Manually Tuning



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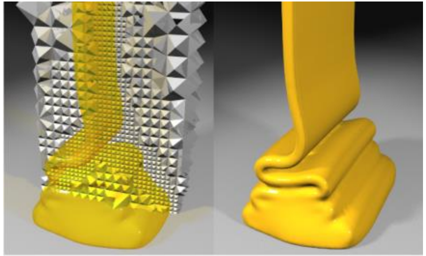
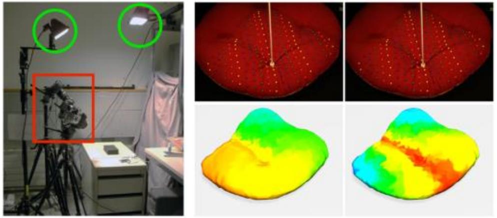


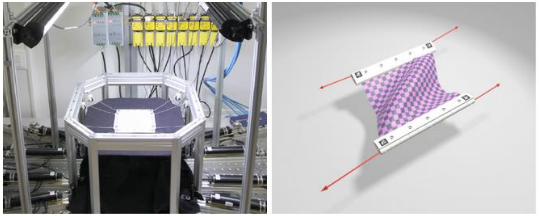
Finite Element [Batty et. al 11]

Manually tuning model’s parameters
is tedious and time consuming.

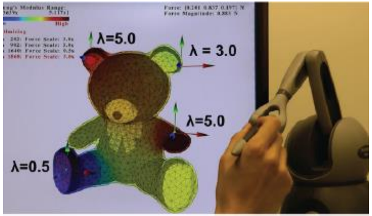
Data-Driven Modeling



[Bickel et. al 09]

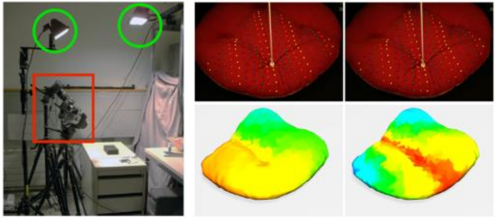


[Miguel et al. 2012]



[Xu et al. 2014]

Limitations



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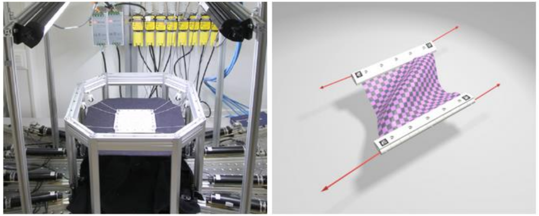

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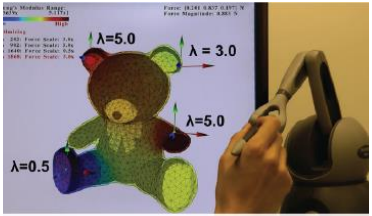
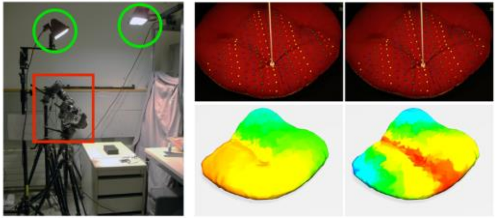


[Xu et al. 2014]

- Customized hardware system

Limitations



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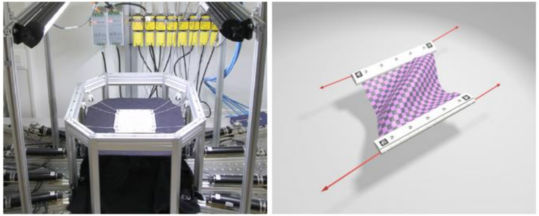

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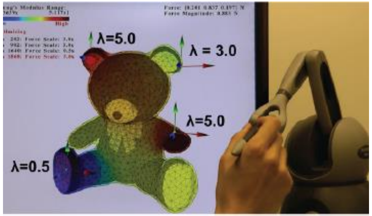
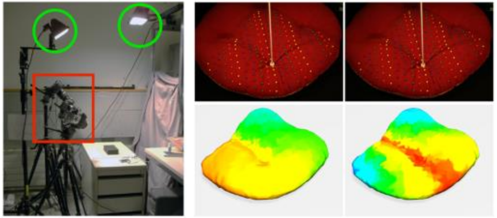


[Xu et al. 2014]

- Customized hardware system
- Oversimplified reference shape

Limitations



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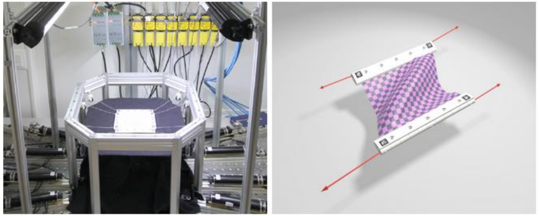

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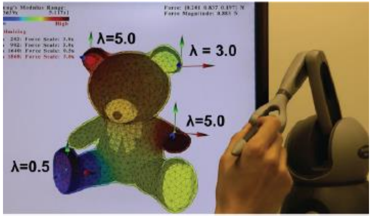


[Xu et al. 2014]

- Customized hardware system
- Oversimplified reference shape
- Dynamic properties are ignored

Our Goal

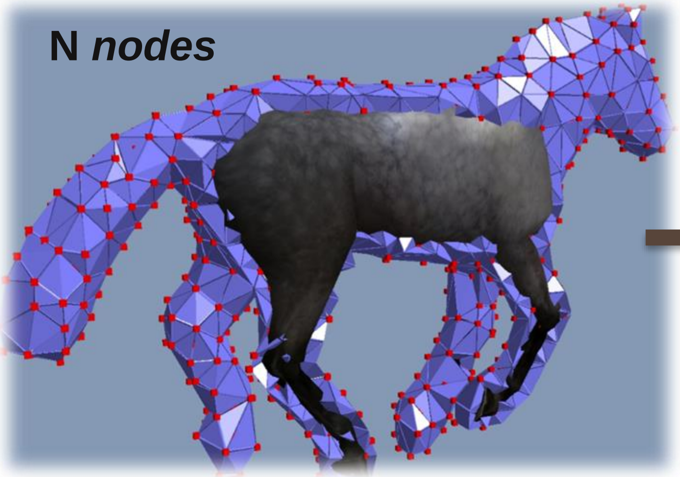
- Target for generic soft objects
- To estimate from pure kinematic data without force-displacement measurements
- To estimate the reference shape as well as material properties and damping coefficients

FEM-Based Deformation Simulation

$$\underbrace{M\ddot{x}}_{\text{Acceleration}} + \underbrace{D\dot{x}}_{\text{Damping Force}} + \underbrace{f_{\text{els}}}_{\text{Elastic Force}} = \underbrace{f_{\text{ext}}}_{\text{External Force}}$$

FEM-Based Deformation Simulation

$$\underline{M\ddot{x}} + \underline{D\dot{x}} + \underline{f_{\text{els}}} = \underline{f_{\text{ext}}}$$



$$\ddot{x}, \dot{x}, f_{\text{els}}, f_{\text{ext}} \in R^{3N\times 1}$$

$$M, D \in R^{3N\times 3N}$$

FEM-Based Deformation Simulation

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{f}_{\mathrm{els}} = \boldsymbol{f}_{\mathrm{ext}}$$

- Co-rotated linear model **[Müller et al. 2012]**

$$\boldsymbol{f}_{\mathrm{els}} = \boldsymbol{R}\boldsymbol{K}(\boldsymbol{R}^T\boldsymbol{x} - \boldsymbol{X}), \ \text{where } \boldsymbol{K} = f(E,\ \nu)$$

FEM-Based Deformation Simulation

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$$\boldsymbol{f}_{\text{els}} = \boldsymbol{R}\boldsymbol{K}(\boldsymbol{R}^T\boldsymbol{x} - \boldsymbol{X}), \quad \text{where } \boldsymbol{K} = f(E,\ \nu)$$

E (Young's modulus): force ⟷ expansion/compression

ν (Poisson ratio): expansion ⟷ compression

FEM-Based Deformation Simulation

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{f}_{\text{els}} = \boldsymbol{f}_{\text{ext}}$$

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$$\boldsymbol{f}_{\text{els}} = \boldsymbol{R}\boldsymbol{K}(\boldsymbol{R}^T\boldsymbol{x} - \boldsymbol{X}), \ \text{where } \boldsymbol{K} = f(E,\ \nu)$$

- Rayleigh damping: $\boldsymbol{D} = \alpha\boldsymbol{M} + \beta\boldsymbol{K}$

FEM-Based Deformation Simulation

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{f}_{\text{els}} = \boldsymbol{f}_{\text{ext}}$$

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$$\boldsymbol{f}_{\text{els}} = \boldsymbol{R}\boldsymbol{K}(\boldsymbol{R}^T\boldsymbol{x} - \boxed{\boldsymbol{X}}), \quad \text{where } \boldsymbol{K} = f(\boxed{E}, \boxed{\nu})$$

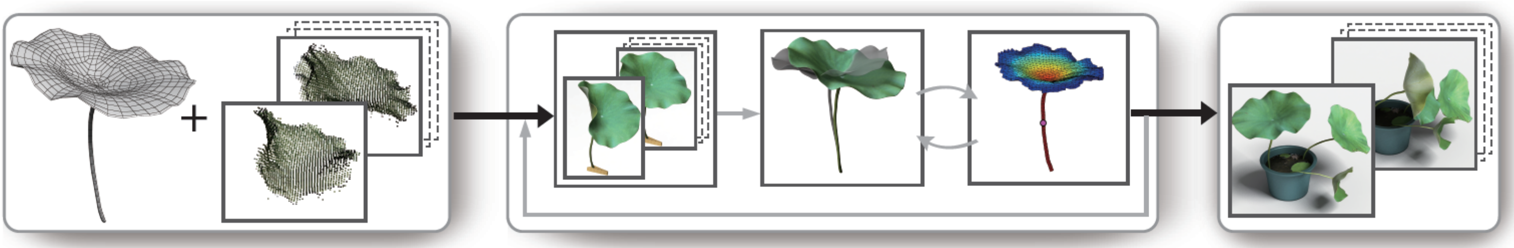
Reference shape

Young's modulus & Poisson ratio

- Rayleigh damping: $\boldsymbol{D} = \boxed{\alpha}\boldsymbol{M} + \boxed{\beta}\boldsymbol{K}$

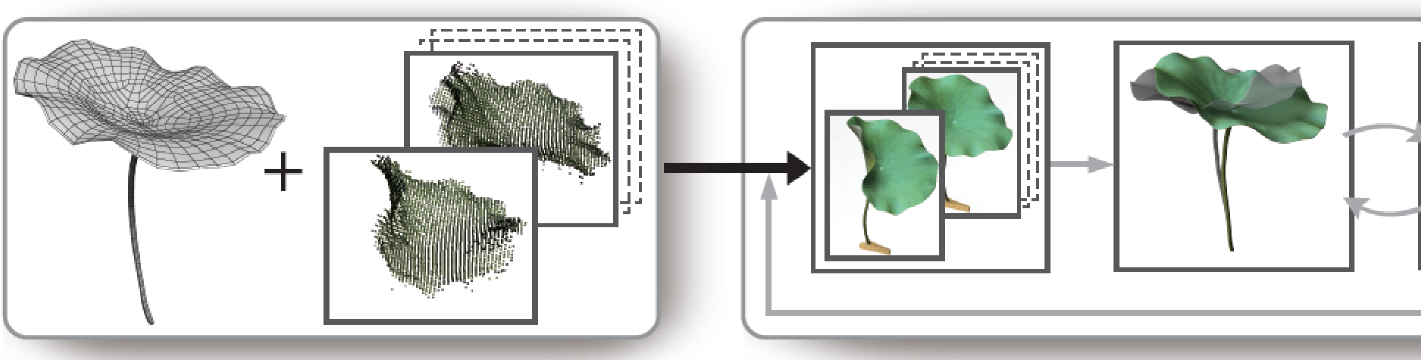
Rayleigh damping coefficients

Overview



(a) Static shape (b) Point cloud sequence (c) Tracking (d) Reference shape optimization (e) Material optimization (f) Simulation

Capture

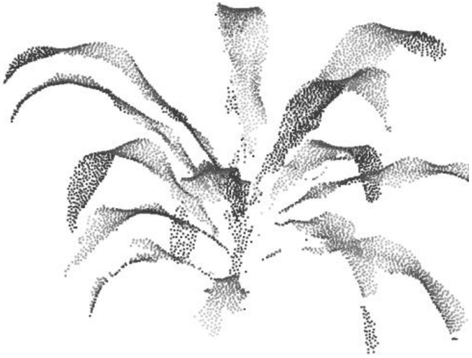


(a) Static shape (b) Point cloud sequence (c) Tracking (d) Reference shape optimization

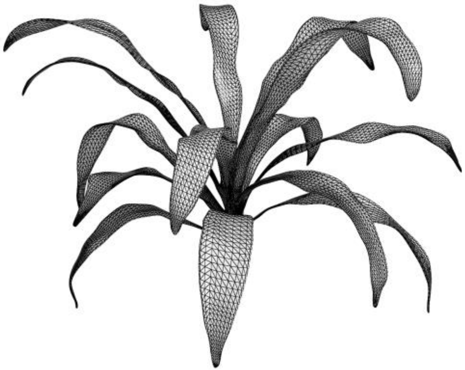
Acquisition of static shape and deformable motion.

Capture

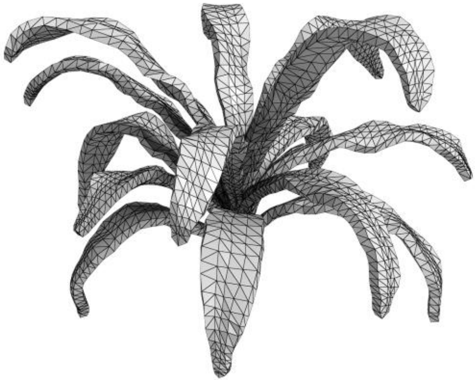
- Static shape



Point cloud



Surface mesh



Volumetric mesh

Capture

- Dynamic motion

Three Kinect sensors

Capture

- Dynamic motion

Three Kinect sensors

Deformation by interaction

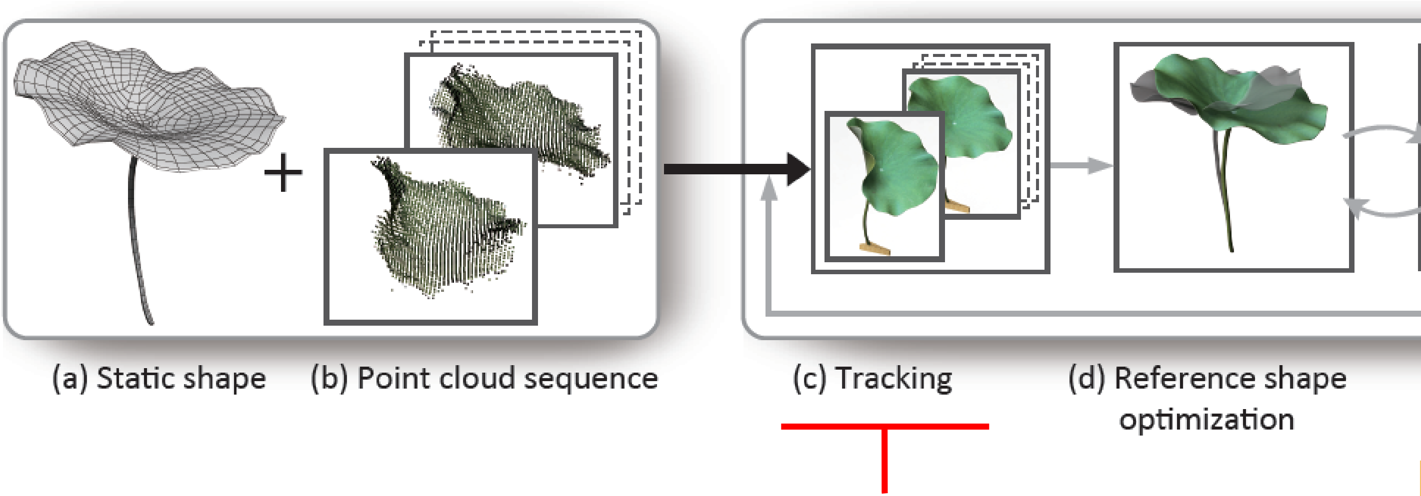
Capture

Real objects

Captured point clouds

REPLAY X 1/2

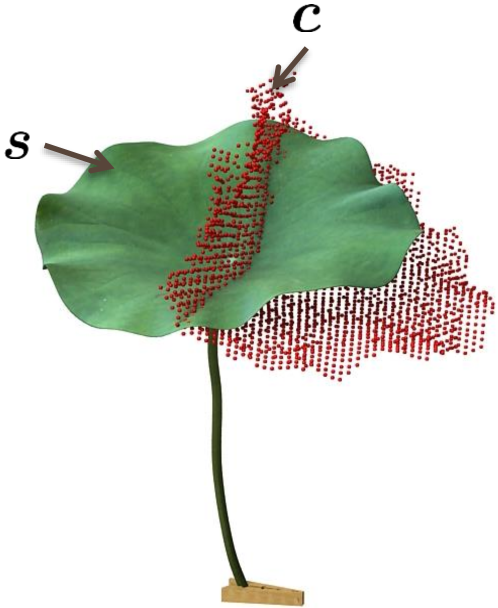
Tracking


(a) Static shape
(b) Point cloud sequence
(c) Tracking
(d) Reference shape optimization

Reconstruct mesh deformation from point clouds

Tracking

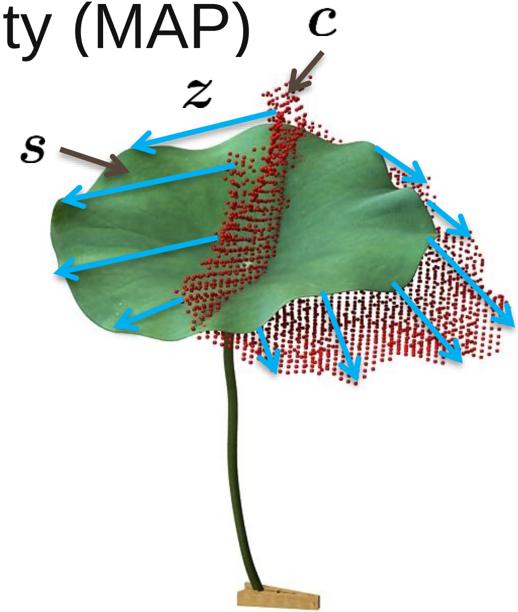
- Challenges
  - Noisy and incomplete
  - Large deformation
  - No correspondence



Tracking

- Maximum a posteriori probability (MAP)

$$\boldsymbol{s} = \arg\max_{\boldsymbol{s}} p(\boldsymbol{s}|\boldsymbol{c})$$

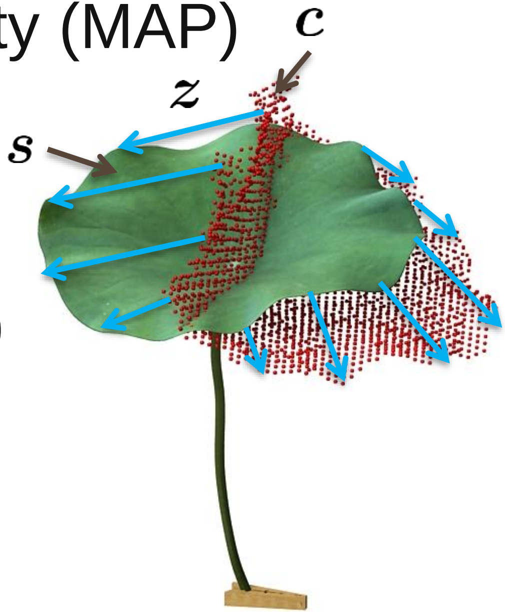


Tracking

- Maximum a posteriori probability (MAP)

$$\boldsymbol{s} = \arg\max_{\boldsymbol{s}} p(\boldsymbol{s}|\boldsymbol{c})$$

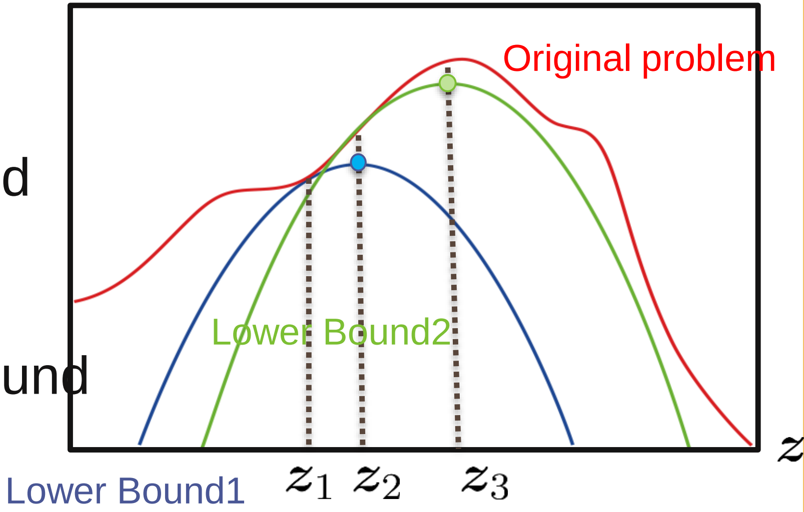
- Expectation-Maximization (EM)
  - $\boldsymbol{z}$: latent variable
  - Normally distributed



Tracking

- E step:
  - expectation
  - generate a lower bound
- M step:
  - maximize the lower bound

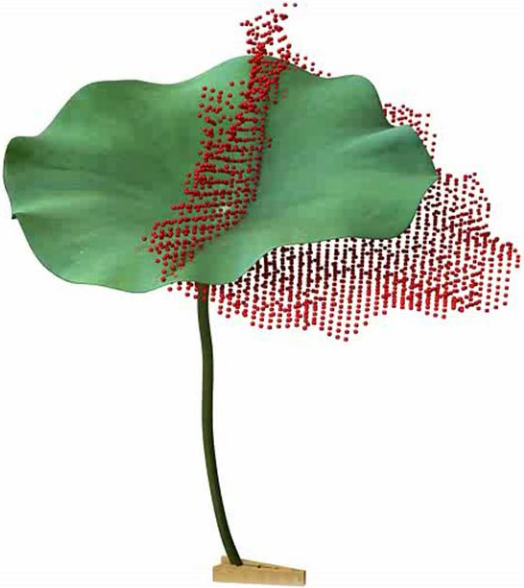
PRML [Bishop 07]



Tracking

- E step:
  - expectation
  - generate a lower bound
- M step:
  - maximize the lower bound
  - explain observation + minimize potential energy
  - virtual force + physics simulation

Tracking



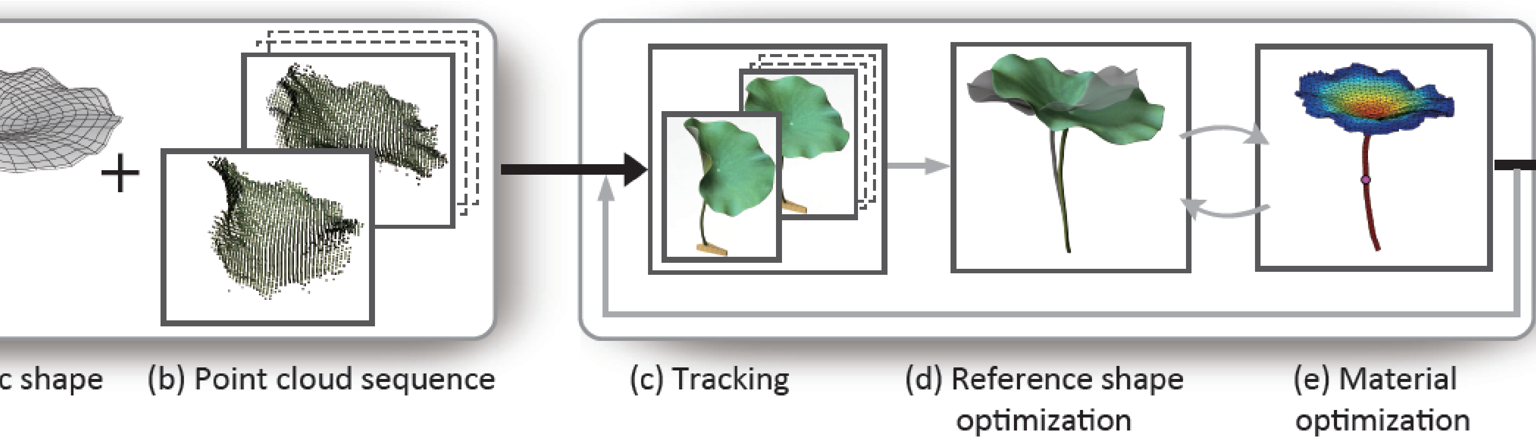
Fitting the static shape to the first frame

Tracking

Capture

Tracking result

Optimization



Learning deformation model from motion trajectories

Optimization

- Space-time optimization

$$\min_{E,\alpha,\beta,\boldsymbol{X}} \mathscr{F}(E,\underbrace{\alpha,\beta}_{\text{Rayleigh damping coefficients}},\boldsymbol{X}) = \sum_t \left\|\boldsymbol{x}_t - \hat{\boldsymbol{x}}_{\boldsymbol{t}}\right\|^2$$

Young's modulus

Rayleigh damping coefficients

Reference shape

- Challenges
  - High dimension, nonlinear
  - Parameters coupling

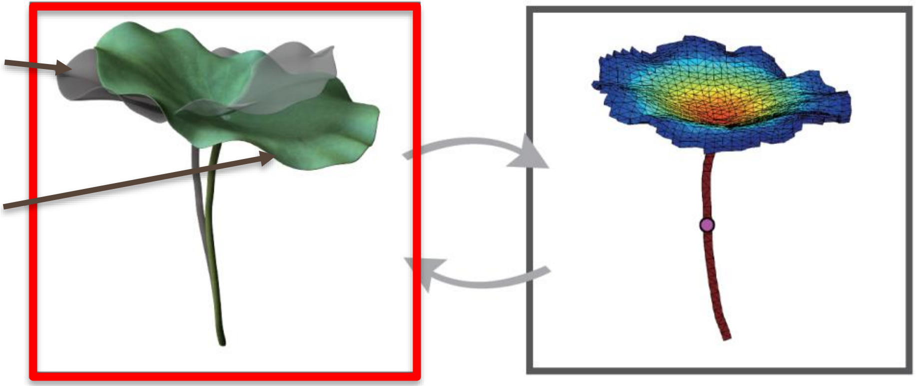
Optimization

- Constrained space-time optimization

$$\min_{E,\alpha,\beta,\boxed{\cancel{\boldsymbol{X}}}} \quad \mathscr{F}(E,\alpha,\beta,\boxed{\cancel{\boldsymbol{X}}}) = \sum\nolimits_t \left\|\boldsymbol{x}_t - \hat{\boldsymbol{x}}_{\boldsymbol{t}}\right\|^2$$

$$\text{s.t.} \quad \boldsymbol{f}_{\text{els}}(\boldsymbol{X}) = \boldsymbol{f}_{\text{gravity}}$$

Splitting Scheme

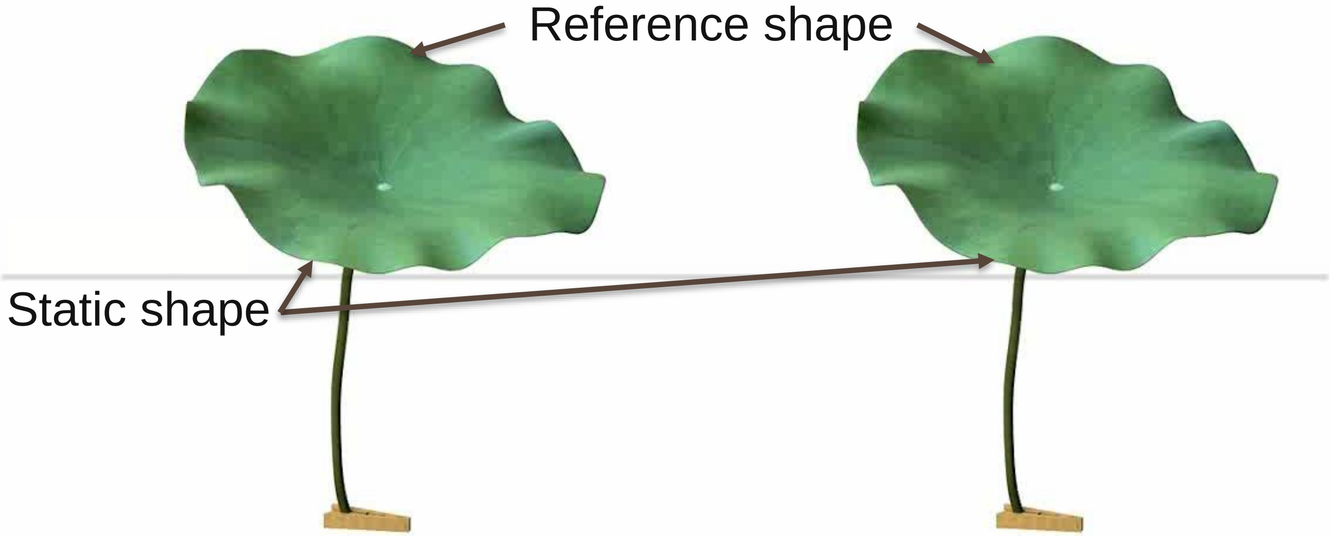


Reference shape

Static shape

- Maintain static equilibrium
- Force residual as virtual force
- Physics simulation $\frac{\partial \boldsymbol{f}}{\partial \mathbf{X}}$

Splitting Scheme

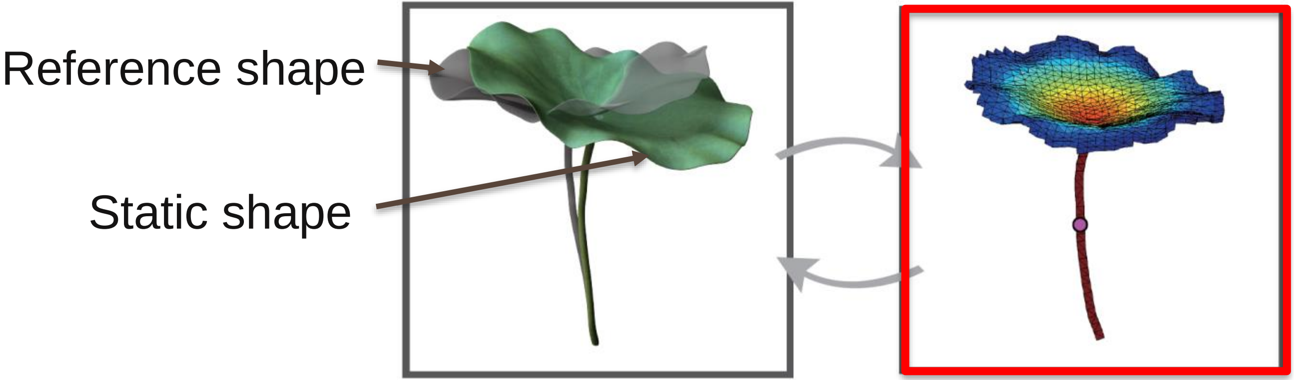


Reference shape

Static shape

Reference shape optimization

Splitting Scheme

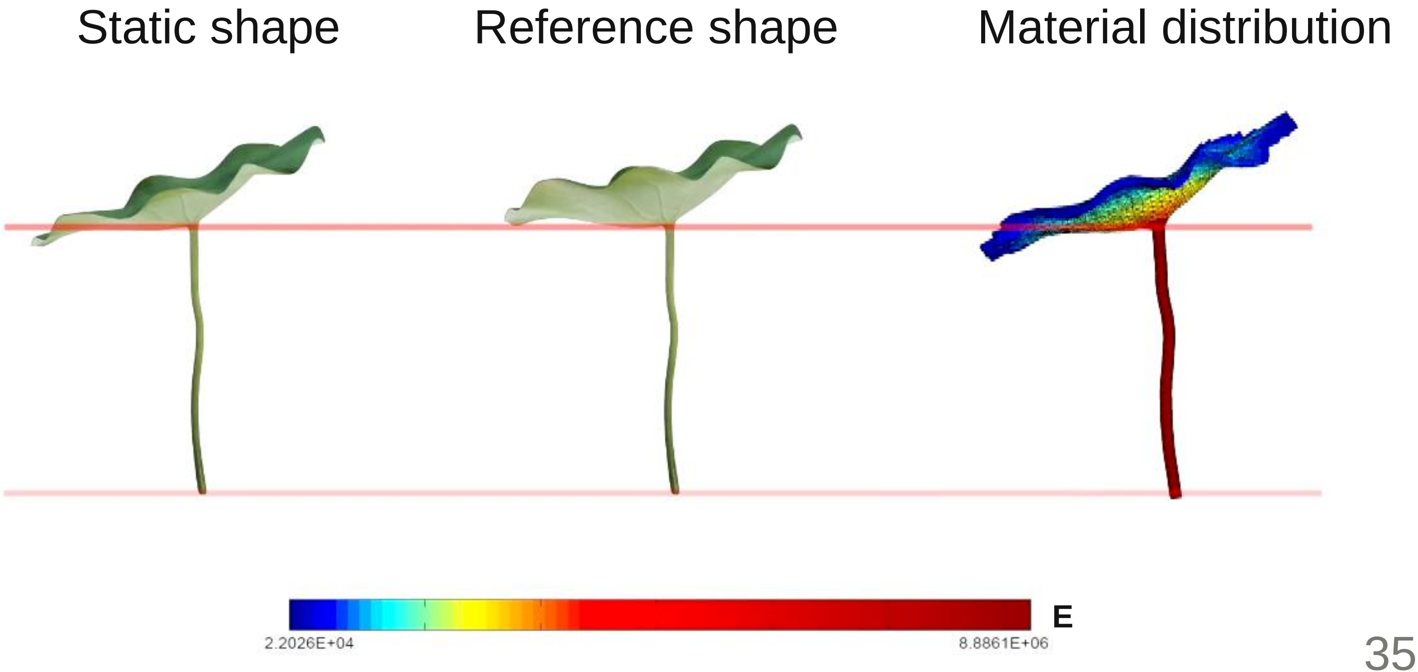


Reference shape

Static shape

- Match full trajectory
- Gradient free downhill

Splitting Scheme



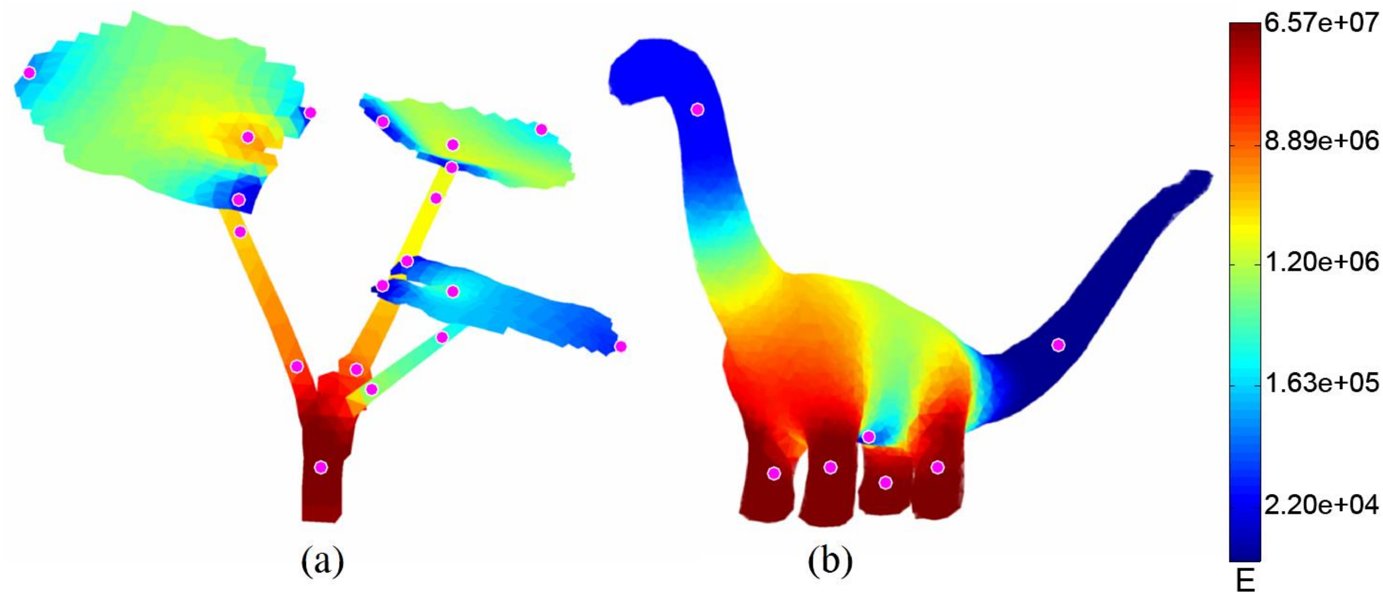
Splitting Scheme

Tracking result

Simulation

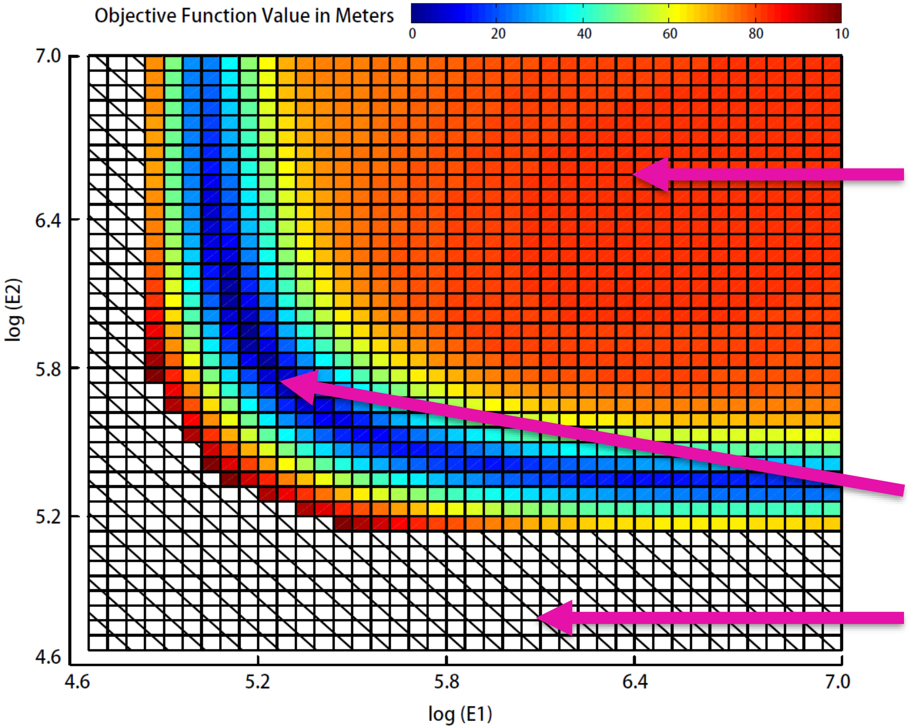
REPLAY X 1/2

Heterogeneous Distribution



Multiple control points

Warm Start



Large plateau

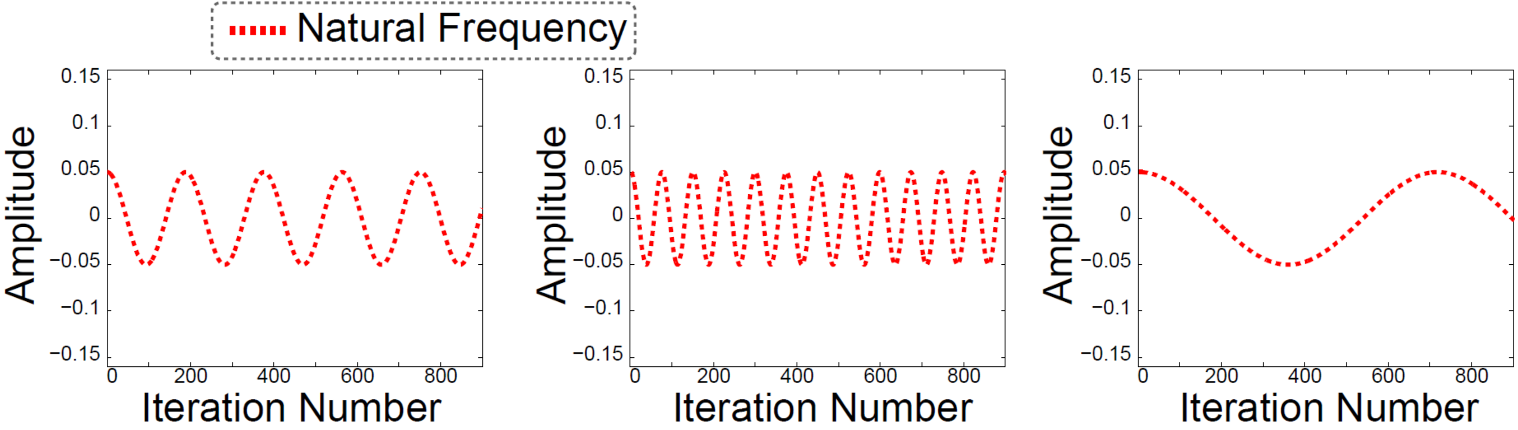
Narrow valley with
local minima

Degenerated areas

Warm Start

- Modal analysis

$$\boldsymbol{K}\boldsymbol{\phi}_{\boldsymbol{i}} = \lambda_i \boldsymbol{M}\boldsymbol{\phi}_{\boldsymbol{i}}$$



E = 6.8e+05

E = 4.0e+06

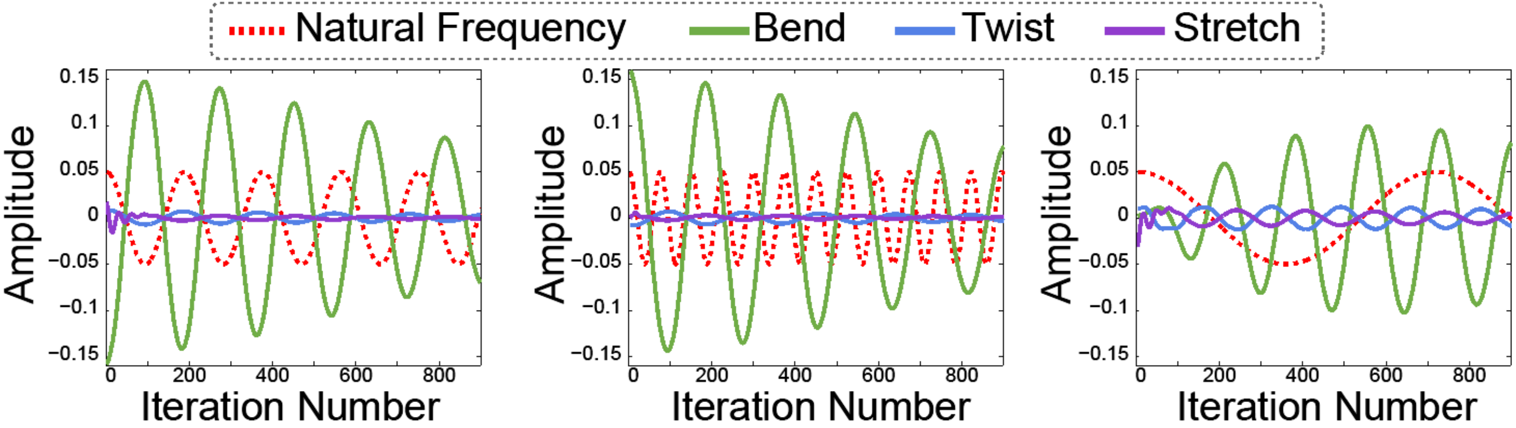
E = 5.0e+04

Warm Start

- Frequency matching
  - Captured trajectory
  - Project on to the Eigen mode

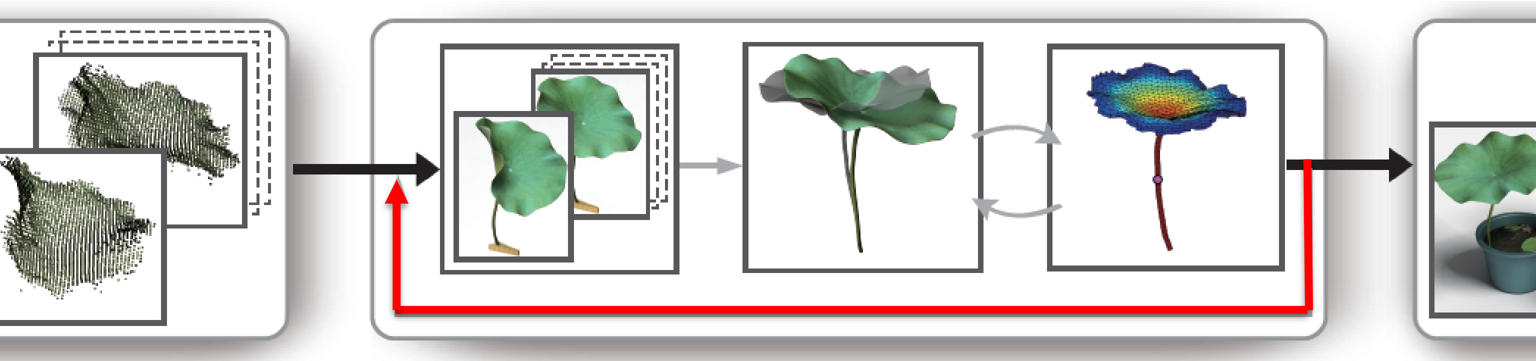
Warm Start

- Frequency matching



E = 6.8e+05 E = 4.0e+06 E = 5.0e+04

Iterative Refinement



Point cloud sequence

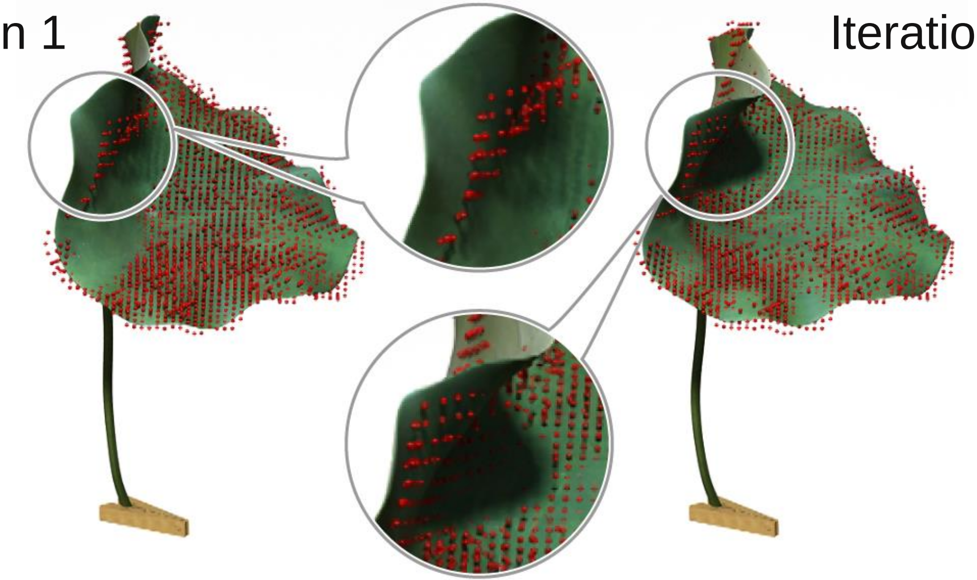
(c) Tracking

(d) Reference shape optimization

(e) Material optimization

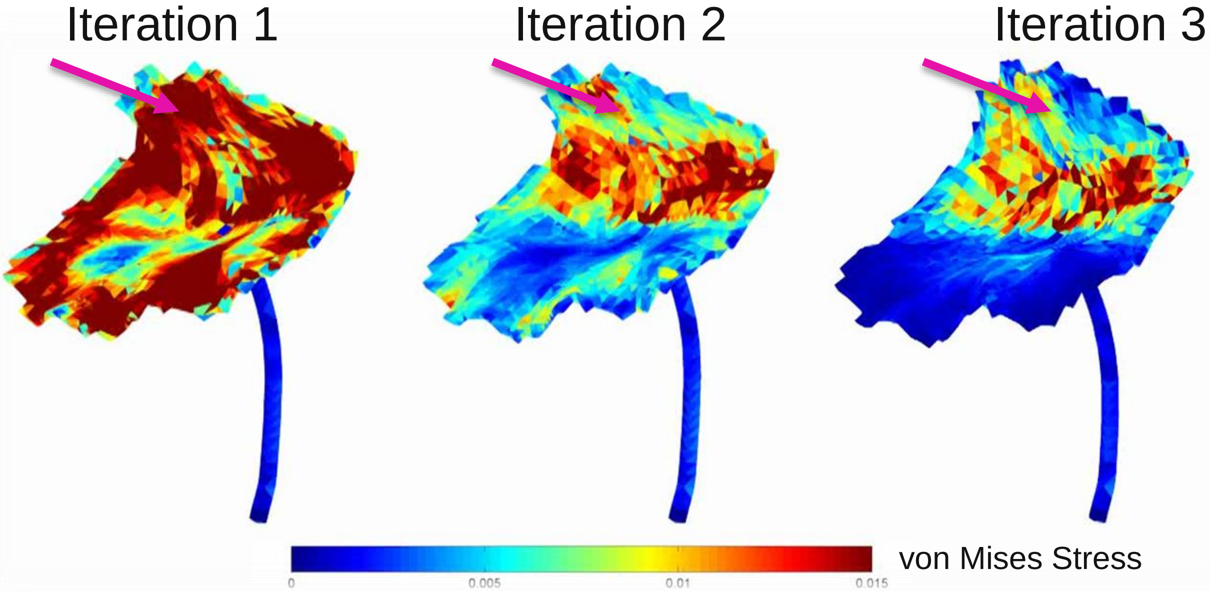
(f)

Iterative Refinement



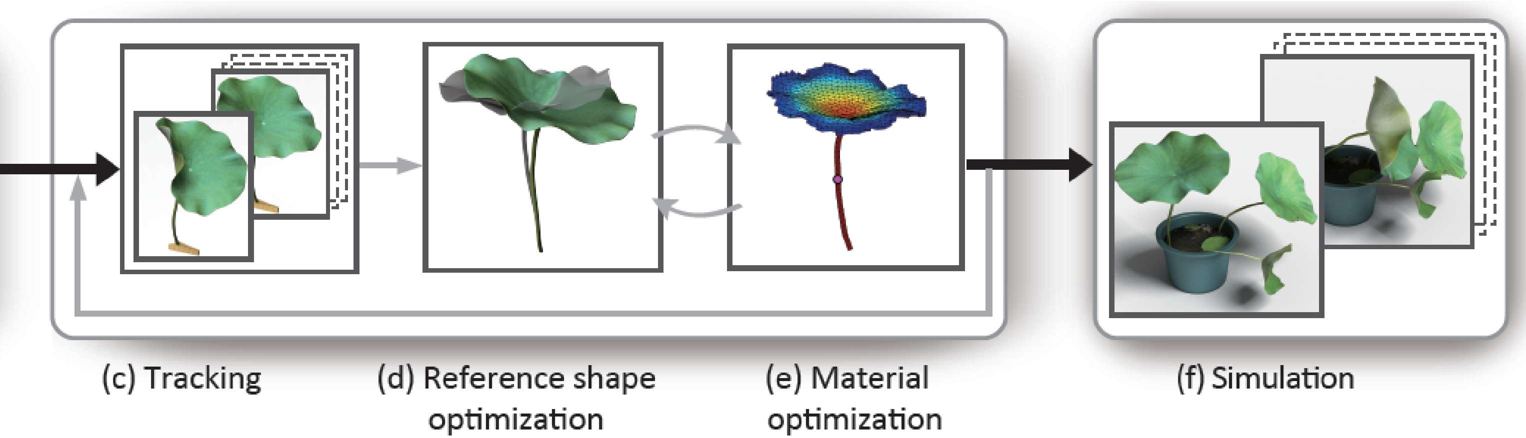
Large deformations can be reconstructed faithfully

Iterative Refinement



The stress field becoms more resonable

Simulation



Synthesis new motion

Simulation

Simulation with water drops

Simulation

Simulation of wind effects

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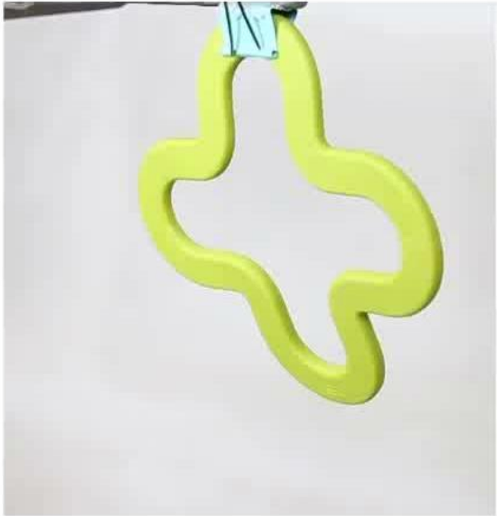
Validation

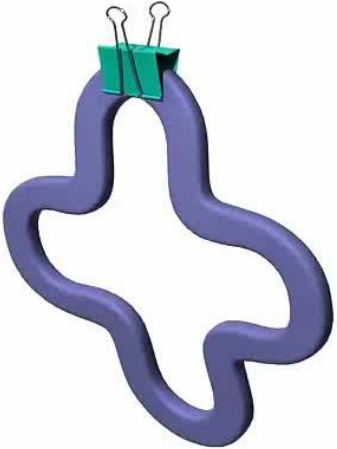
Validation

Ground truth



Tracking result

Simulation



Mode 2 X 1/4

Validation

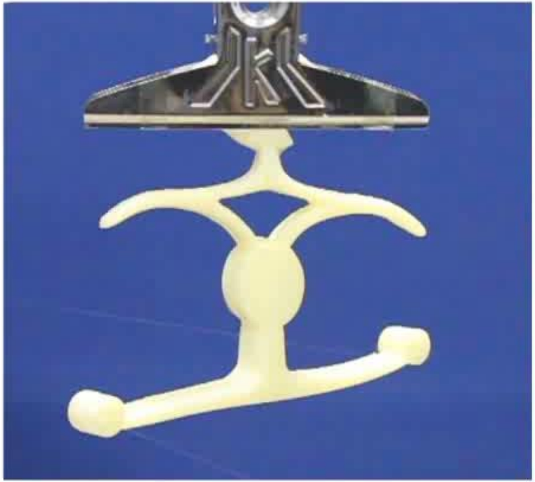
Simulation

X 1/4

Ground truth

Validation

Ground truth



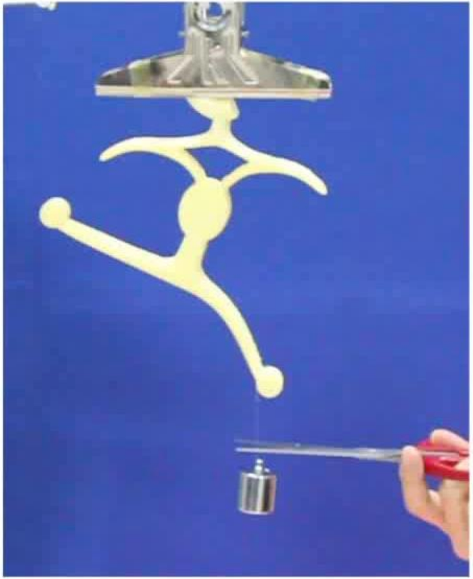
Tracking result

Simulation

Mode 2 X 1/2

Validation

Simulation



X 1/2

Ground truth

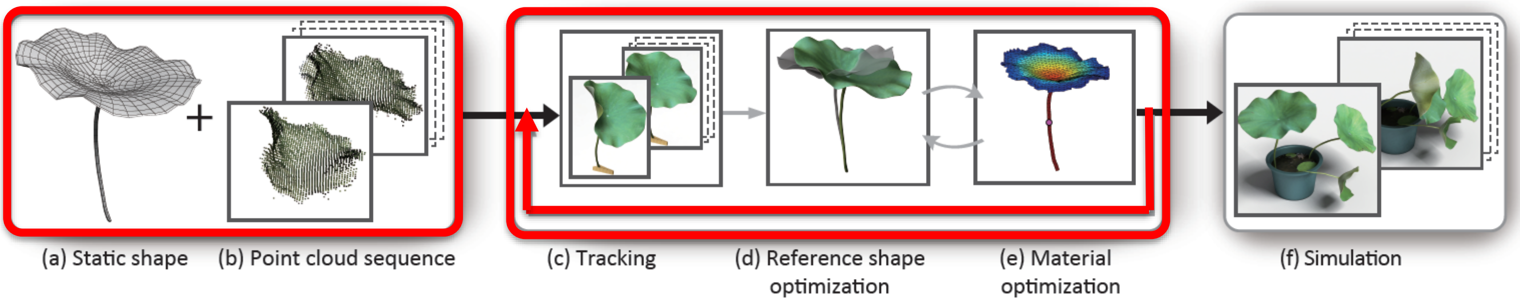
More Results

Simulation under user interaction

Simulation under user interaction

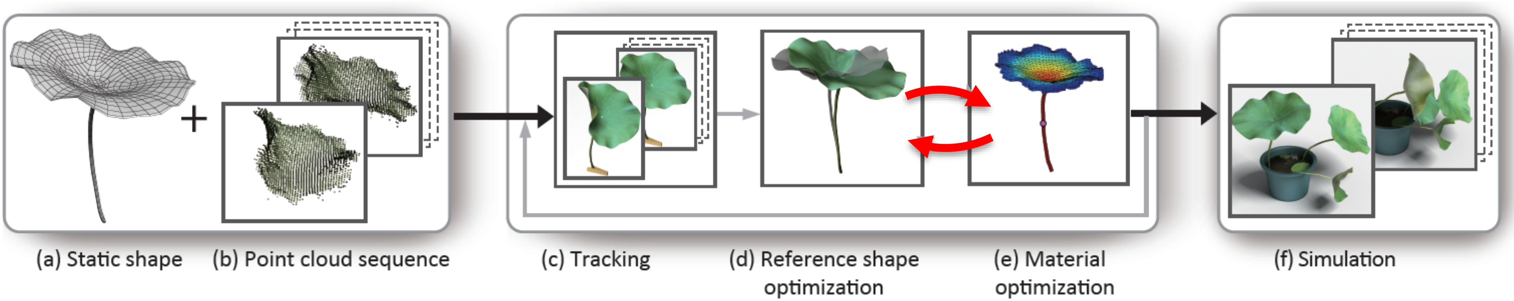
Simulation under user interaction

Conclusion



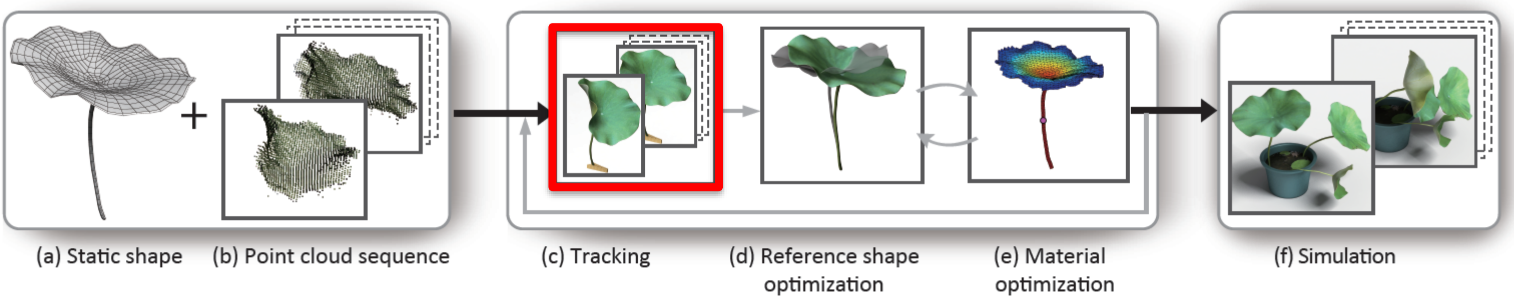
- Iterative tracking and optimization framework

Conclusion



- Iterative tracking and optimization framework
- Splitting scheme for spacetime optimization

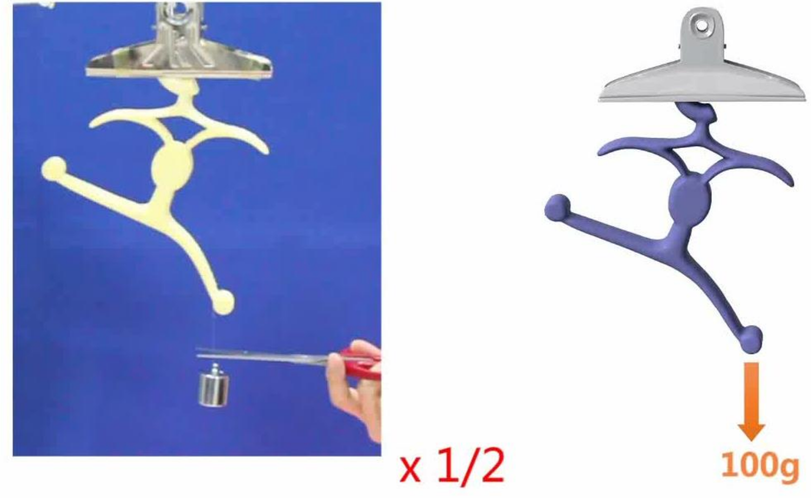
Conclusion



- Iterative tracking and optimization framework
- Splitting scheme for spacetime optimization
- Physics-based deformation tracking

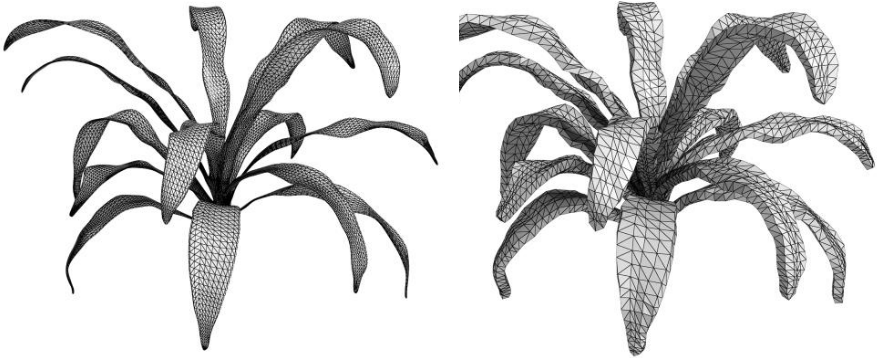
Limitations

- Missing high frequency vibration
- Poisson ratio estimation



Limitations

- Missing high frequency vibration
- Poisson ratio estimation
- Artificial stiffness

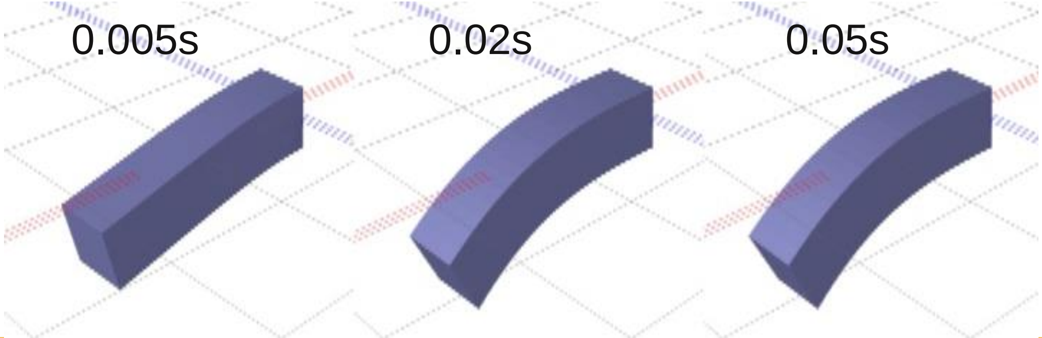


Surface mesh Volumetric mesh

Limitations

- Missing high frequency vibration
- Poisson ratio estimation
- Artificial stiffness
- Numerical damping

Time Step:

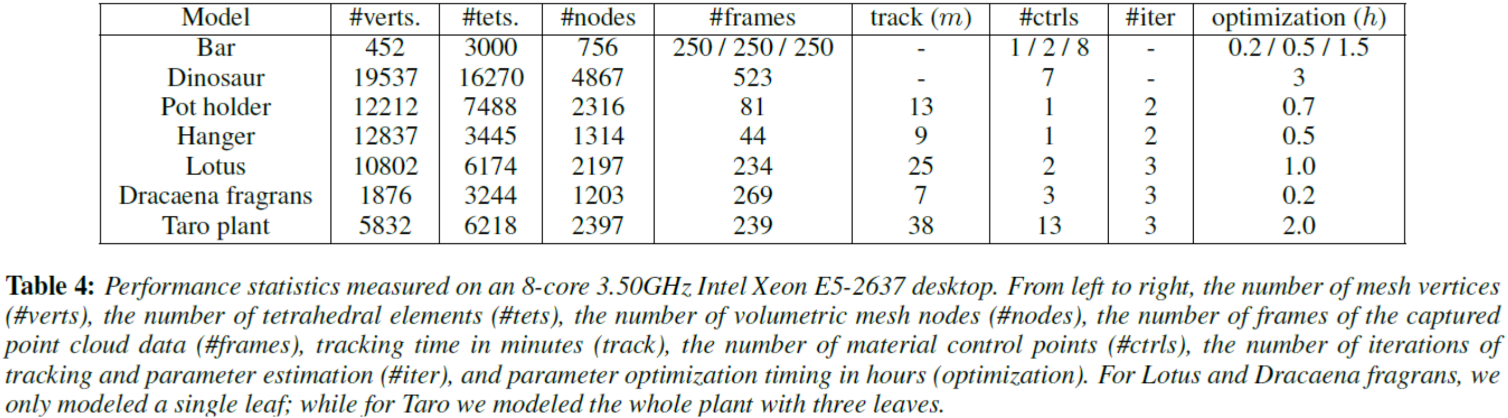


Future Work

- More advanced elastic models
- Gradient-based deformation parameter optimization
- Contact-rich trajectories

Thank You!

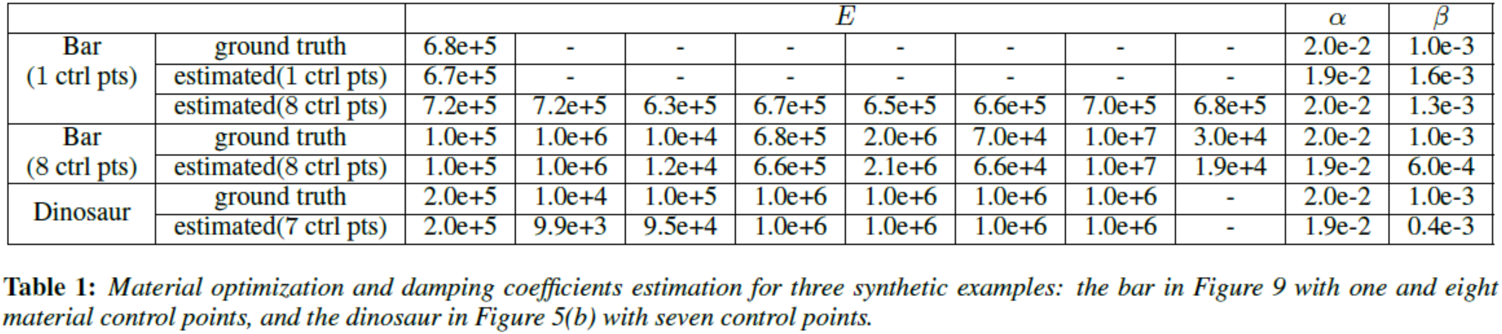
Performance



Model	#verts.	#tets.	#nodes	#frames	track (m)	#ctrls	#iter	optimization (h)
Bar	452	3000	756	250 / 250 / 250	-	1 / 2 / 8	-	0.2 / 0.5 / 1.5
Dinosaur	19537	16270	4867	523	-	7	-	3
Pot holder	12212	7488	2316	81	13	1	2	0.7
Hanger	12837	3445	1314	44	9	1	2	0.5
Lotus	10802	6174	2197	234	25	2	3	1.0
Dracaena fragrans	1876	3244	1203	269	7	3	3	0.2
Taro plant	5832	6218	2397	239	38	13	3	2.0

Table 4: *Performance statistics measured on an 8-core 3.50GHz Intel Xeon E5-2637 desktop. From left to right, the number of mesh vertices (#verts), the number of tetrahedral elements (#tets), the number of volumetric mesh nodes (#nodes), the number of frames of the captured point cloud data (#frames), tracking time in minutes (track), the number of material control points (#ctrls), the number of iterations of tracking and parameter estimation (#iter), and parameter optimization timing in hours (optimization). For Lotus and Dracaena fragrans, we only modeled a single leaf; while for Taro we modeled the whole plant with three leaves.*

Accuracy



		E								α	β
Bar (1 ctrl pts)	ground truth	6.8e+5	-	-	-	-	-	-	-	2.0e-2	1.0e-3
	estimated(1 ctrl pts)	6.7e+5	-	-	-	-	-	-	-	1.9e-2	1.6e-3
	estimated(8 ctrl pts)	7.2e+5	7.2e+5	6.3e+5	6.7e+5	6.5e+5	6.6e+5	7.0e+5	6.8e+5	2.0e-2	1.3e-3
Bar (8 ctrl pts)	ground truth	1.0e+5	1.0e+6	1.0e+4	6.8e+5	2.0e+6	7.0e+4	1.0e+7	3.0e+4	2.0e-2	1.0e-3
	estimated(8 ctrl pts)	1.0e+5	1.0e+6	1.2e+4	6.6e+5	2.1e+6	6.6e+4	1.0e+7	1.9e+4	1.9e-2	6.0e-4
Dinosaur	ground truth	2.0e+5	1.0e+4	1.0e+5	1.0e+6	1.0e+6	1.0e+6	1.0e+6	-	2.0e-2	1.0e-3
	estimated(7 ctrl pts)	2.0e+5	9.9e+3	9.5e+4	1.0e+6	1.0e+6	1.0e+6	1.0e+6	-	1.9e-2	0.4e-3

Table 1: *Material optimization and damping coefficients estimation for three synthetic examples: the bar in Figure 9 with one and eight material control points, and the dinosaur in Figure 5(b) with seven control points.*

Convergence

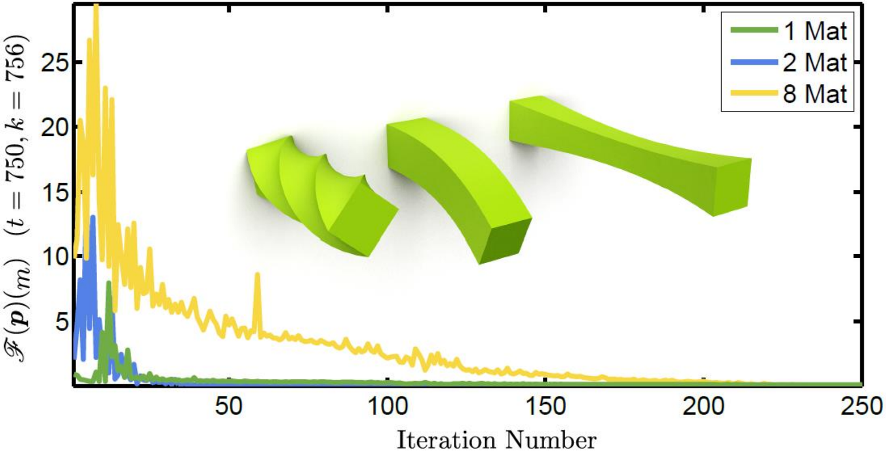
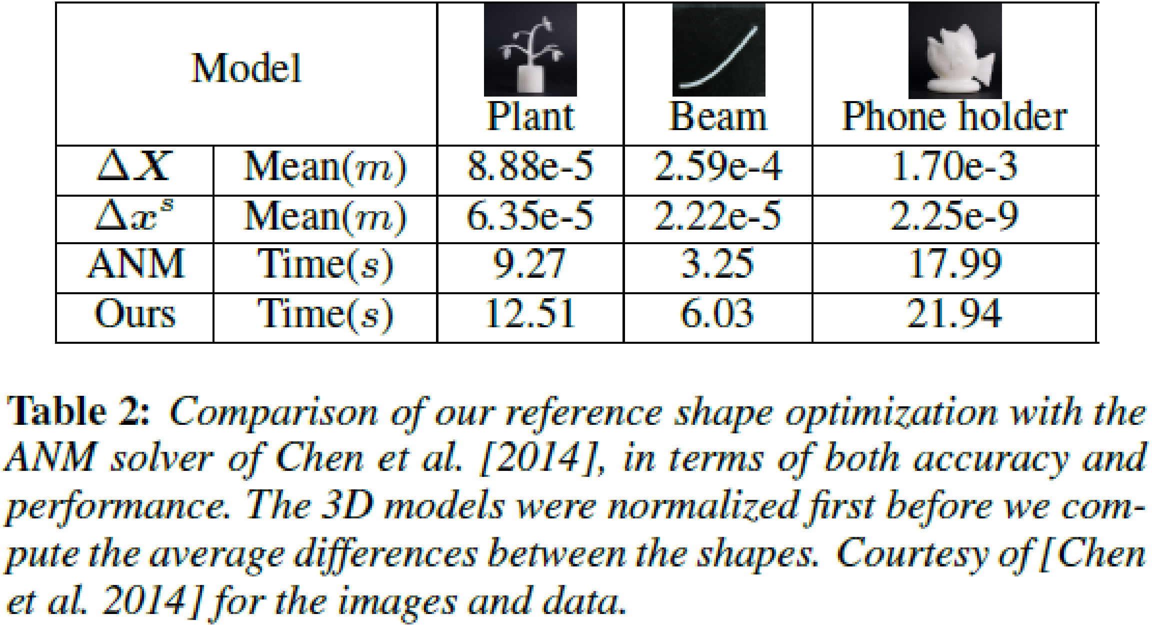


Figure 9: *Convergence characteristics of our deformation parameter estimation algorithm for a synthetic bar example with three material configurations (one, two and eight material control points). The trajectories contain* 750 *frames and the volumetric mesh has* 756 *nodes.*

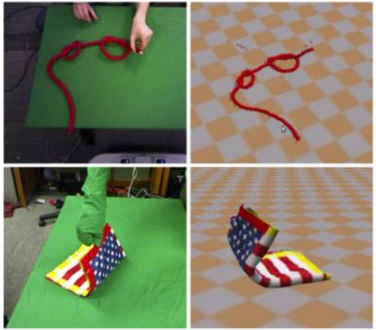
Reference Shape Estimation



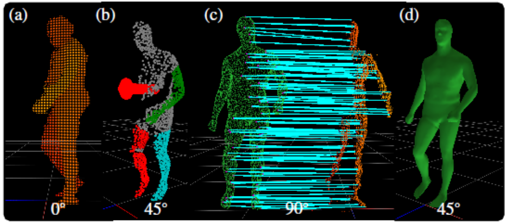
Model		Plant	Beam	Phone holder
ΔX	Mean(m)	8.88e-5	2.59e-4	1.70e-3
Δx^s	Mean(m)	6.35e-5	2.22e-5	2.25e-9
ANM	Time(s)	9.27	3.25	17.99
Ours	Time(s)	12.51	6.03	21.94

Table 2: *Comparison of our reference shape optimization with the ANM solver of Chen et al. [2014], in terms of both accuracy and performance. The 3D models were normalized first before we compute the average differences between the shapes. Courtesy of [Chen et al. 2014] for the images and data.*

Related Work: Animation Capture

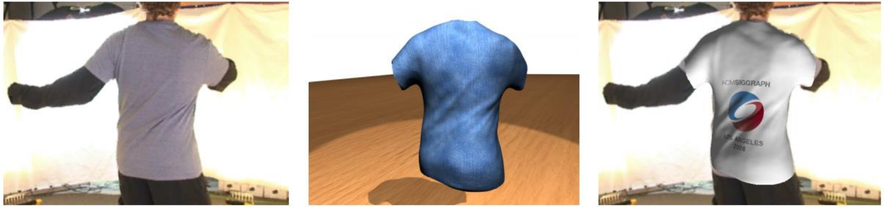


[Schulman et. al 13]



[Helten et. al 13]

[de Aguiar et. al 08]



[Bradley et. al 08]

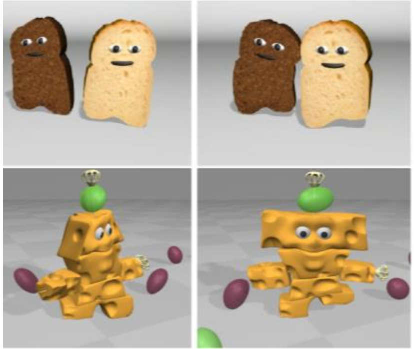
[Li et. al 09]

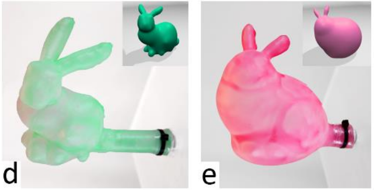
Related Work: Fabrication-oriented Deformation Design


[Skouras et. al 13]


[Derouet-Jourdan et. al 13]


[Bickel et. al 10]


[Coros et. al 12]



[Skouras et. al 12]


(a) (b)

[Chen et. al 14]

FEM-Based Deformation Simulation

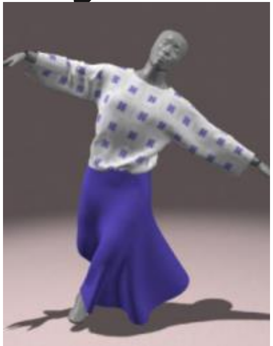
$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{R}\boldsymbol{K}(\boldsymbol{R}^T\boldsymbol{x} - \boldsymbol{X}) = \boldsymbol{f}_{\text{ext}}$$

- Co-rotated Elastic Model

- Rayleigh Damping

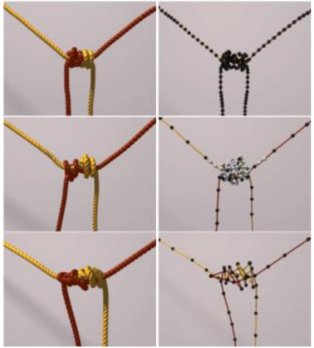
$$\boldsymbol{D} = \alpha\boldsymbol{M} + \beta\boldsymbol{K}$$

Physically-based Simulation

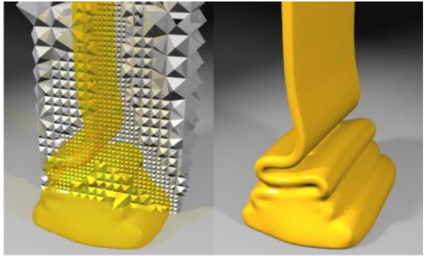


Mass Spring [Baraff et. al 98]

Thin Shell [Pfaff et. al 14]



Rod Element [Spillmann et. al 07]



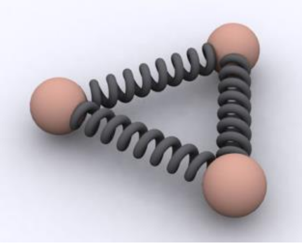
Finite Element [Batty et. al 11]

Yarn [Yuksel et. al 12]

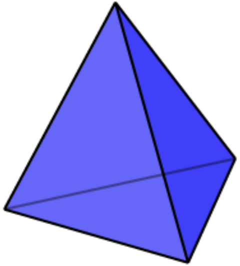
Physically-based Deformation Models

- Spring model

$$f = \underline{k}(x - \underline{x_0})$$



- FEM (Finite Element Method)



k → Young's modulus, Poisson ratio

x_0 → Reference shape

Manual tuning these parameters for heterogeneous objects is tedious and error prone