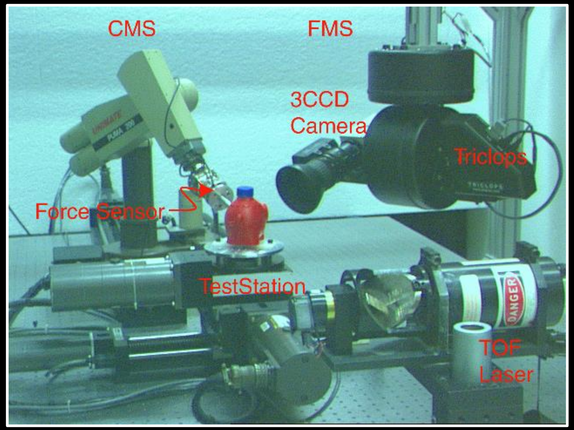
Scanning Physical Interaction Behavior of 3D Objects

Dinesh K. Pai, Kees van den Doel, Doug L. James, Jochen Lang, John E. Lloyd, Joshua L. Richmond, Som H. Yau

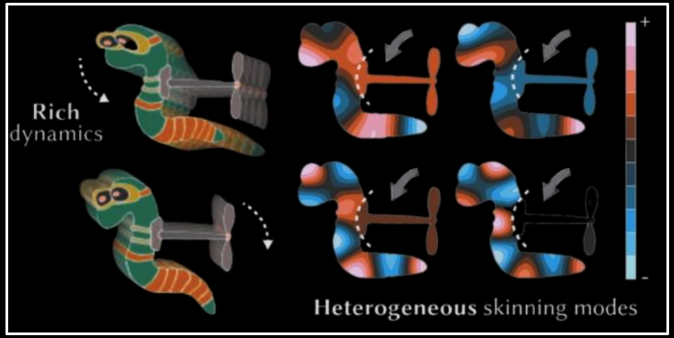


Presented by
Rishit Dagli

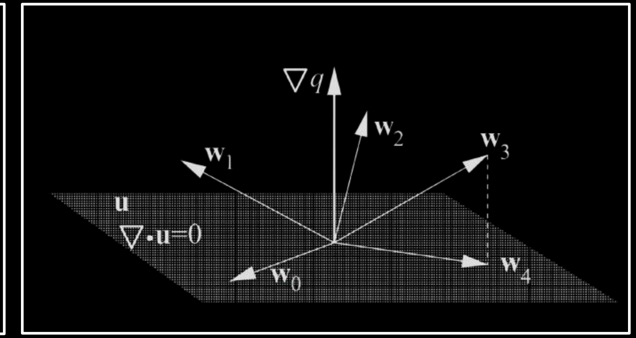
some content taken
from the paper

what did we do up until now?

- start with physical laws
- develop some numerical methods to solve these equations
- make sure you have good accuracy and stability in your simulation
- predict behavior from the first laws



[BZCGZJ 2023]



[S 1999]

let us introduce a new problem

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- develop some numerical methods to solve these equations
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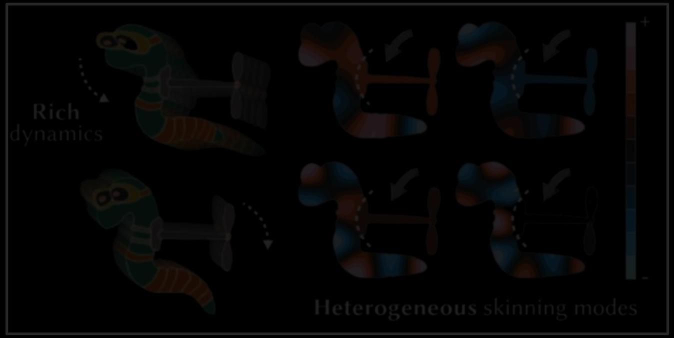

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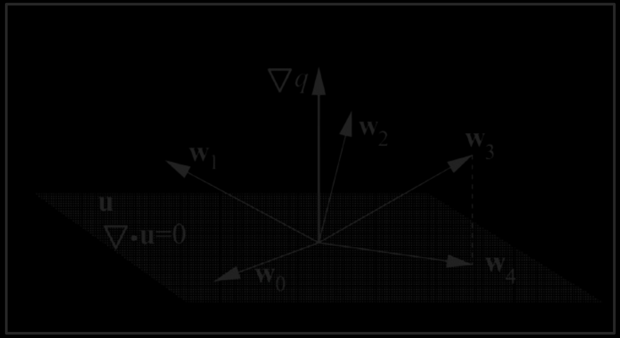


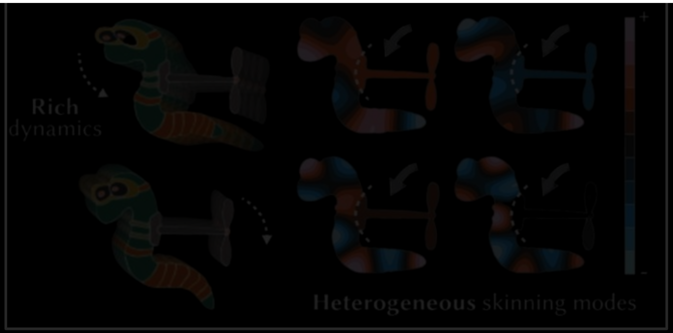
[S 1999]

- observe the behavior of a real object
- reproduce the observed phenomena
- make sure you can well capture or measure the phenomena

let us introduce a new problem

- start with physical laws

- no longer need models of complex phenomena
- can easily capture certain behaviors which are hard to simulate
- often very efficient for real-time (producing behaviors in real-time)



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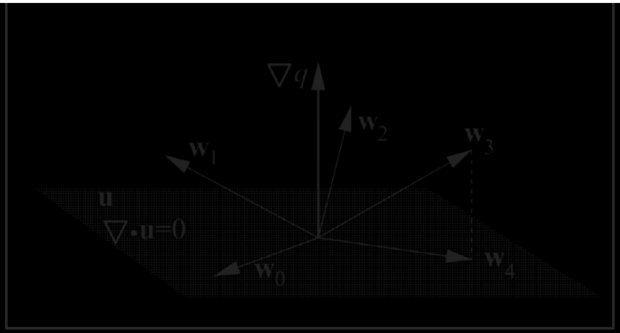

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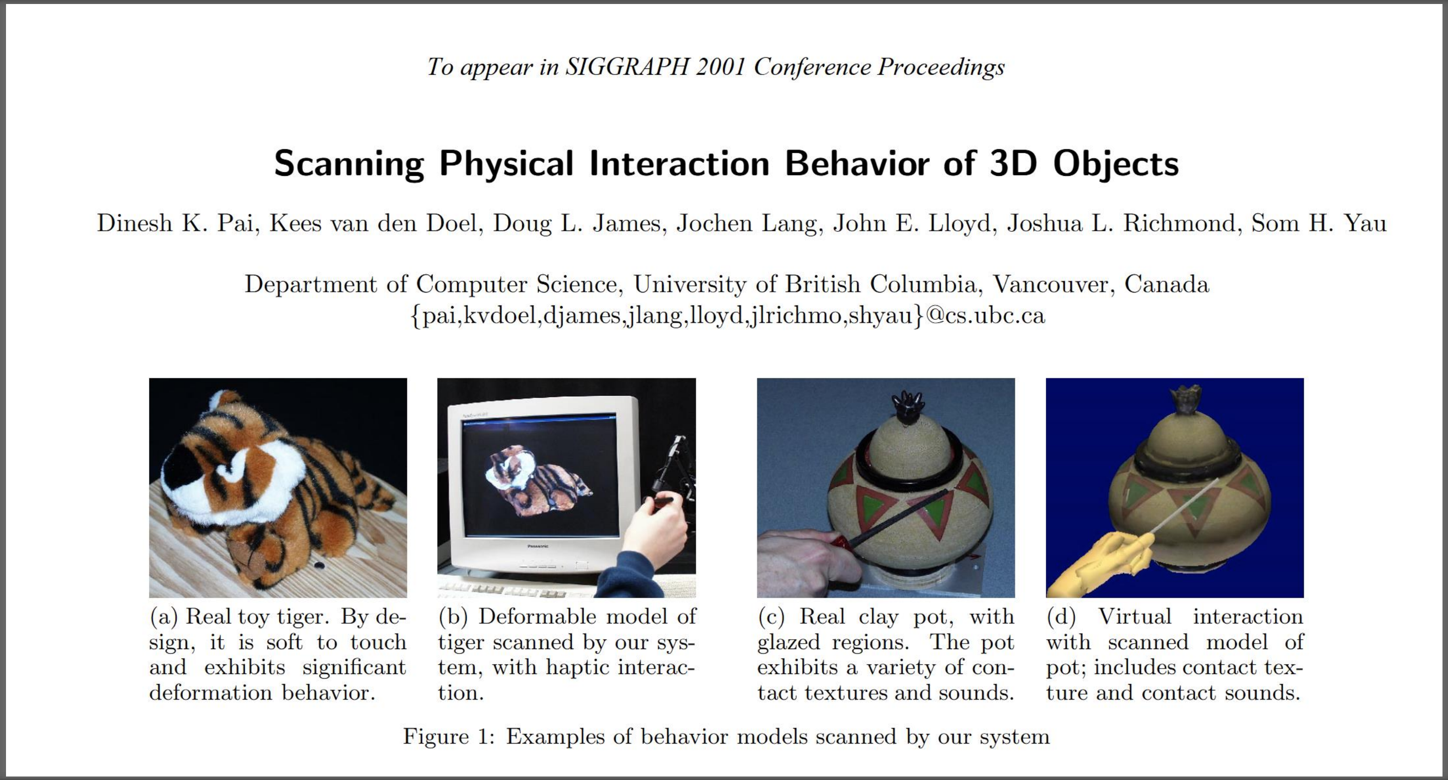
what will we talk about today?



To appear in SIGGRAPH 2001 Conference Proceedings

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Department of Computer Science, University of British Columbia, Vancouver, Canada
{pai,kvdoel,djames,jlang,lloyd,jlrichmo,shyau}@cs.ubc.ca

(a) Real toy tiger. By design, it is soft to touch and exhibits significant deformation behavior.

(b) Deformable model of tiger scanned by our system, with haptic interaction.

(c) Real clay pot, with glazed regions. The pot exhibits a variety of contact textures and sounds.

(d) Virtual interaction with scanned model of pot; includes contact texture and contact sounds.

Figure 1: Examples of behavior models scanned by our system

from 2001

[PDJLLRY 2001]

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- deformation
- contact texture
- sound

deformation behavior. tion. tact textures and sounds. ture and contact sounds.

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focus on measurement

- deformation
- contact texture
- sound

deformation behavior. tion. tact textures and sounds. ture and contact sounds.

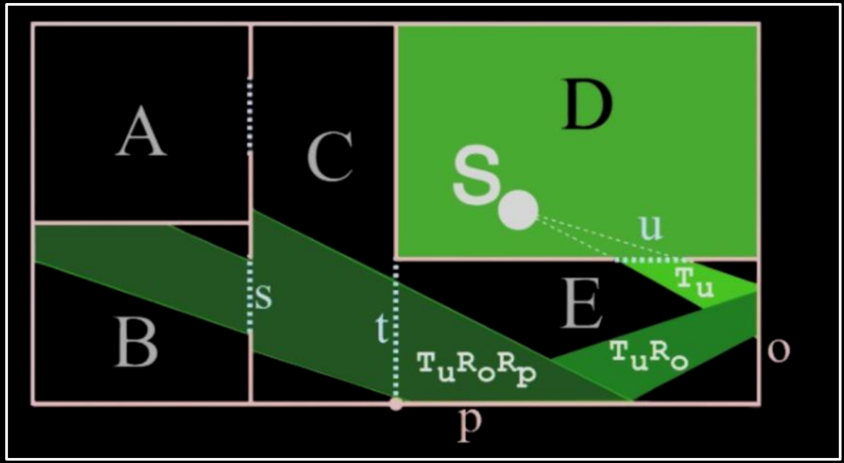
Figure 1: Examples of behavior models scanned by our system

from 2001 🦖

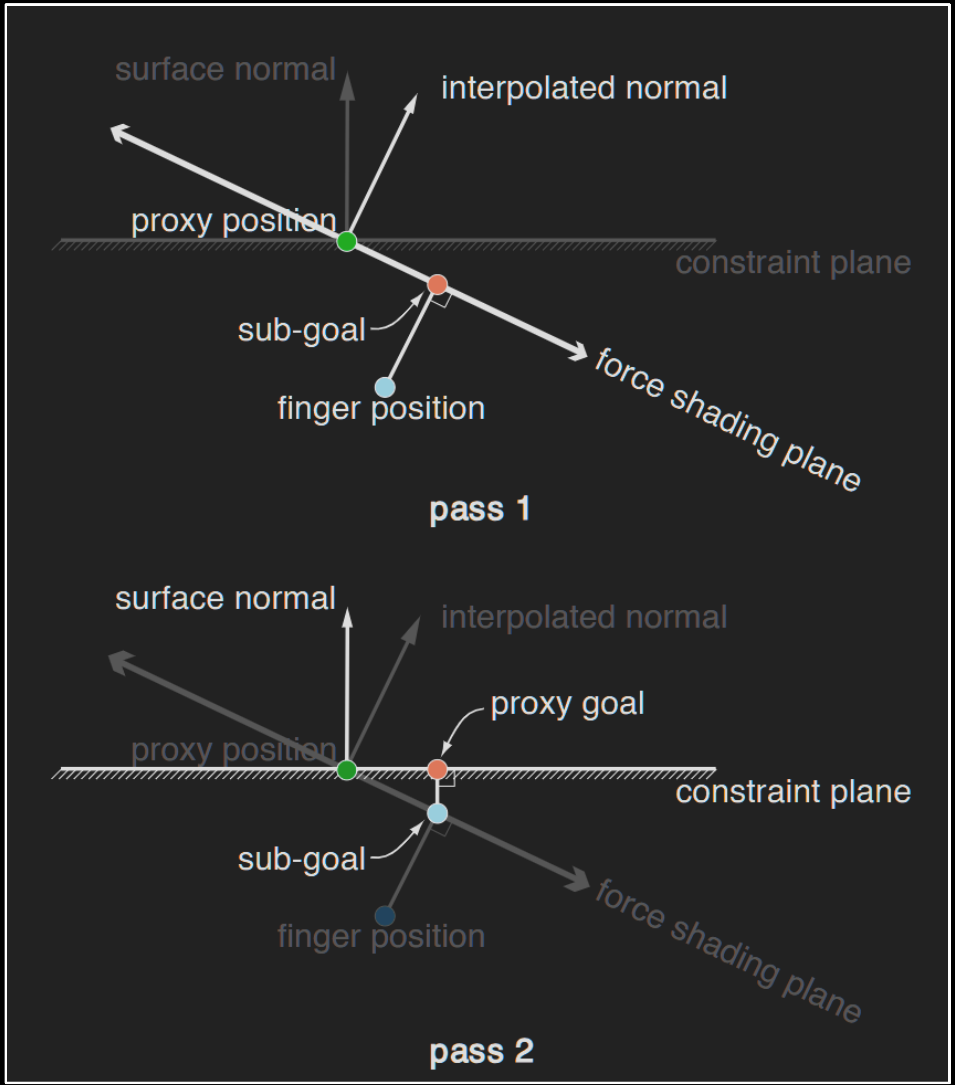
[PDJLLRY 2001]

motivation

- there were some deformation models back then that kind of worked
- there did exist haptic simulations
- and acoustic modelling techniques or more accurately spatialization techniques



[FCEPSW 1999]



[RKK 1997]

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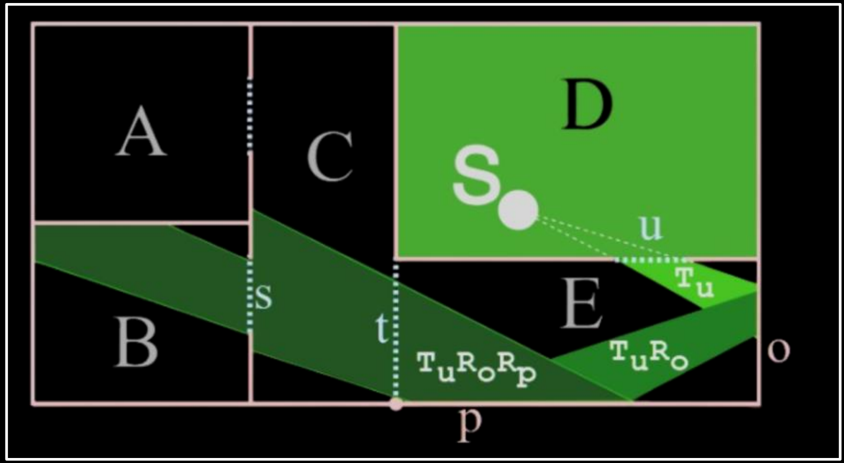
- there did exist haptic simulations
- and acoustic modelling techniques or more accurately spatialization techniques

often require completely different frameworks



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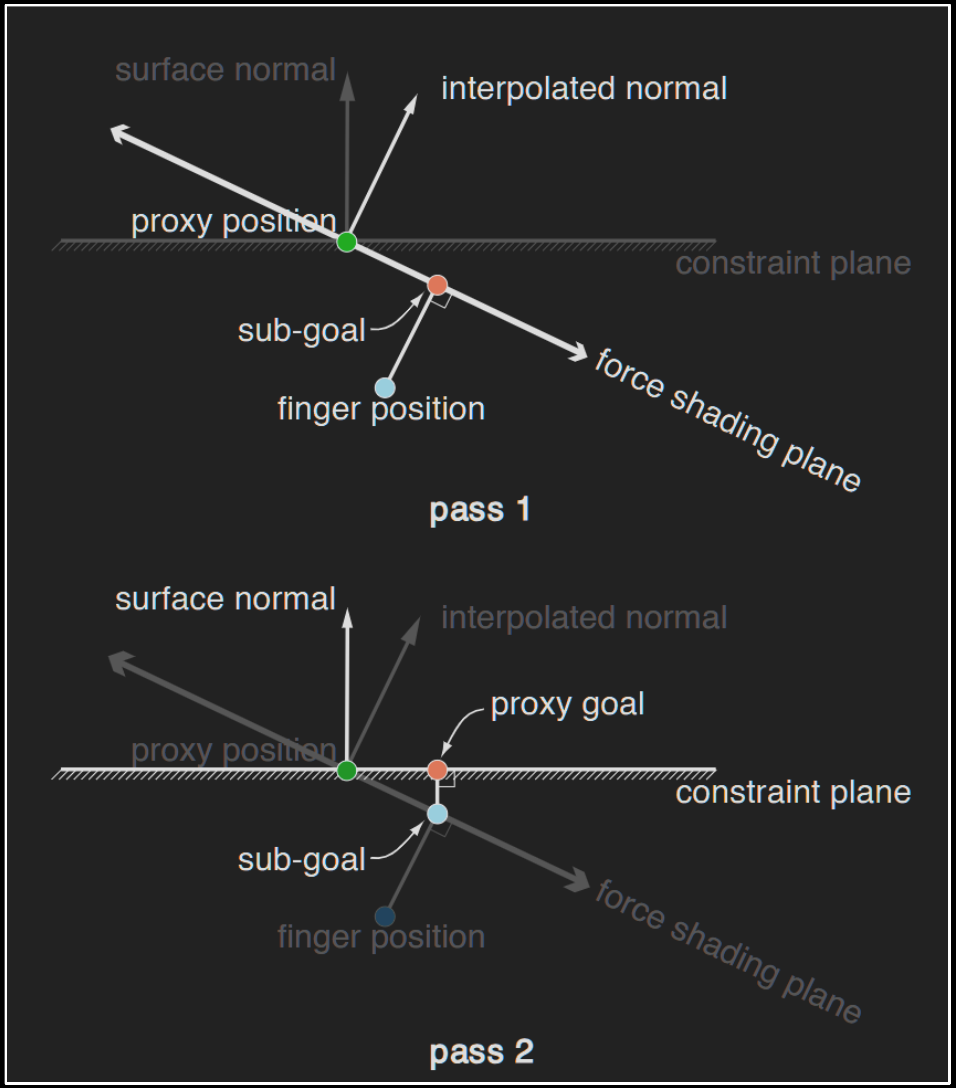

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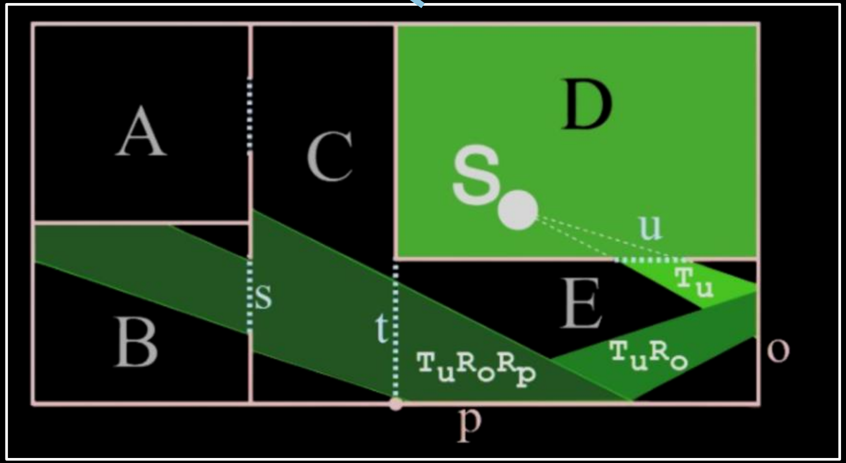
very far from simulating
all the relevant information



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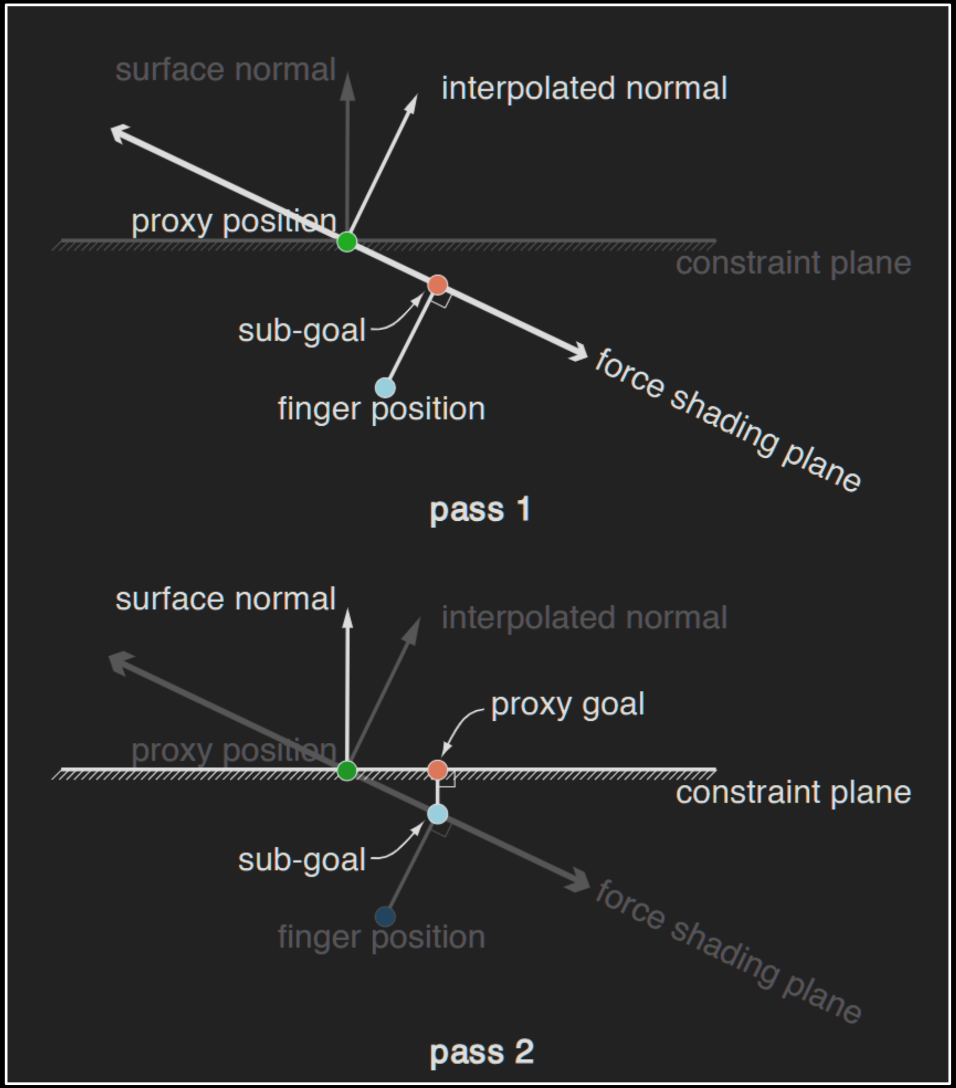

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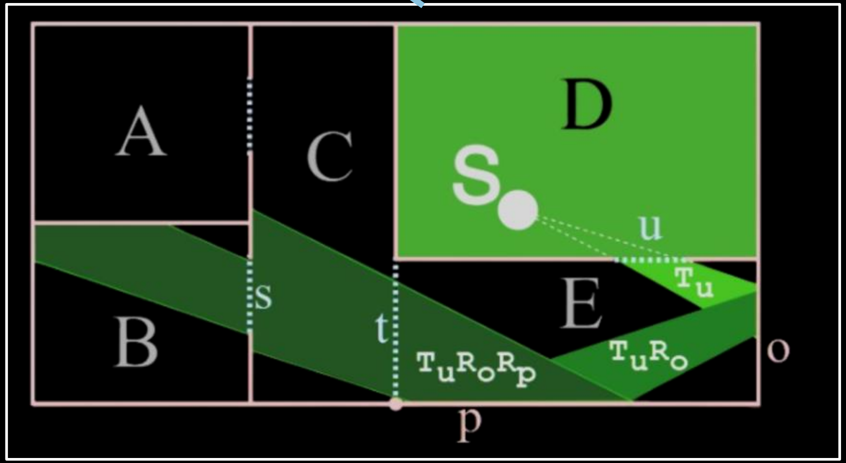

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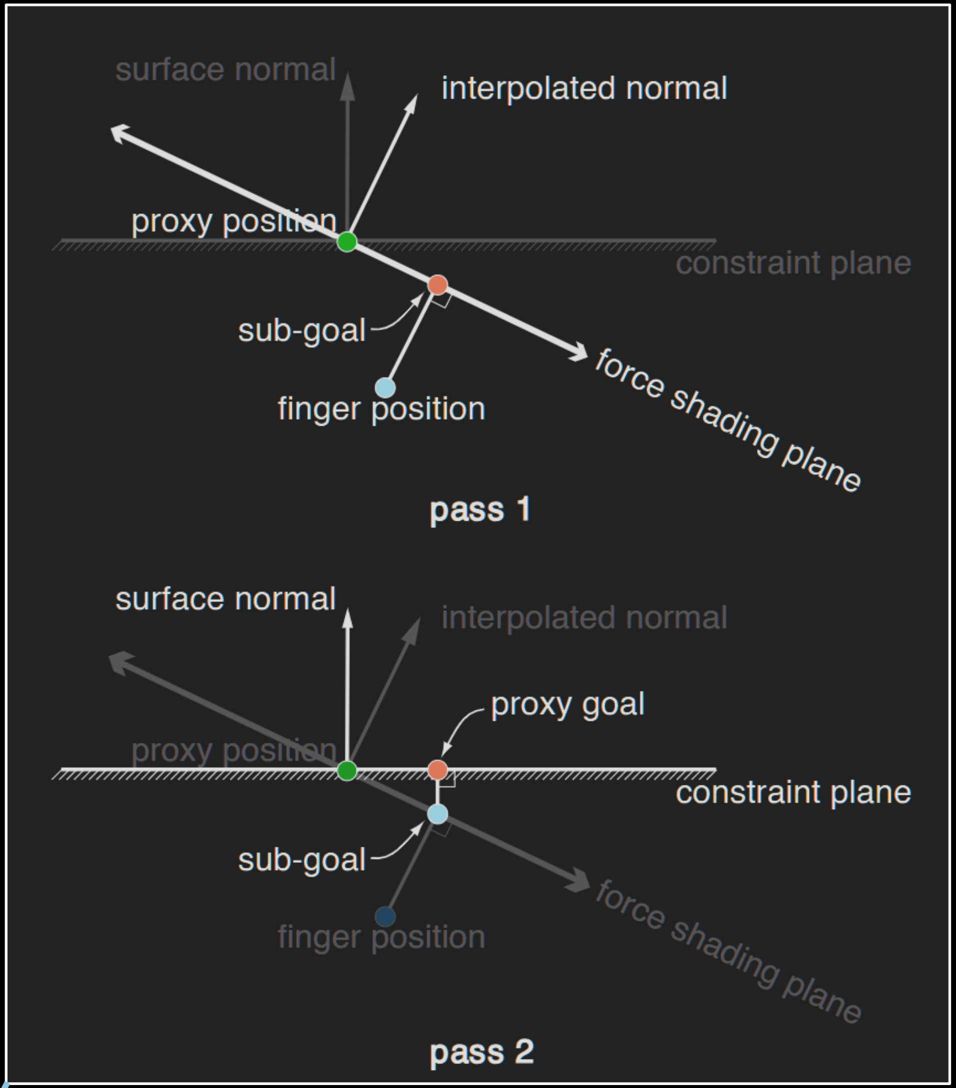
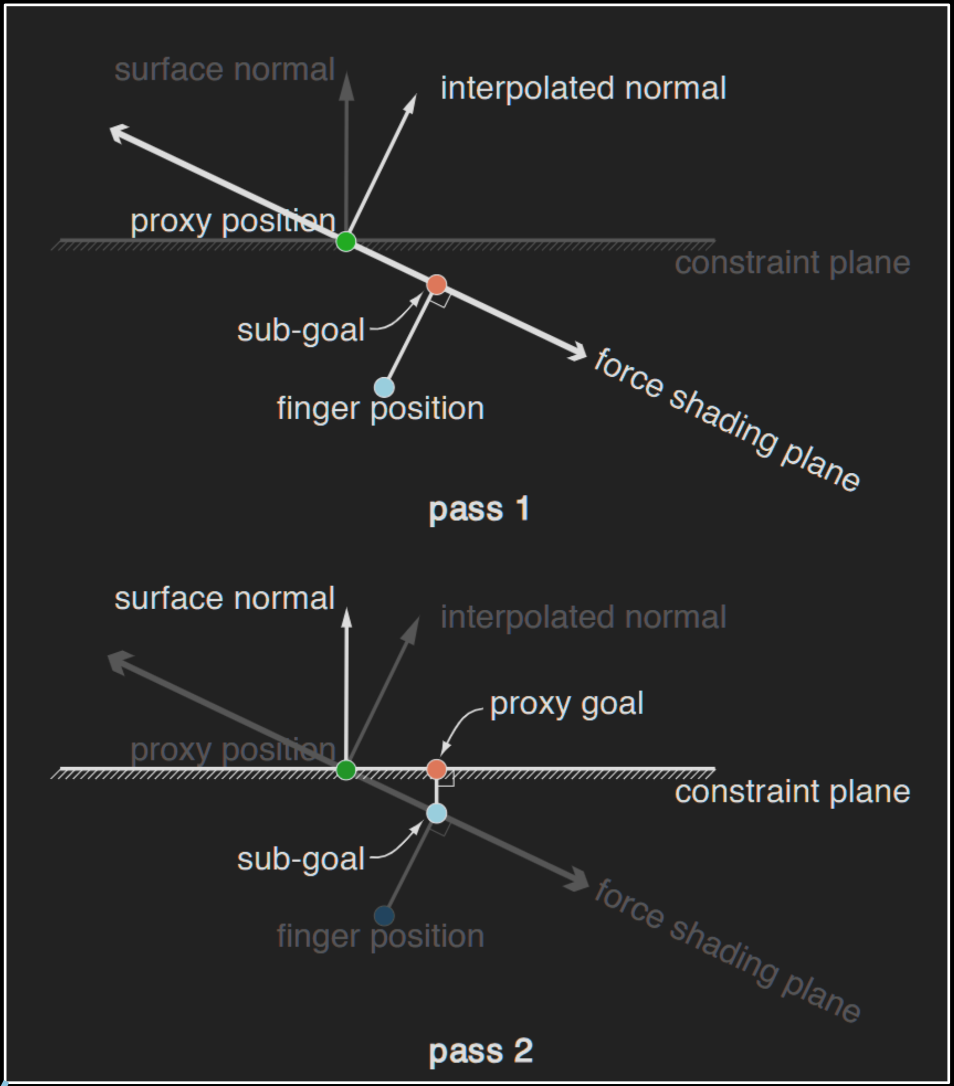


[RKK 1997]

very hard to make this
work to mimic a real object

motivation

make models which have such parameters such that they can all be efficiently (automatically) captured just through a real object



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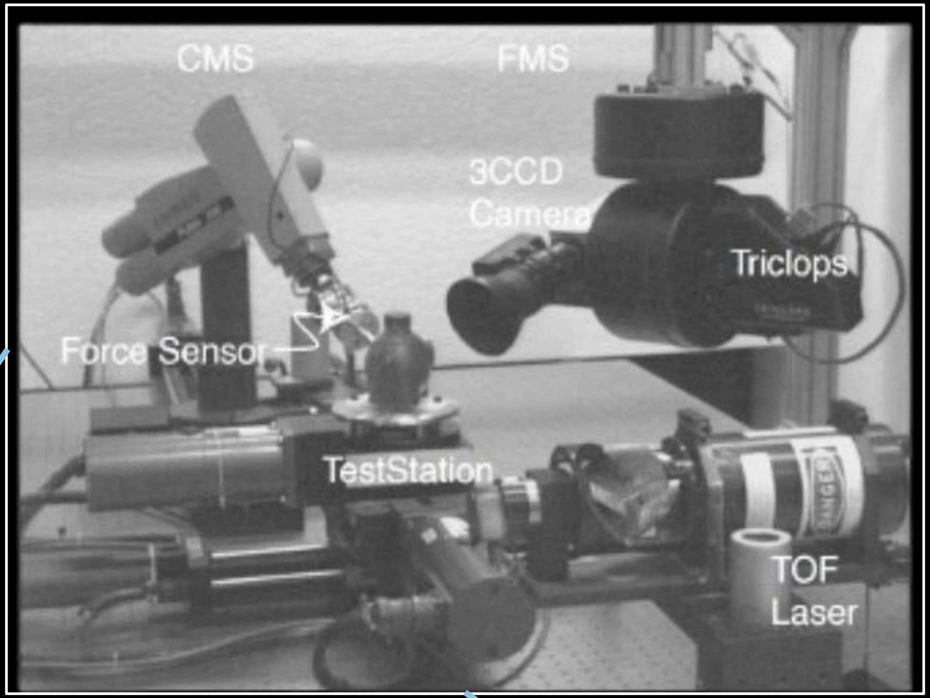
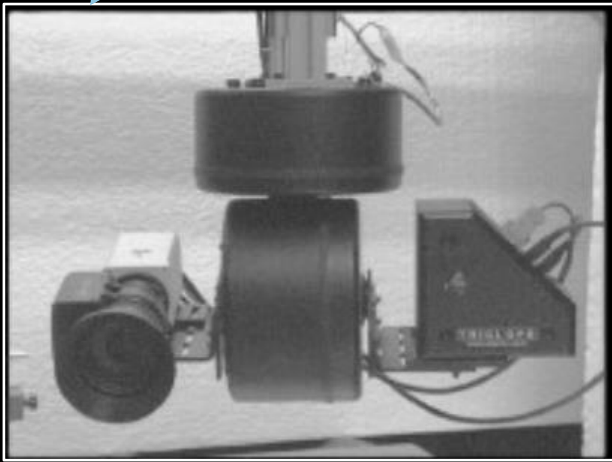
what to measure and how to measure?

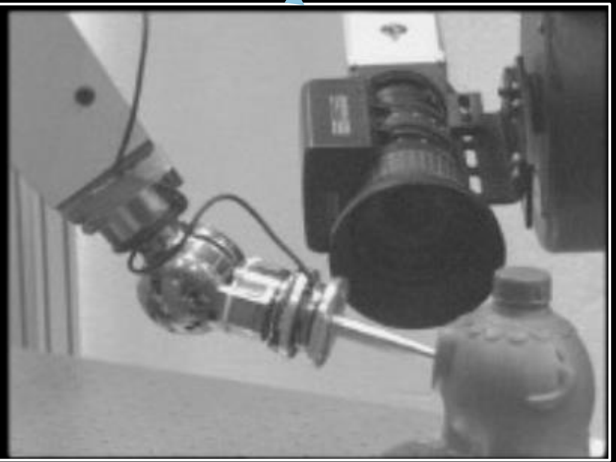
measurement system

[PLLW 1999]



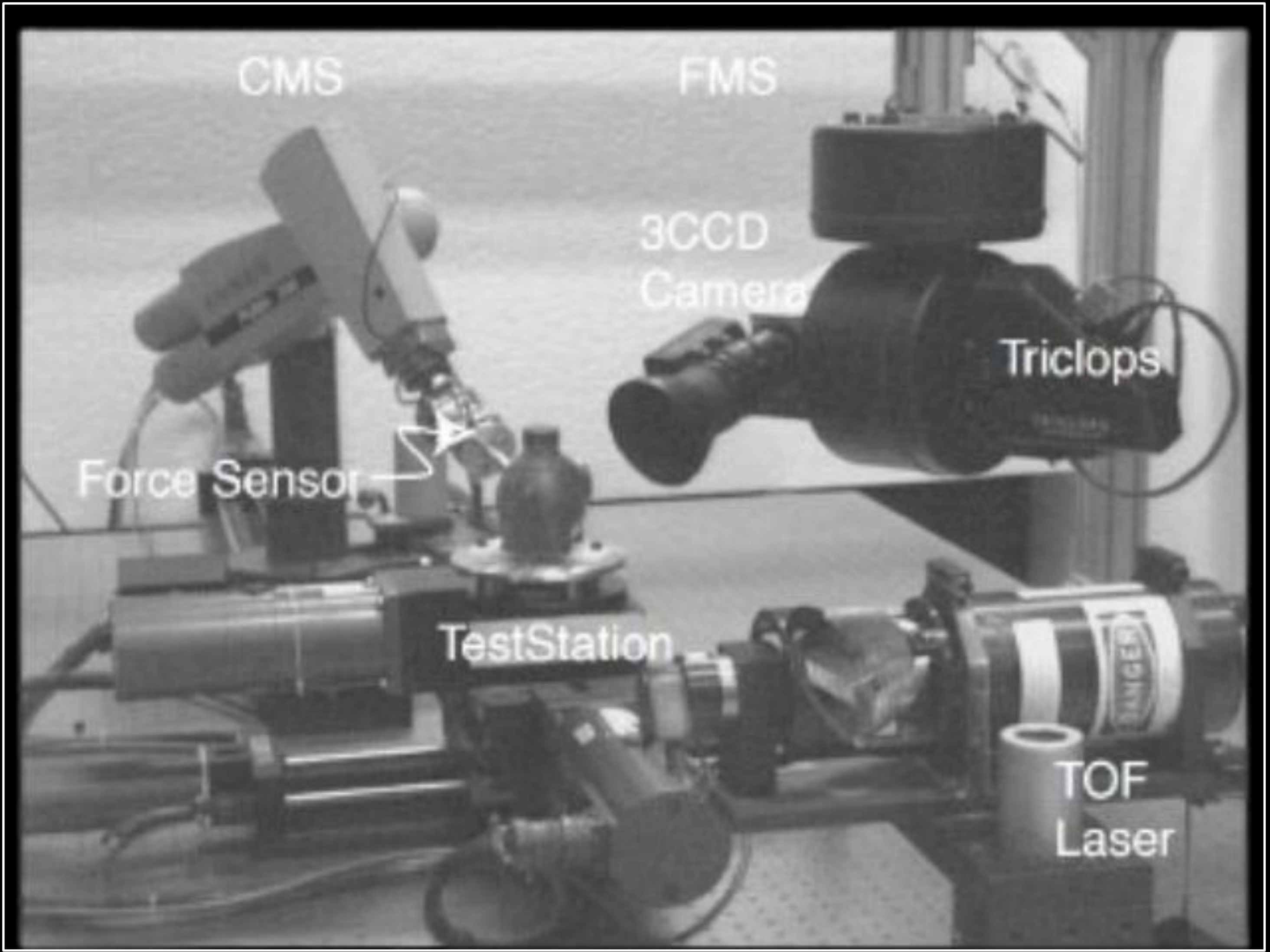


field
measurement system



force/position
measurement system

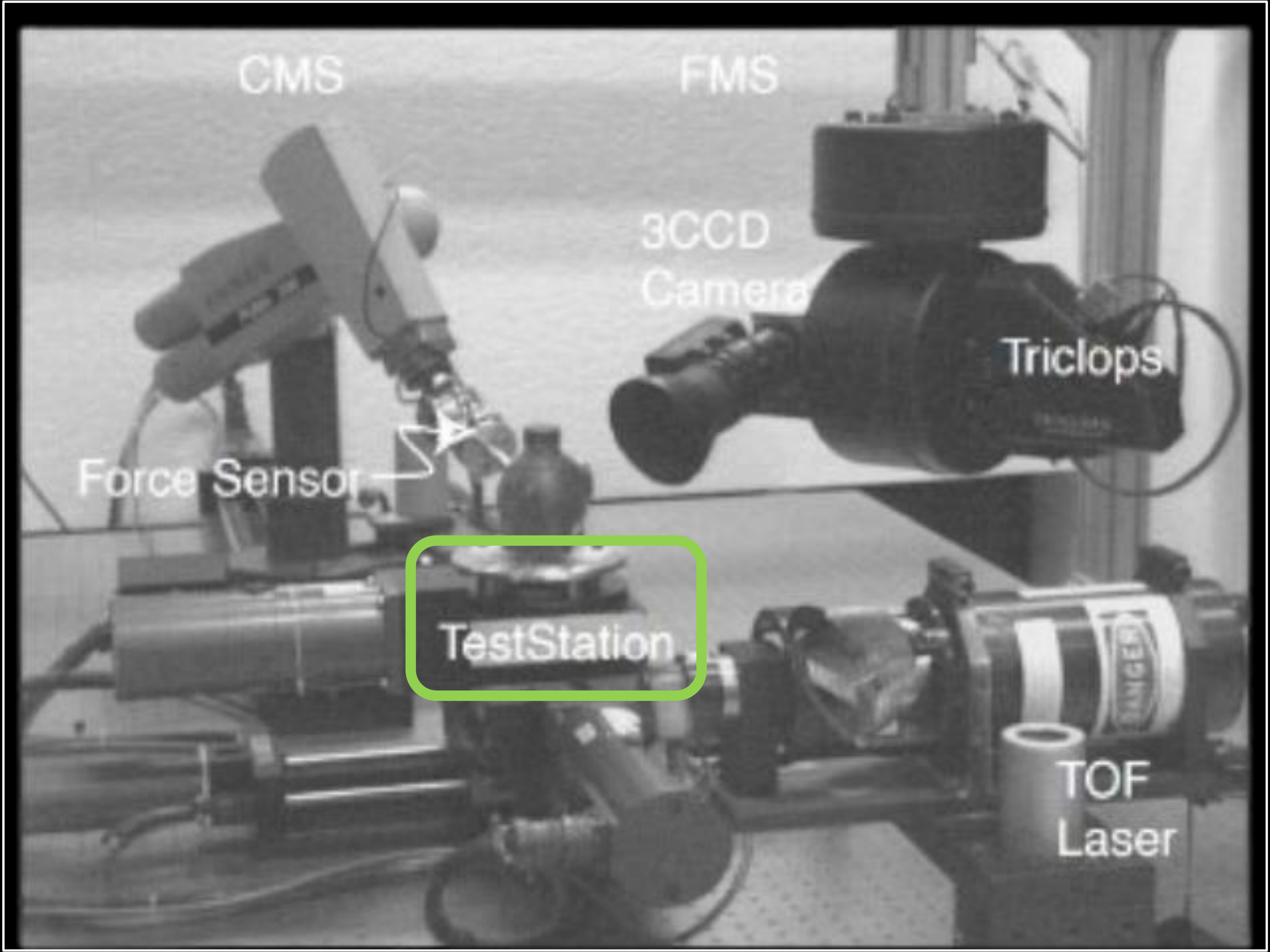
measurement system



[PLLW 1999]

measurement system

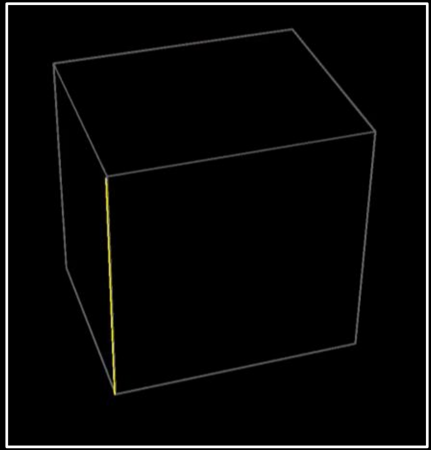
3 DOF placement



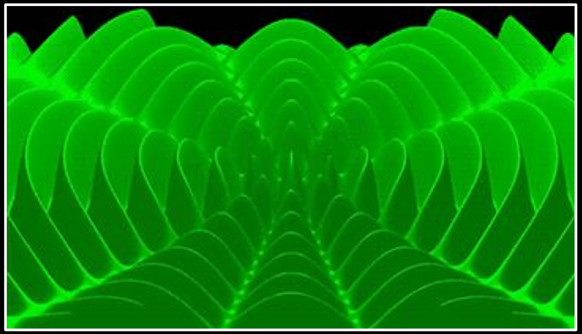
[PLLW 1999]

measurement system

field measurement system
(stereo vision + rgb camera + mic)
on a 5 DOF positioning robot

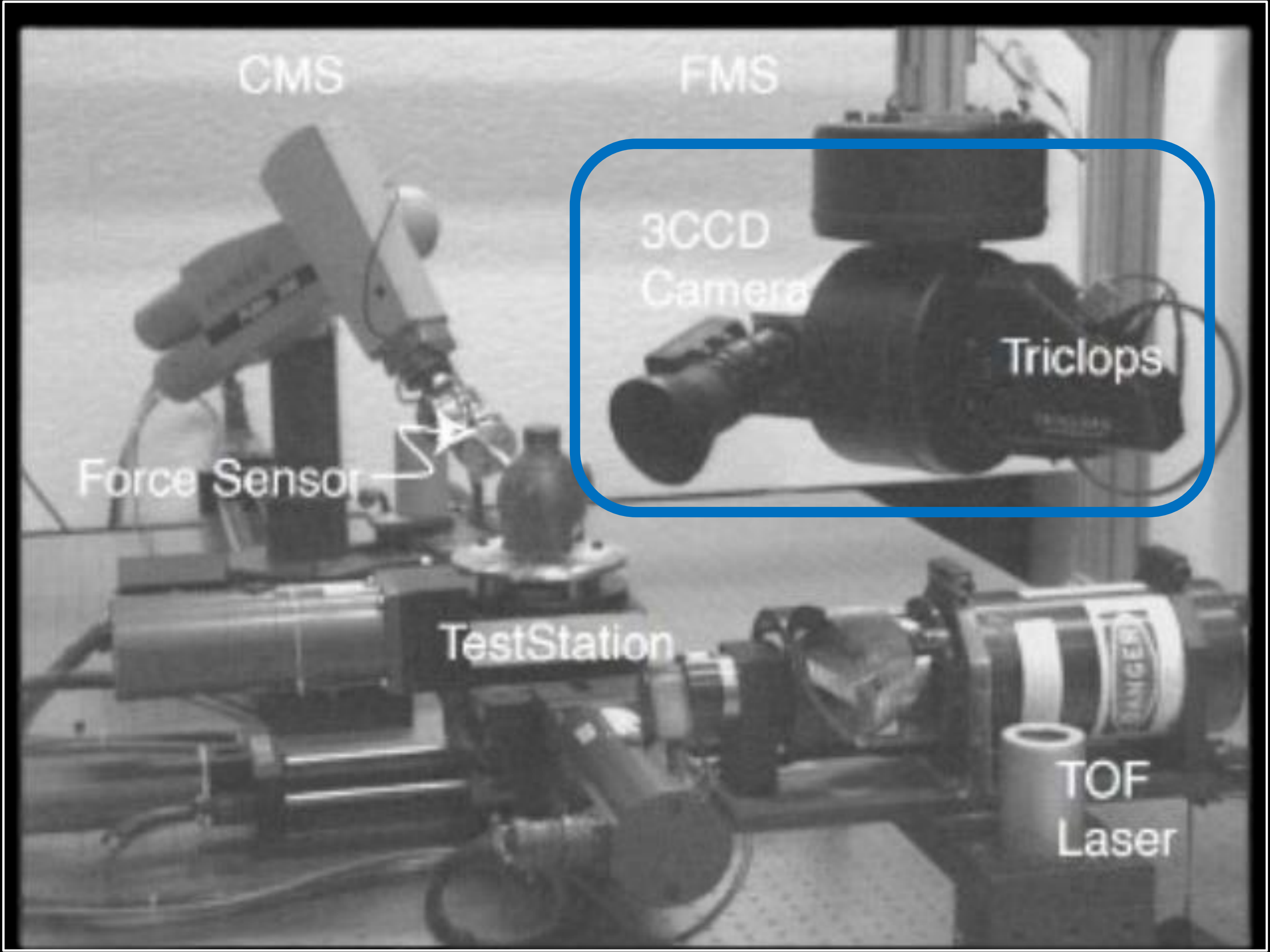


light field



sound field

[MID 2002]



[PLLW 1999]

measurement system

[MID 2002]

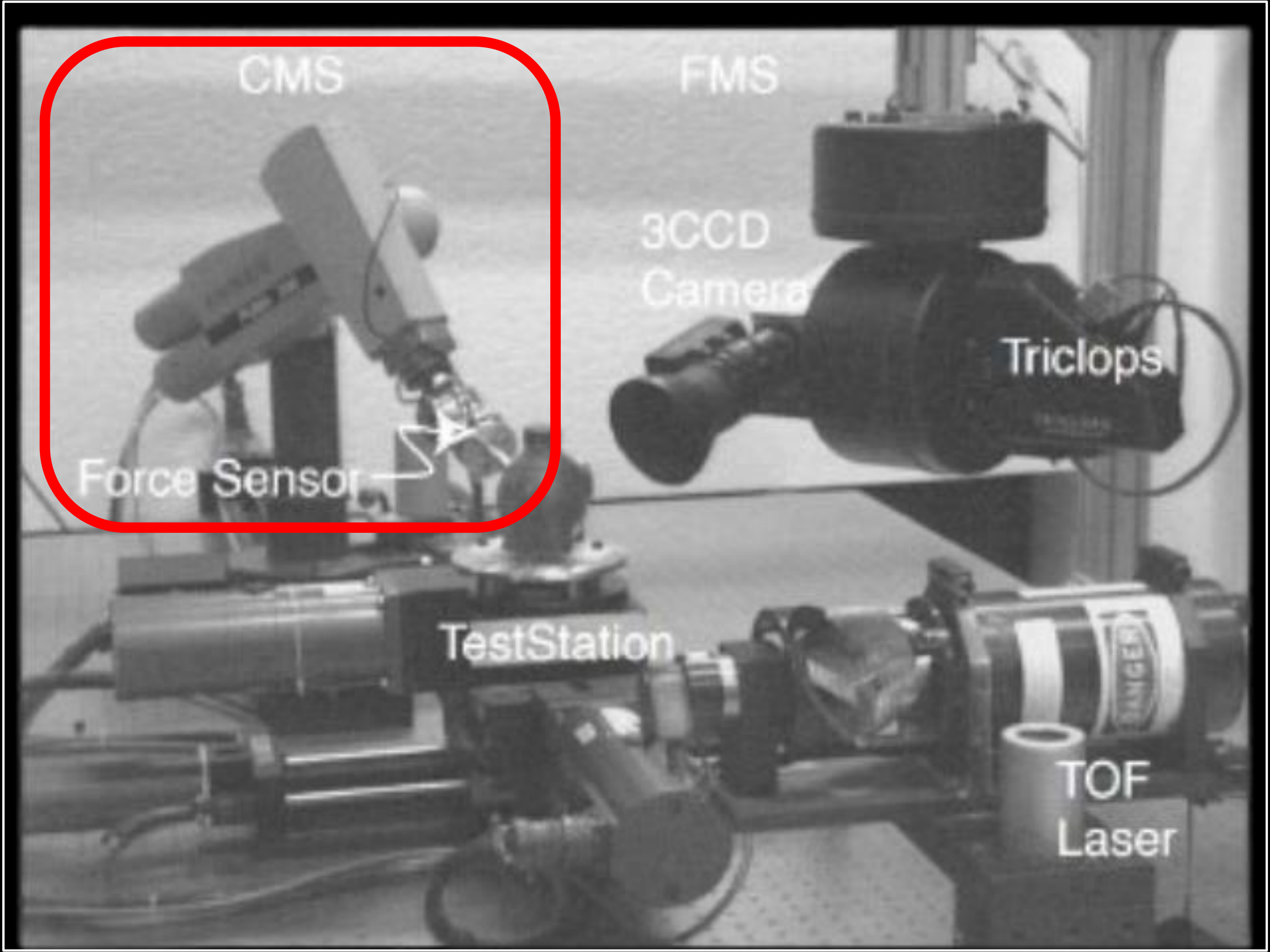
stereo range data is highly noisy
we need some kind of filtering to decide what stereo range data we need

some classical techniques:

- variable mask size voting
- estimate (local) surface normal
- decide some handcrafted ways of choosing what to keep

measurement system

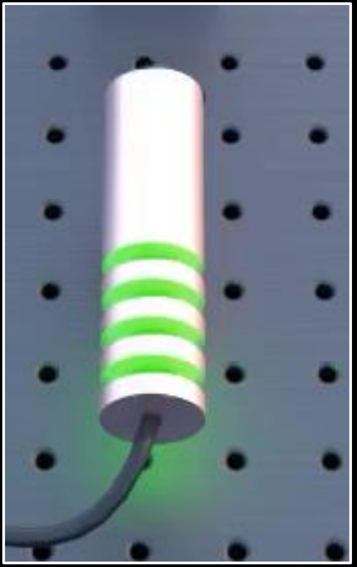
force/position measurement system
(force/torque sensor)
on a linear stage

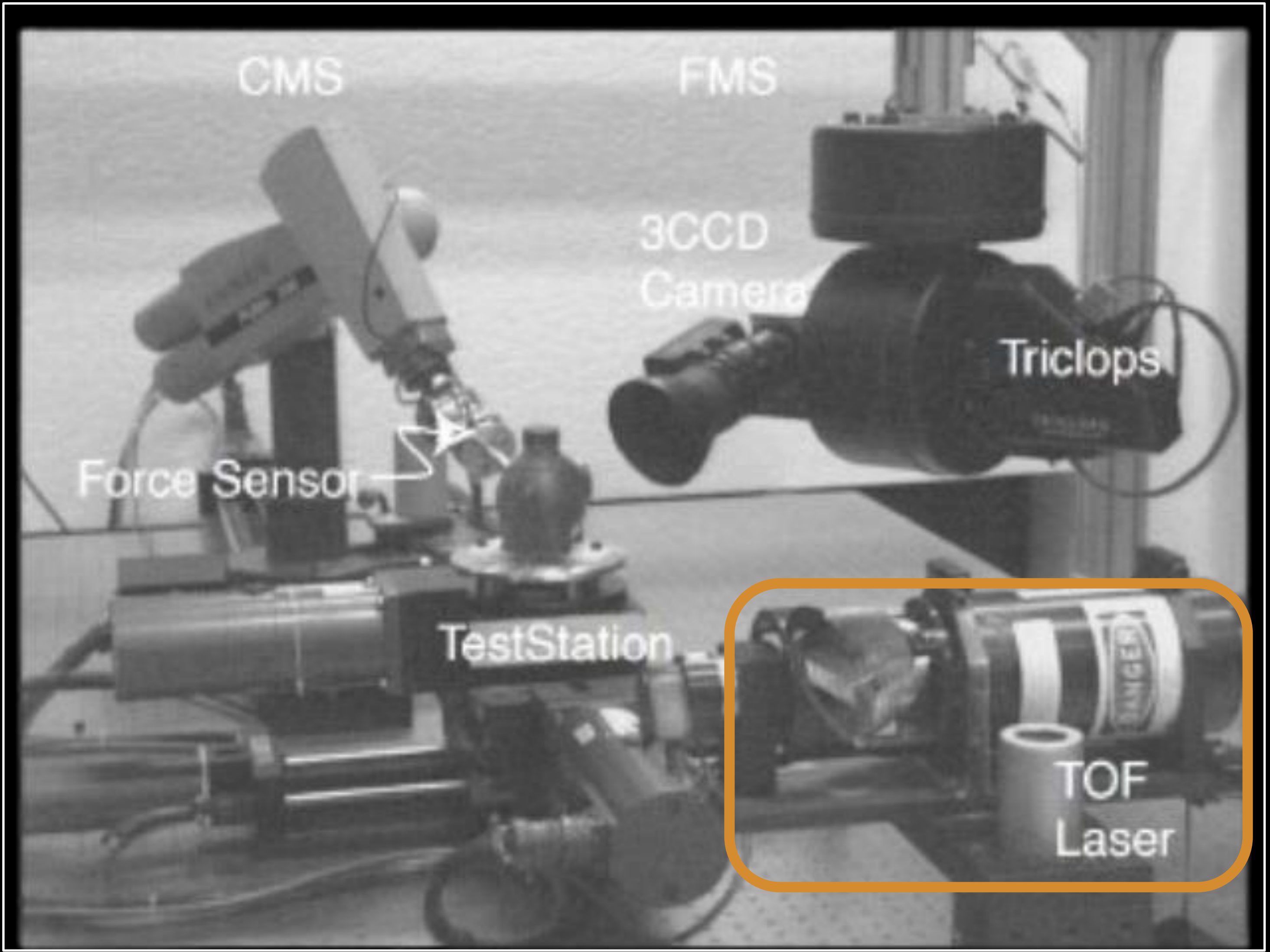


[PLLW 1999]

measurement system

time-of-flight laser range finder





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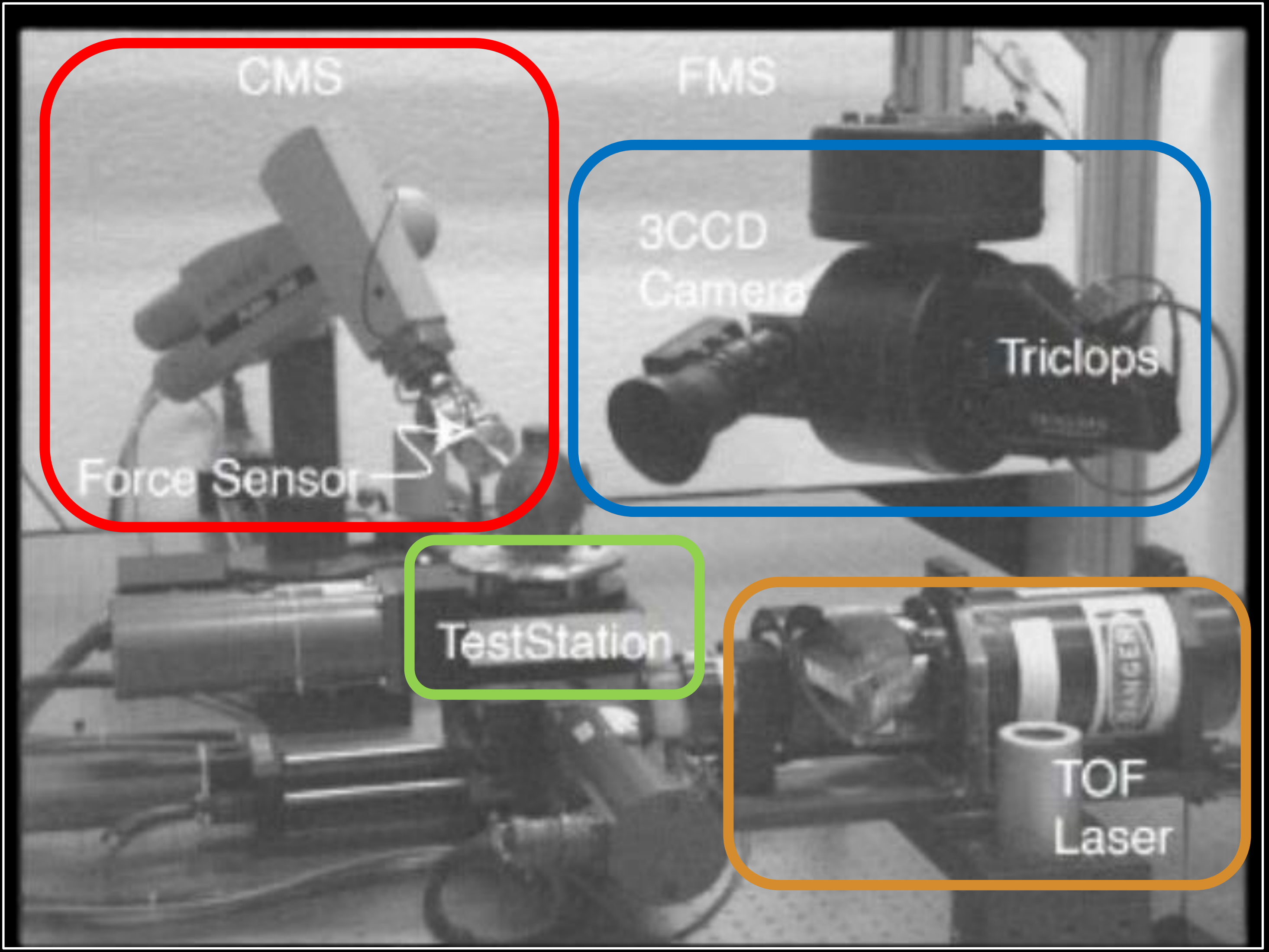
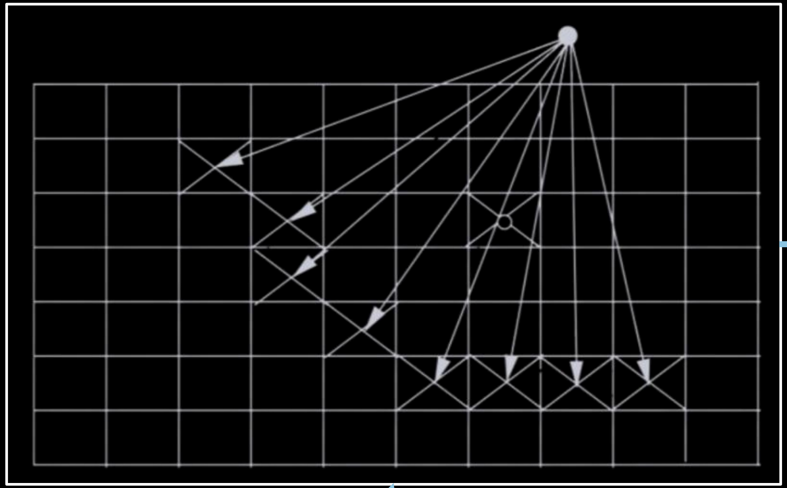


[PLLW 1999]

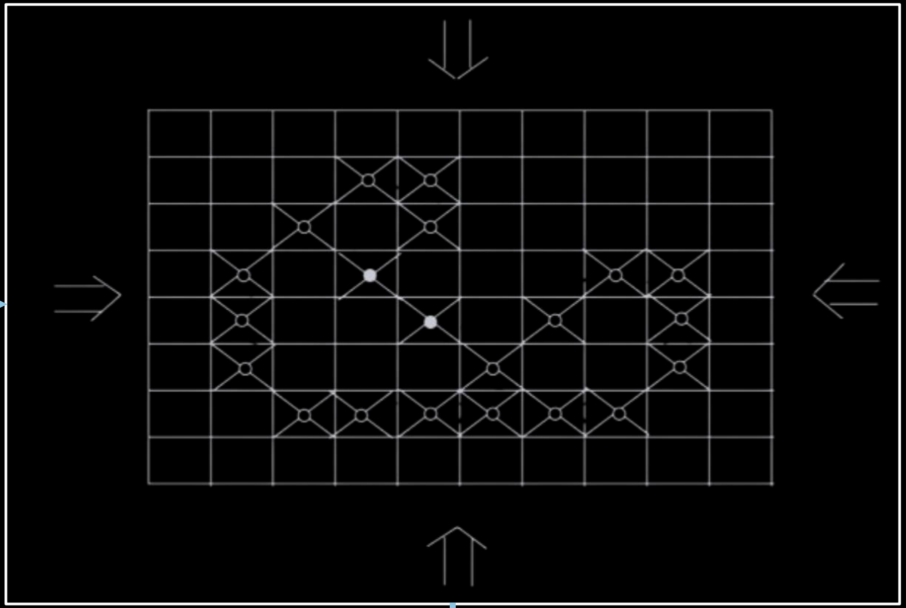
mesh reconstruction

[CWLWCZZL 2024]

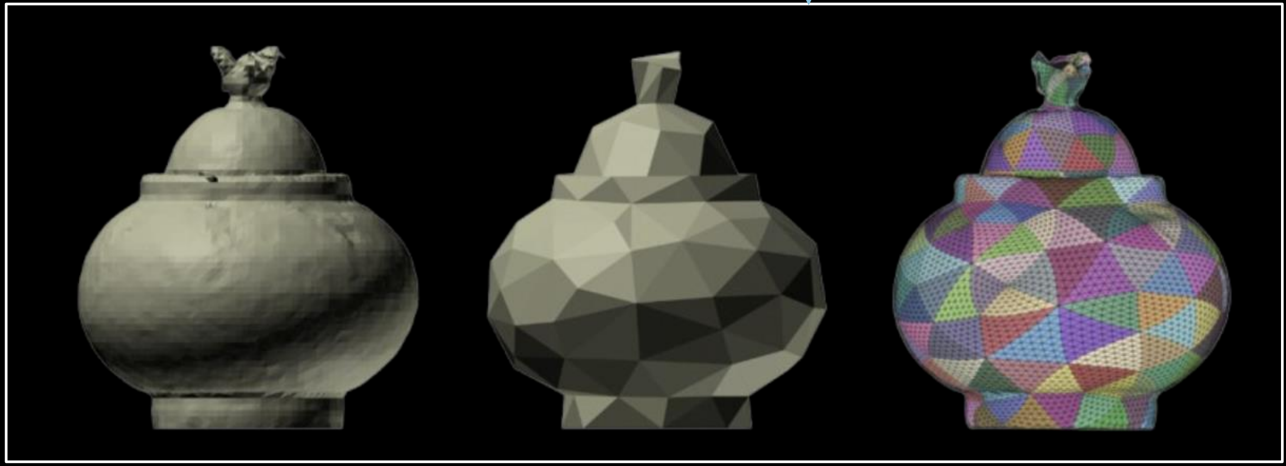
multiresolution mesh



range data



subdivision with displaced subdivision + tricks



[RW 1997]

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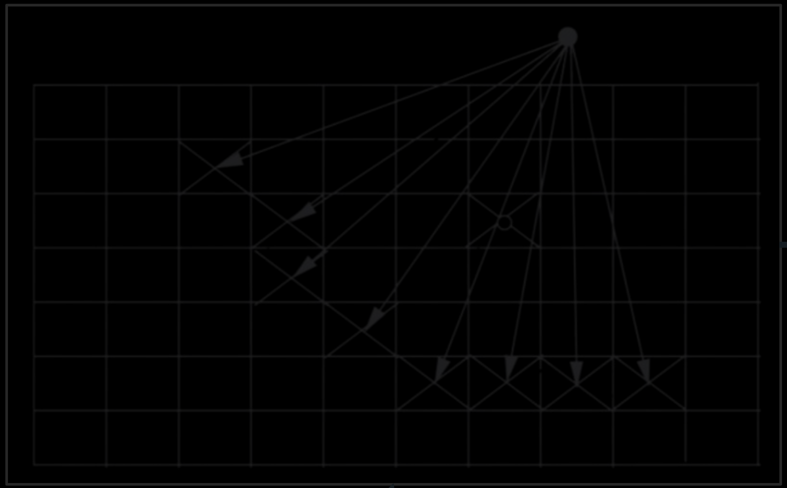
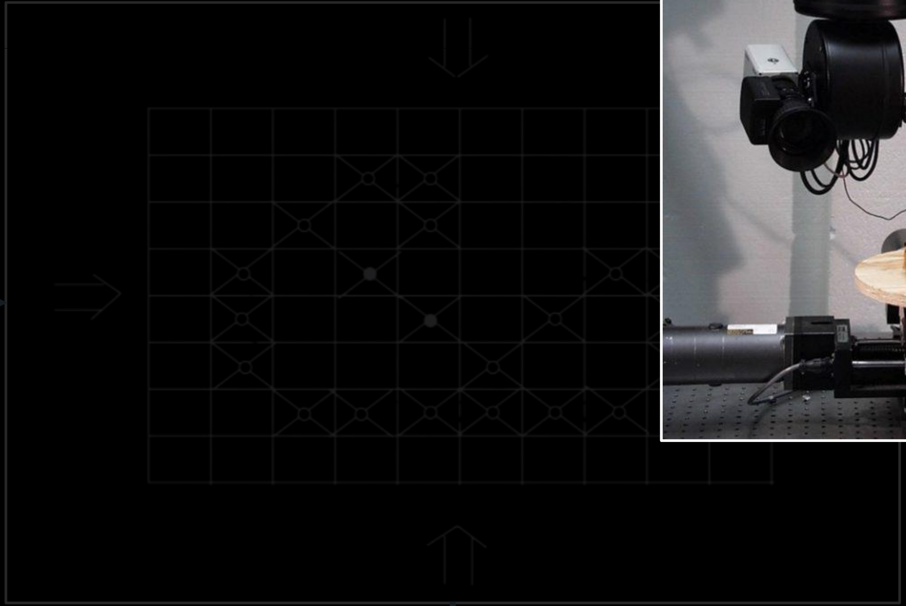
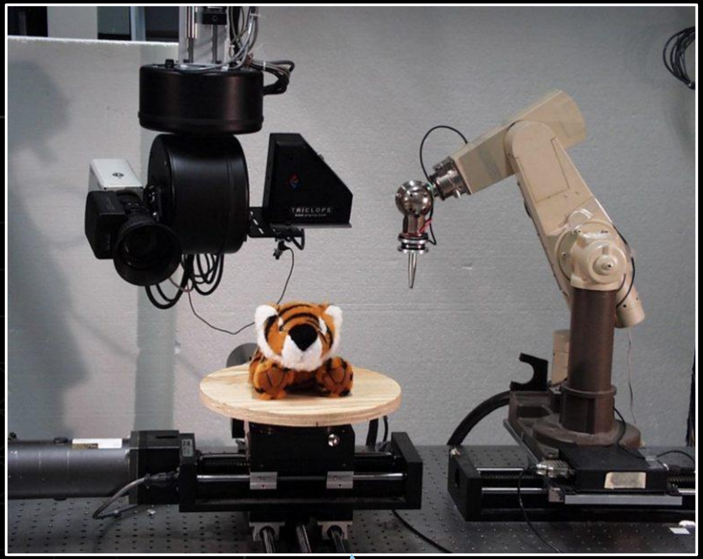


range data





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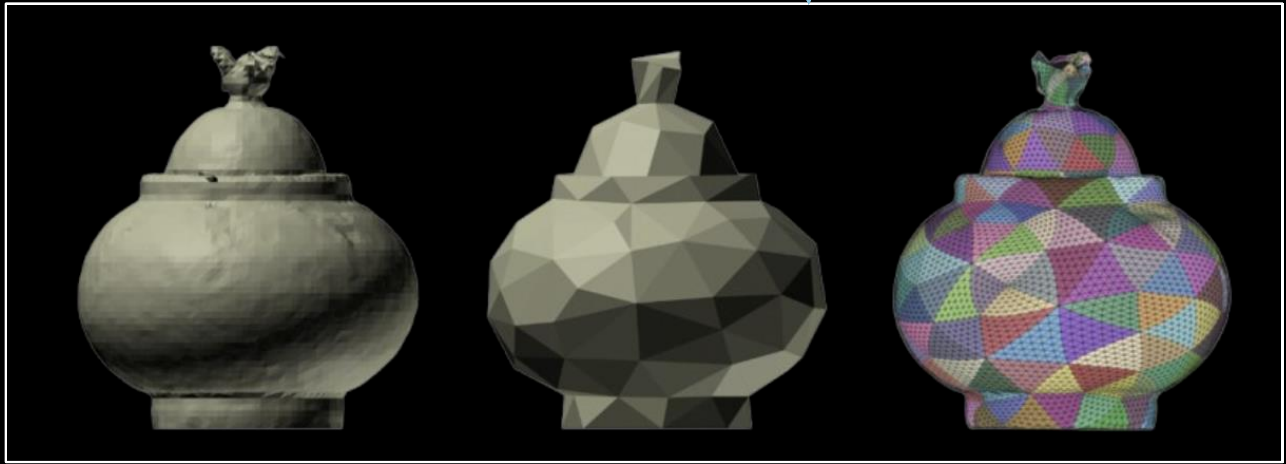

[RW 1997]

multiresolution textured mesh

multiview color images

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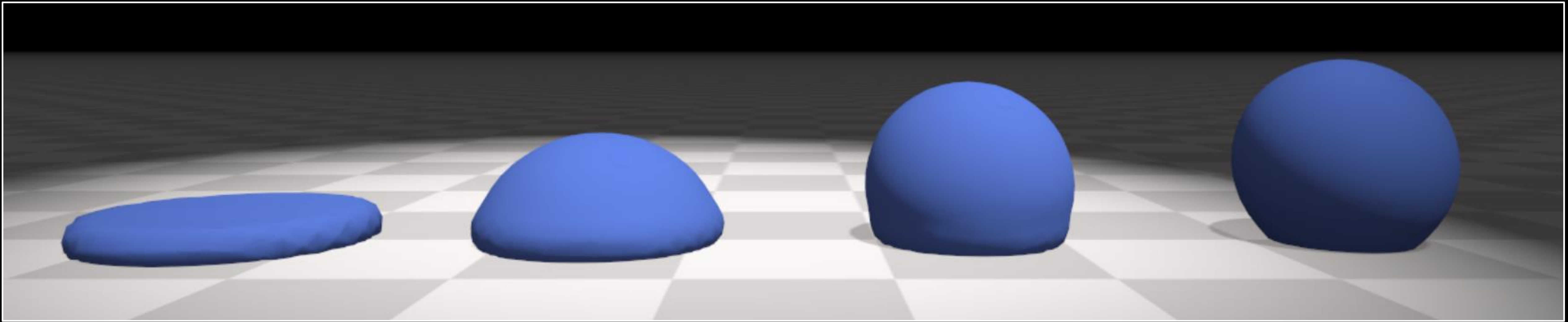
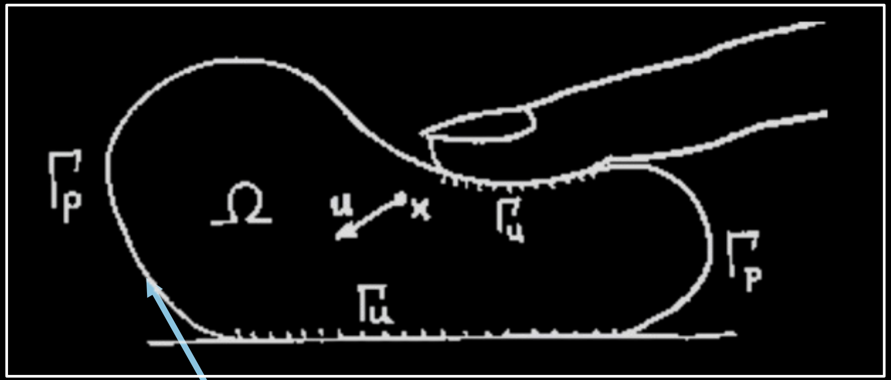


deformation

[MMC 2016]

what model do we use?



boundaries

linear elasticity operator

body forces

$$G \sum_{k=1}^{3} \left(\frac{\partial^2 u_i}{\partial x_k^2} + \frac{1}{1-2\nu} \frac{\partial^2 u_k}{\partial x_k \partial x_i} \right) + b_i = 0,$$

$$(\mathbf{Nu})(\mathbf{x}) + \mathbf{b}(\mathbf{x}) = 0, \qquad \mathbf{x} \in \Omega.$$

[JP 1999]

$$\overbrace{G\nabla^2\mathbf{u}}^{\textbf{Pure shear}} + \overbrace{\frac{G}{1-2\nu}\nabla(\nabla\cdot\mathbf{u})}^{\textbf{Volume change}} + \overbrace{b}^{\textbf{Body force}} = \mathbf{0}$$

$$\mathbf{u} = \bar{\mathbf{u}} \quad \text{on} \quad \Gamma_u$$

$$\mathbf{p} = \bar{\mathbf{p}} \quad \text{on} \quad \Gamma_p$$

[JP 1999]

aside: make greens functions

$$\overbrace{G\nabla^2\mathbf{u}}^{\text{Pure shear}} + \overbrace{\frac{G}{1-2\nu}\nabla(\nabla\cdot\mathbf{u})}^{\text{Volume change}} + \overbrace{b}^{\text{Body force}} = \mathbf{0}$$

$$\boxed{\text{but body force is a point force}}$$

$$G\nabla^2\mathbf{u}^* + \frac{G}{1-2\nu}\nabla(\nabla\cdot\mathbf{u}^*) = -\delta(x-y)\mathbf{I}$$

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exploit linearity

$$G\nabla^2 u^*_{ij} + \frac{G}{1-2\nu}\frac{\partial}{\partial x_i}\left(\sum_{k=1}^{3}\underbrace{\frac{\partial u^*_{kj}}{\partial x_k}}_{\text{divergence}}\right) = -\overbrace{\delta(x-y)\delta_{ij}}^{\text{point force in direction j}}$$

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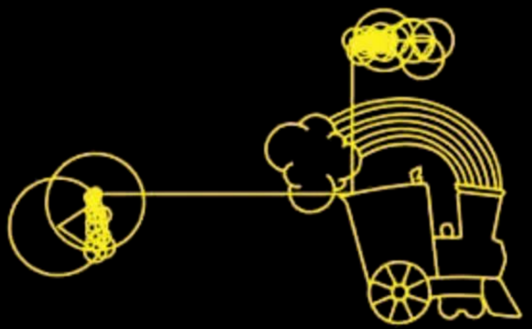

fourier transform

$$G(-|\xi|^2)\hat{u}^*_{ij} + \frac{G}{1-2\nu}(-\xi_i\xi_j\hat{u}^*_{ij}) = -e^{-i\xi\cdot y}\delta_{ij}$$

aside: make greens functions

$$G(-|\xi|^2)\hat{u}^*_{ij} + \frac{G}{1-2\nu}(-\xi_i\xi_j\hat{u}^*_{ij}) = -e^{-i\xi\cdot y}\delta_{ij}$$

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solve this in fourier space

$$u^*_{ij}(x,y) = \frac{1}{16\pi G(1-\nu)}\left[\frac{\overbrace{(3-4\nu)\delta_{ij}}^{\text{isotropic expansion}}}{r} + \underbrace{\frac{r_i r_j}{r^3}}_{\text{directional deformation}}\right]$$

$$\overbrace{G\nabla^2\mathbf{u}}^{\textbf{Pure shear}} + \overbrace{\frac{G}{1-2\nu}\nabla(\nabla\cdot\mathbf{u})}^{\textbf{Volume change}} + \overbrace{b}^{\textbf{Body force}} = \mathbf{0}$$

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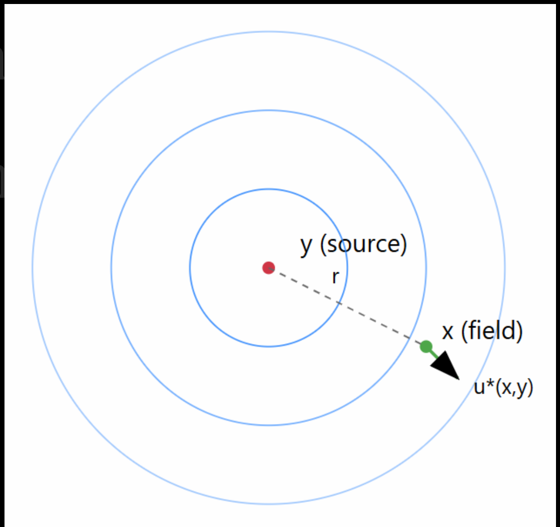


$$\overbrace{\mathcal{N}\mathbf{u}^*(x,y)}^{\text{Elastic operator}} + \underbrace{\delta(x-y)\mathbf{I}}_{\text{Point force}} = \mathbf{0}$$

green function

$$u^*_{ij}(x,y) = \frac{1}{16\pi G(1-\nu)}\left[\overbrace{\frac{(3-4\nu)\delta_{ij}}{r}}^{\text{Isotropic expansion}} + \underbrace{\frac{r_i r_j}{r^3}}_{\text{Directional deformation}}\right]$$

$$p^*_{ij}(x,y) = -\frac{1}{8\pi(1-\nu)r^2}\left[\overbrace{\frac{\partial r}{\partial n}\left((1-2\nu)\delta_{ij} + 3\frac{r_i r_j}{r^2}\right)}^{\text{Normal traction}} + \underbrace{(1-2\nu)(n_i r_j - n_j r_i)}_{\text{Shear traction}}\right]$$

[JP 1999]

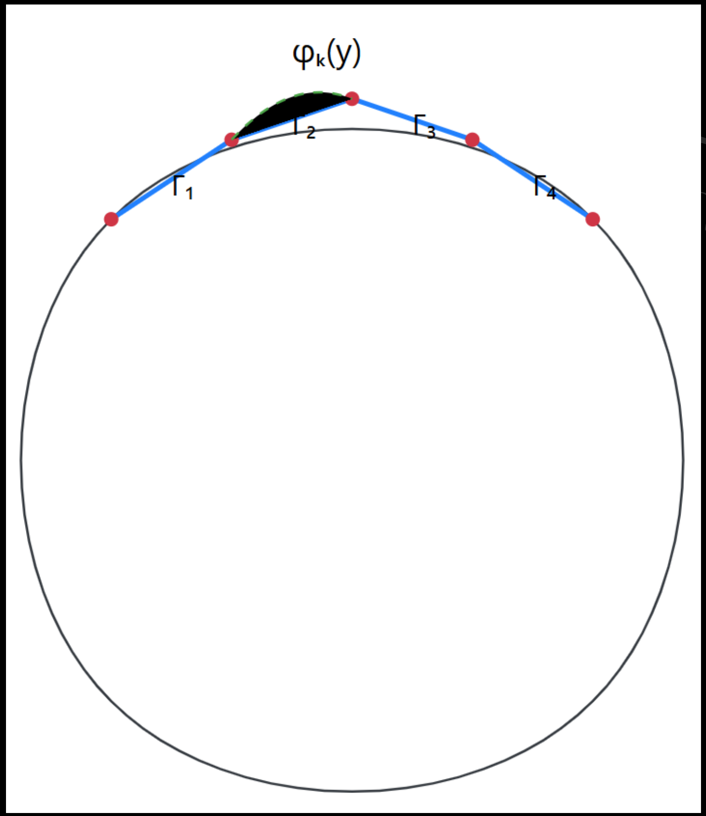
weighted residual

$$\overbrace{\int_\Omega \mathbf{u}^* \cdot \mathcal{N}\mathbf{u}\, d\Omega}^{\text{Volume work}} = \underbrace{\oint_\Gamma \mathbf{u}^* \cdot \mathbf{p}\, d\Gamma}_{\text{Boundary work}} - \overbrace{\int_\Omega \nabla \mathbf{u}^* : \boldsymbol{\sigma}(\mathbf{u})\, d\Omega}^{\text{Internal strain energy}}$$

reciprocal theorem and by parts

$$\overbrace{\int_\Omega (\mathbf{u}^* \cdot \mathcal{N}\mathbf{u} - \mathbf{u} \cdot \mathcal{N}\mathbf{u}^*)\, d\Omega}^{\text{Difference of virtual works in volume}} = \underbrace{\oint_\Gamma (\mathbf{u}^* \cdot \mathbf{p} - \mathbf{u} \cdot \mathbf{p}^*)}_{\text{Difference of virtual works on boundary}} \, d\Gamma$$

[JP 1999]



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reciprocal theorem
and by parts

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discretize the boundary into non-overlapping pieces
do field approximations for u and p

$$\overbrace{c_{ij}(x^m)\mathbf{u}_j(x^m)}^{\text{Point displacement}} + \underbrace{\sum_{e=1}^{N} \int_{\Gamma_e} \mathbf{p}^*_{ij}(x^m, y)\phi_k(y) d\Gamma(y) \mathbf{u}^k_j}_{\text{Influence of all displacements}} = \overbrace{\sum_{e=1}^{N} \int_{\Gamma_e} \mathbf{u}^*_{ij}(x^m, y)\phi_k(y) d\Gamma(y) \mathbf{p}^k_j}^{\text{Influence of all tractions}}$$

[JP 1999]

now let us bring it all together

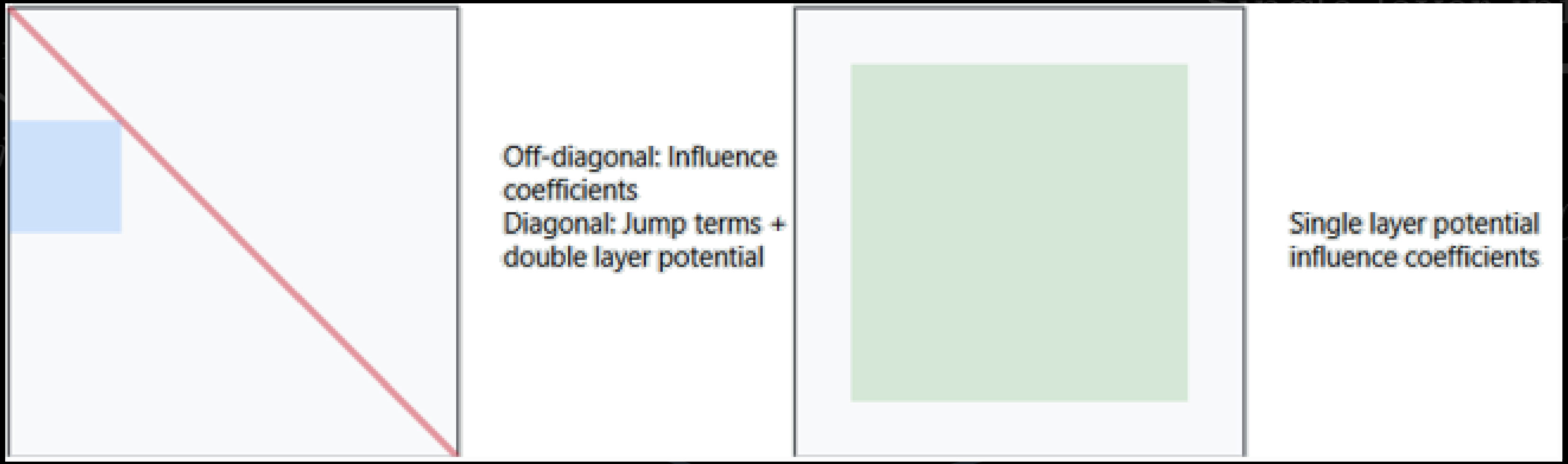
$$\mathbf{H}_{ij} = \overbrace{c_{ij}\delta_{ij}}^{\text{Jump term}} + \underbrace{\sum_{e=1}^{N}\int_{\Gamma_e} \mathbf{p}^*_{ij}(x,y)\phi_k(y)d\Gamma(y)\}}_{\text{Double layer influence coefficients}}$$

$$\mathbf{G}_{ij} = \overbrace{\sum_{e=1}^{N}\int_{\Gamma_e} \mathbf{u}^*_{ij}(x,y)\phi_k(y)d\Gamma(y)}^{\text{Single layer influence coefficients}}$$

$$\overbrace{\mathbf{H}}^{\text{System matrix}} \underbrace{\mathbf{u}}_{\text{Displacements}} = \overbrace{\mathbf{G}}^{\text{Influence matrix}} \underbrace{\mathbf{p}}_{\text{Tractions}}$$

[JP 1999]

now let us bring it all together



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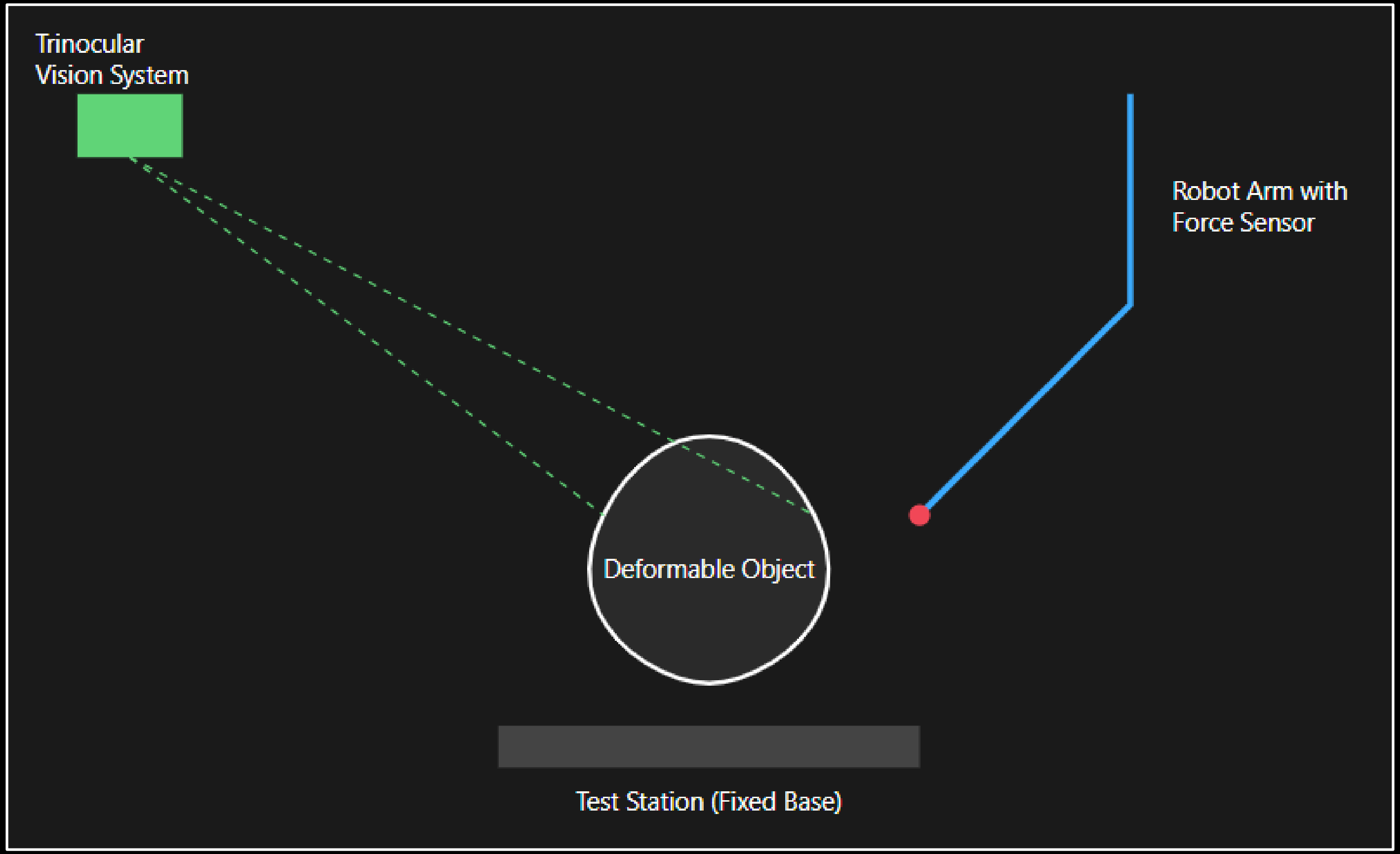
$$\overbrace{\mathbf{H}}^{\text{System matrix}} \underbrace{\mathbf{u}}_{\text{Displacements}} = \overbrace{\mathbf{G}}^{\text{Influence matrix}} \underbrace{\mathbf{p}}_{\text{Tractions}}$$

does this look familiar?

[JP 1999]

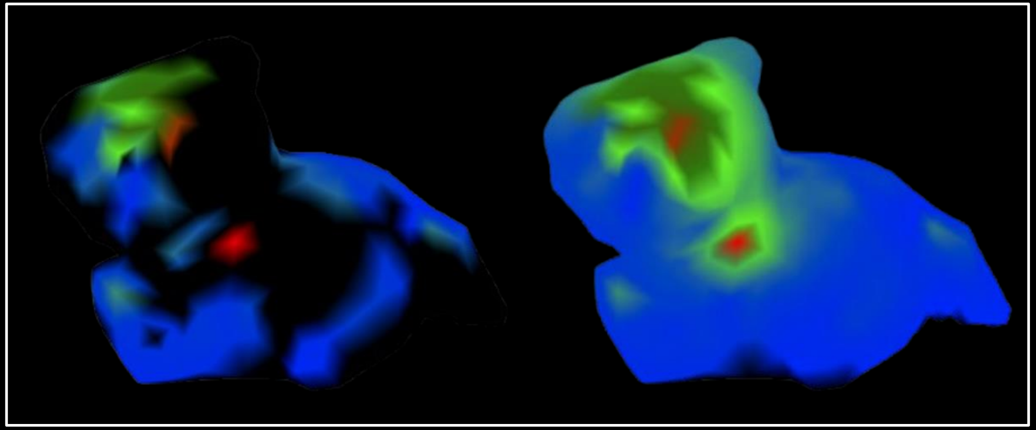
getting back to capturing



- apply a controlled force
- records 6D force/torque data at 1000Hz
- trinocular vision system captures the surface deformation at 30Hz
- repeat

use vision system:

- track visual features from optical flow
- reconstructing 3D motion field
- map the deformation onto the mesh vertices



[PDJLLRY 2001]

get model parameters

- we already have displacement field and force for vertices of mesh

$$[\mathbf{p}_j^1 \mathbf{p}_j^2 \cdots \mathbf{p}_j^M]^T \mathbf{U}_{ij}^T = [\mathbf{u}_i^1 \mathbf{u}_i^2 \cdots \mathbf{u}_i^M]^T$$

does this look familiar?
tsvd + least trimmed squares

get model parameters

- we already have displacement field and force for vertices of mesh

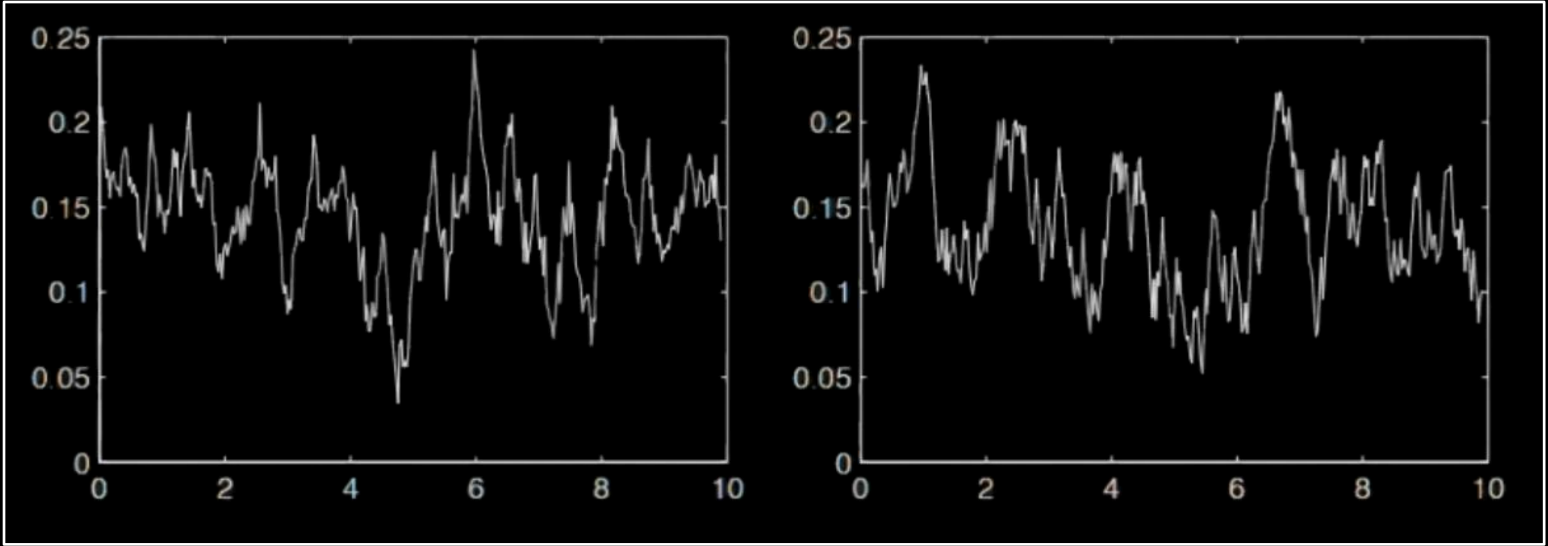
$$[\mathbf{p}_j^1\mathbf{p}_j^2\cdots\mathbf{p}_j^M]^T\mathbf{U}_{ij}^T = [\mathbf{u}_i^1\mathbf{u}_i^2\cdots\mathbf{u}_i^M]^T$$

does this look familiar?

tsvd + least trimmed squares
also interpolate missing values
also interpolate across resolutions

$$\overbrace{\mathbf{H}}^{\text{System matrix}} \underbrace{\mathbf{u}}_{\text{Displacements}} = \overbrace{\mathbf{G}}^{\text{Influence matrix}} \underbrace{\mathbf{p}}_{\text{Tractions}}$$

make this system



contact texture

in general: model, measurement, rendering

[PDJLLRY 2001]

model $\rightarrow$ friction

$$\mathbf{f}_f = -\mu \|\mathbf{f}_n\| \mathbf{u}_m$$

model $\rightarrow$ surface roughness

$$\mu_e(x) = \mu + \tilde{\mu}(x)$$

non-typical

model

friction

surface roughness

$$\mathbf{f}_f = -\mu \|\mathbf{f}_n\| \mathbf{u}_m$$

$$\mu_e(x) = \mu + \tilde{\mu}(x)$$ non-typical

model all these variations as an auto-regressive process

$$\tilde{\mu}(x) = \tilde{\mu}(\boxed{k}\Delta) \equiv \tilde{\mu}(k) = \sum_{i=1}^{\boxed{p}} \boxed{a_i}\tilde{\mu}(k-i) + \boxed{\sigma}\,\boxed{\epsilon(k)}$$

index

how many times do you do this

ar coefficients

std dev of noise

zero mean and std. dev 1 noise

model

friction

$$\mathbf{f}_f = -\mu \|\mathbf{f}_n\| \mathbf{u}_m$$

surface roughness

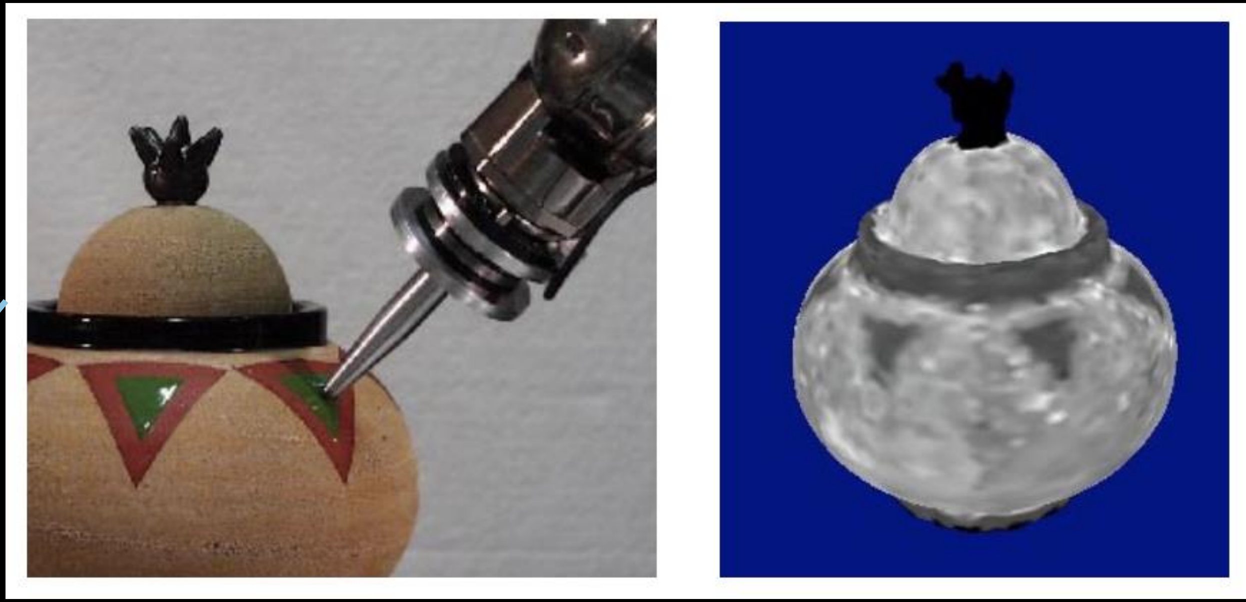
$$\mu_e(x) = \mu + \tilde{\mu}(x)$$

non-typical

$\boxed{\text{model all these variations as an auto-regressive process}}$

$$\begin{bmatrix} \mu(x) \\ \mu(x-\Delta) \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \mu(x-\Delta) \\ \mu(x-2\Delta) \end{bmatrix} + \begin{bmatrix} \sigma \\ 0 \end{bmatrix} \epsilon(x)$$

measurement



use multi resolution mesh

$$\mu = \tan(\theta/2)$$

measurement

$$\mathbf{n}(x) = \frac{\mathbf{f}_f^+ + \mathbf{f}_f^-}{\|\mathbf{f}_f^+ + \mathbf{f}_f^-\|}$$

measurement

$$\mathbf{n}(x) = \frac{\mathbf{f}_f^+ + \mathbf{f}_f^-}{\|\mathbf{f}_f^+ + \mathbf{f}_f^-\|}$$

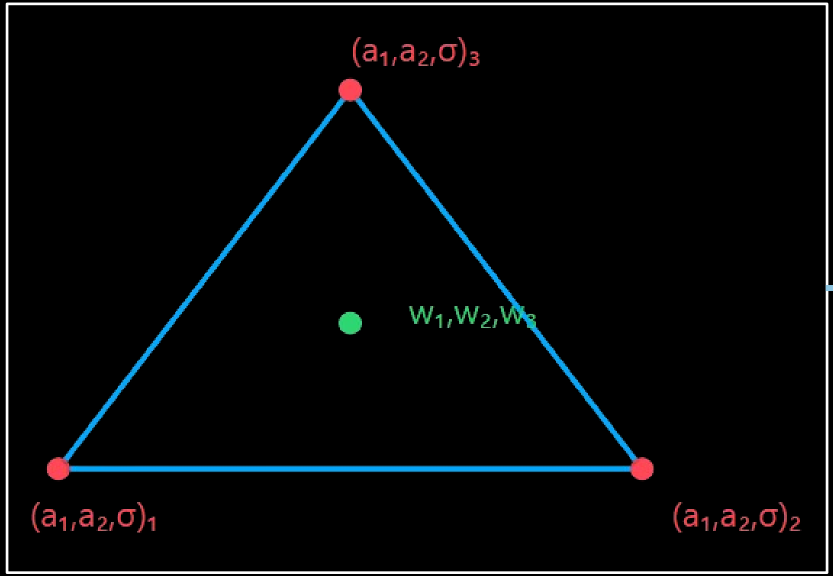
$$\mathbf{f} = \mathbf{f}_n[\mathbf{n}(x) - \mu_e \mathbf{u}_m(x)]$$

sensor

from our estimate

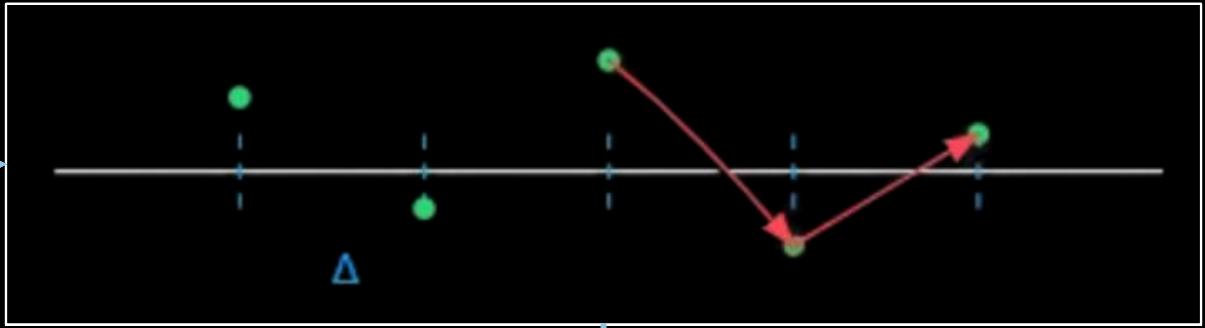
direction of motion from a sensor

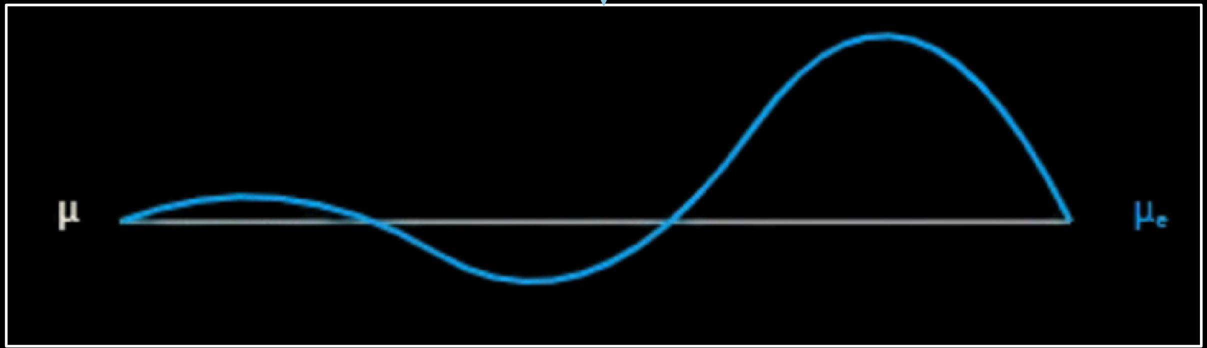
rendering



barycentric interpolation

ar process
discretize by Δ





find effective friction

sound

[DPWK 2024]

model

$$M = \{ \overbrace{\mathbf{f}}^{\text{frequencies}}, \overbrace{\mathbf{d}}^{\text{decay rates}}, \underbrace{\mathbf{A}}_{\text{mode gains}} \}$$

$$y_k(t) = \sum_{n=1}^{N} \overbrace{a_{nk}}^{\text{mode amplitude}} \underbrace{e^{-d_n t}}_{\text{decay}} \overbrace{\sin(2\pi f_n t)}^{\text{oscillation}}$$

model

$$M = \{ \overbrace{\mathbf{f}}^{\text{frequencies}} , \overbrace{\mathbf{d}}^{\text{decay rates}} , \underbrace{\mathbf{A}}_{\text{mode gains}} \}$$

$$y_k(t) = \sum_{n=1}^{N} \overbrace{a_{nk}}^{\text{mode amplitude}} \underbrace{e^{-d_n t}}_{\text{decay}} \overbrace{\sin(2\pi f_n t)}^{\text{oscillation}}$$

$$F_{audio}(t) = \overbrace{F_N}^{\text{normal force}} \cdot \underbrace{\mu_e(v \cdot t)}_{\text{friction variation}} \cdot \overbrace{v(t)}^{\text{sliding velocity}}$$

measurement

measure impulse repsonse

$$h(t) = \sum_{n=1}^{N} \overbrace{A_n e^{-d_n t}}^{\text{amplitude envelope}} \cdot \underbrace{\cos(2\pi f_n t + \phi_n)}_{\text{oscillation}}$$

rendering

$$\overbrace{\ddot{x}_n + 2d_n\dot{x}_n + \omega_n^2 x_n}^{\text{resonator dynamics}} = \underbrace{F_{audio}(t)}_{\text{input force}}$$

rendering

$$\overbrace{\ddot{x}_n + 2d_n\dot{x}_n + \omega_n^2 x_n}^{\text{resonator dynamics}} = \underbrace{F_{audio}(t)}_{\text{input force}}$$

$$\begin{bmatrix} x_n(t+\Delta t)\\ \dot{x}_n(t+\Delta t)\end{bmatrix} = \overbrace{e^{A\Delta t}}^{\text{state transition}} \begin{bmatrix}x_n(t)\\ \dot{x}_n(t)\end{bmatrix} + \underbrace{\int_t^{t+\Delta t} e^{A(t+\Delta t-\tau)} b F_{audio}(\tau)\,d\tau}_{\text{force response}}$$

$$A = \begin{bmatrix}0 & 1\\ -\omega_n^2 & -2d_n\end{bmatrix}, \quad b = \begin{bmatrix}0\\ 1\end{bmatrix}$$

summary

Synthesized or Real?

2

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