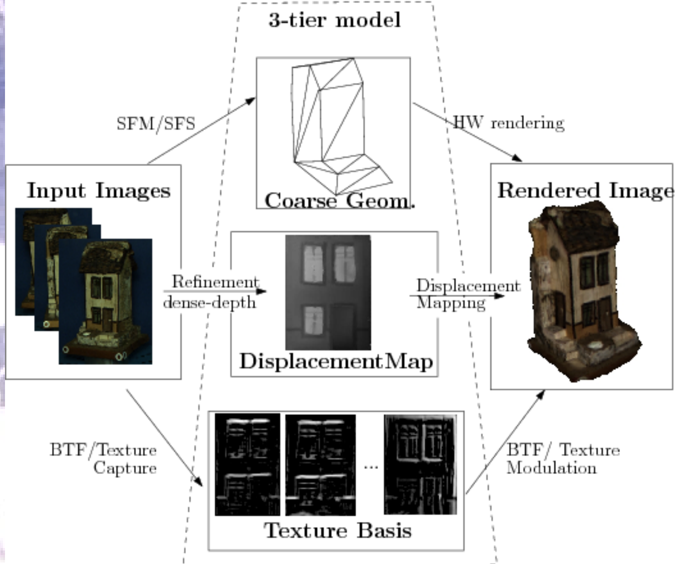
A 3-Tier Model from 2D Video

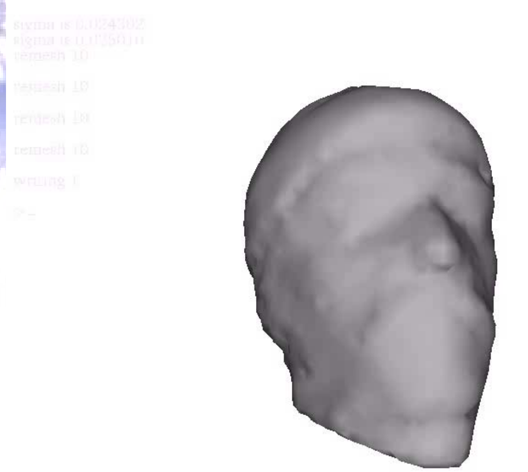
Martin Jagersand

joint work with Neil Birkbeck, Dana Cobzas, Adam Rachmielowski, Keith Yerex

University of Alberta

Computing Science





video

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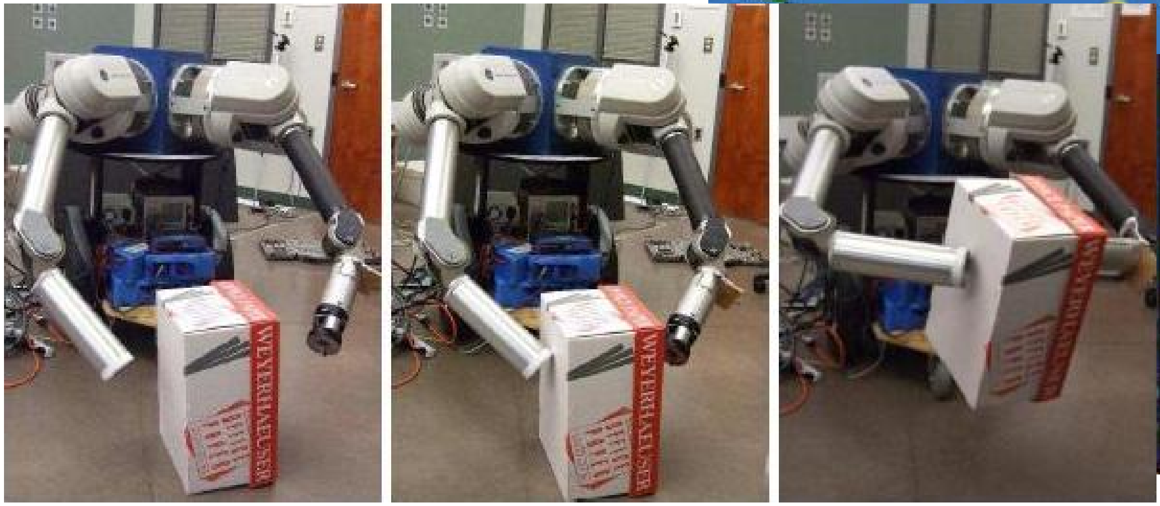
1. Overview of Research Interests & Projects

- Mathematical imaging models
- Computer vision
- Medical imaging
- Robotics
- Visual Servoing



Current project with CSA, Neptec, Xiphos and Barrett in Space Tele-robotics

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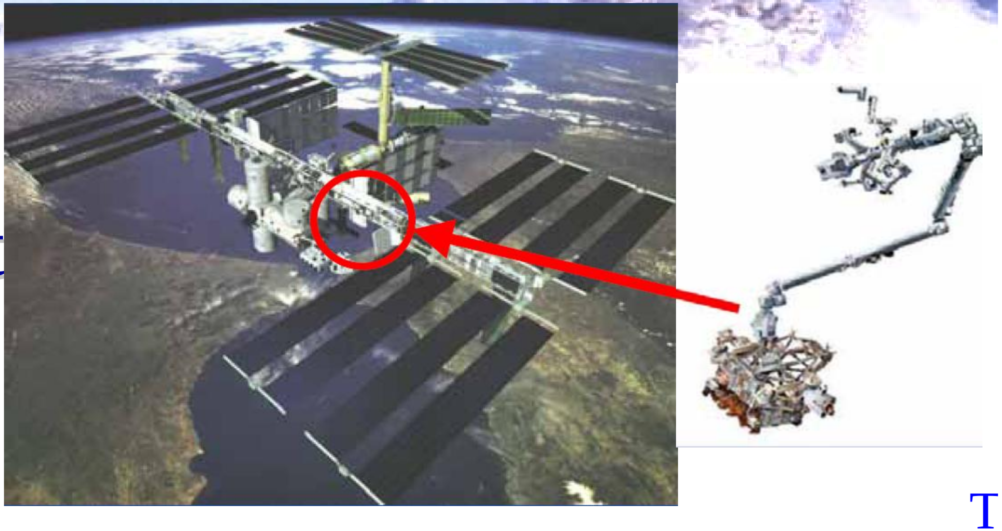
Human-in-the-loop teleoperation is a current mission bottleneck

- Current ground-based tele-manipulation inefficient
  - Transmission delays
  - Non-anthophomorphic arms
- Space craft don’t fit enough operators



T

Shuttle flight trainer, Johnson Space Ctr

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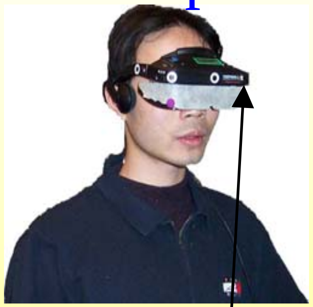
Predictive Display for Tele-robotics

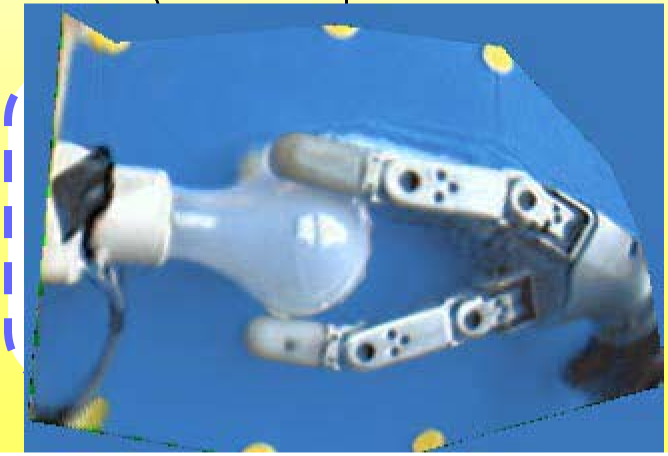
Problem: Even small delays (~¼ s) degrade operator performance

Solution: Predict and synthesize immediate visual feedback

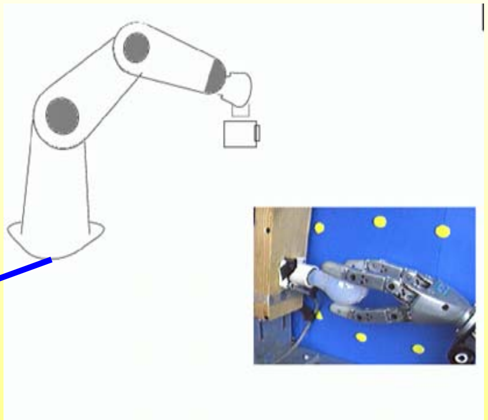
Local operator



Model renders
new views
synchronously



Remote site

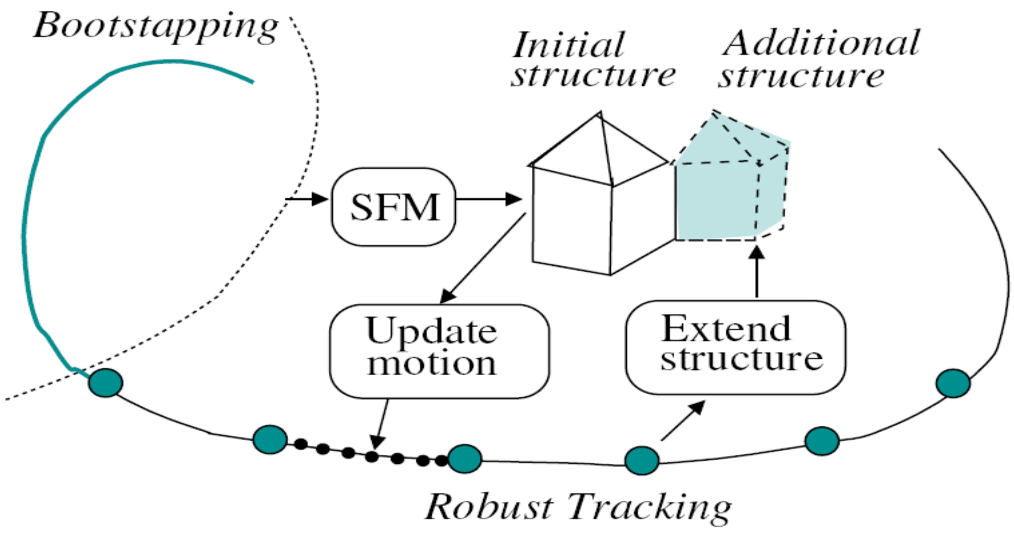


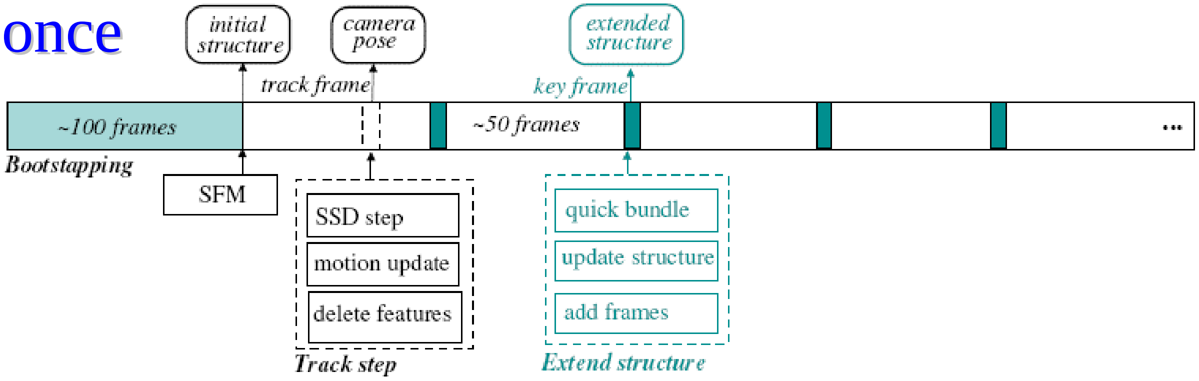
Model is captured by
remote camera and
transmitted asynchronously

Types of Predictive Display

Rachmielowski, Jagersand Cobzas '06

- What type of model?
  - CAD line model
  - Video image warping
  - Textured graphics model
- How is it acquired?
  - A-priori
  - Sensed from scene once
  - Updated on-line





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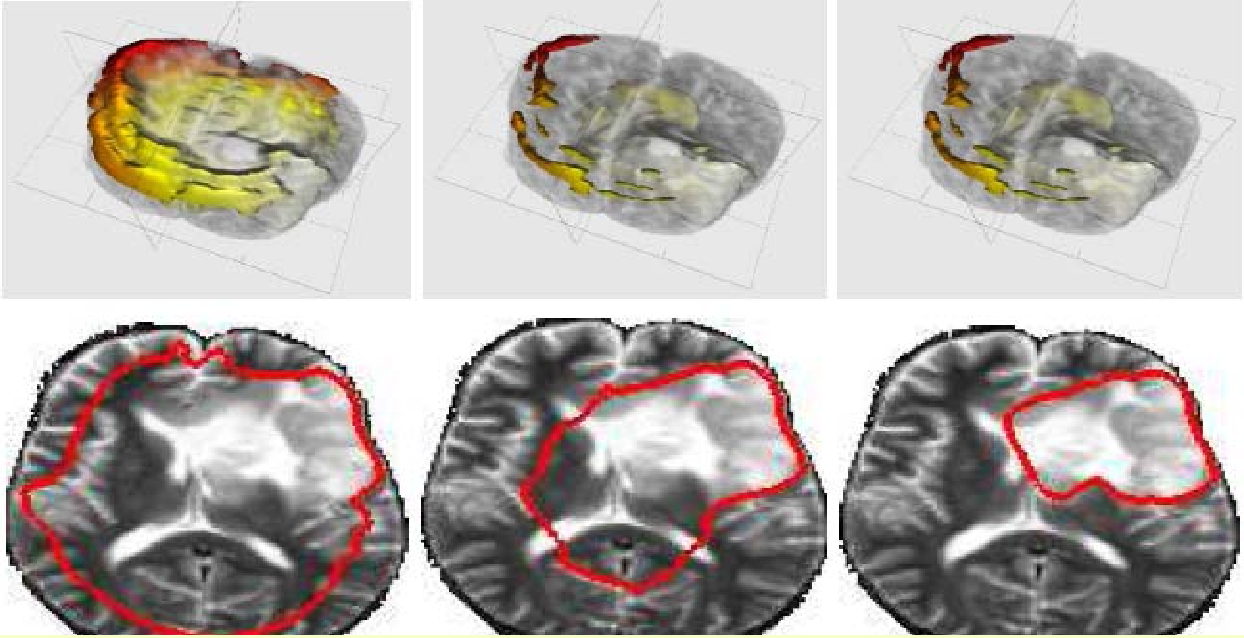
Medical Imaging:
Variational Segmentation of Tumours



Segmentation = surface/curve evolution such that an

energy functional is minimized

Energy :defined using data + [shape/atlas priors] + geometric priors (regularizers
such that it has minimum at the desired segmentation

Surface/curve evolution: calculus of variation/PDE’s

Where we are?
Western Canada!

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Winter in the Rockies

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And summer …

Low budget 3D from video (Main talk)

- Inexpensive
- Quick and convenient for the user
- Integrates with existing SW e.g. Blender, Maya

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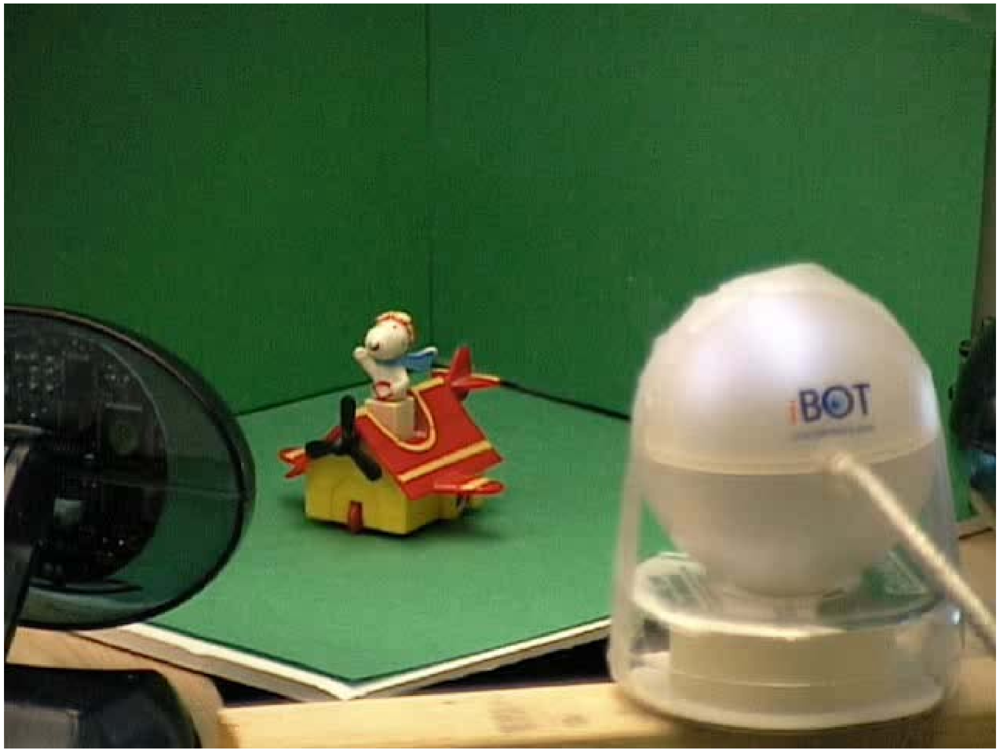
Low budget 3D from video

- Inexpensive

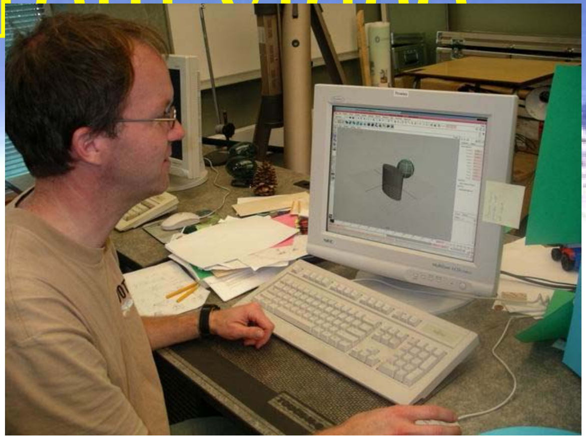


$100: Webcams, Digital Cams

$100,000 Laser scanners etc.

Low budget 3D from video

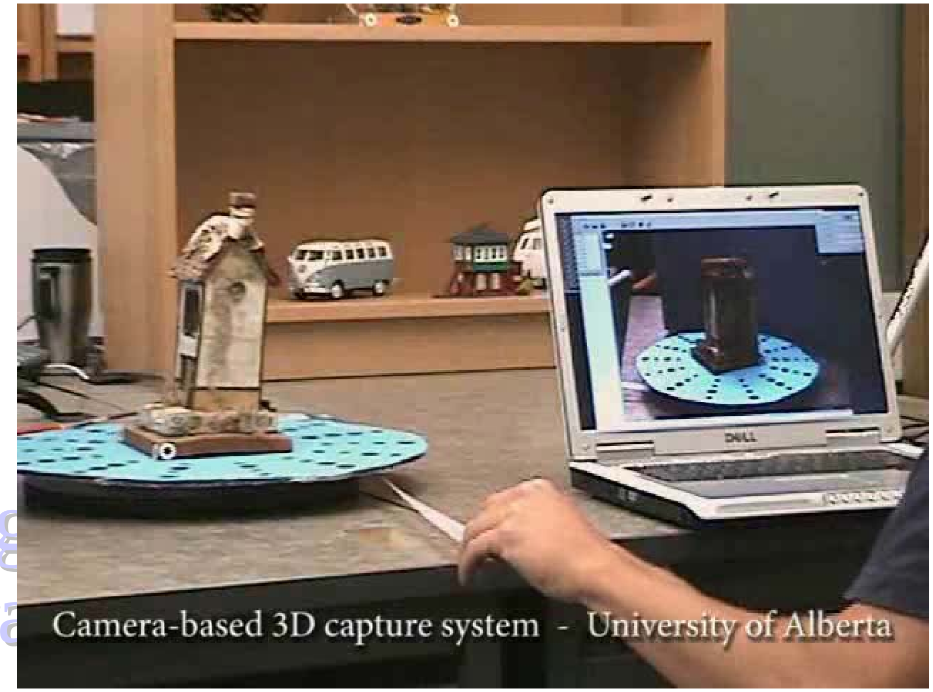
- Inexpensive



Modeling geom primitives into scenes: >>Hours

- Quick and convenient for the user

- Integrates with existing SW e.g. Blender, Maya



Capturing 3D from 2D video: minutes

Low budget 3D from video

- Inexpensive

- Quick and convenient for the user

- Integrates with existing SW e.g. Blender, Maya

Camera-based 3D capture system - University of Alberta

Application Case Study
Modeling Inuit Artifacts

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- New acquisition at the UofA: A group of 8 sculptures depicting Inuit seal hunt
- Acquired from sculptor by Hudson Bay Company

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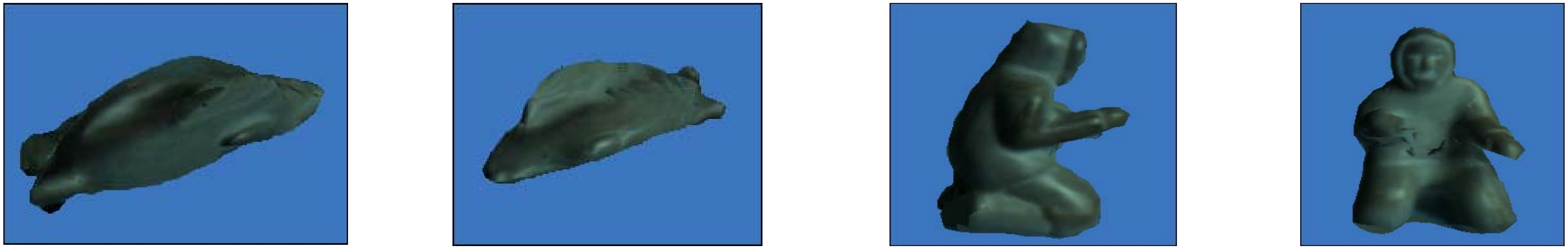
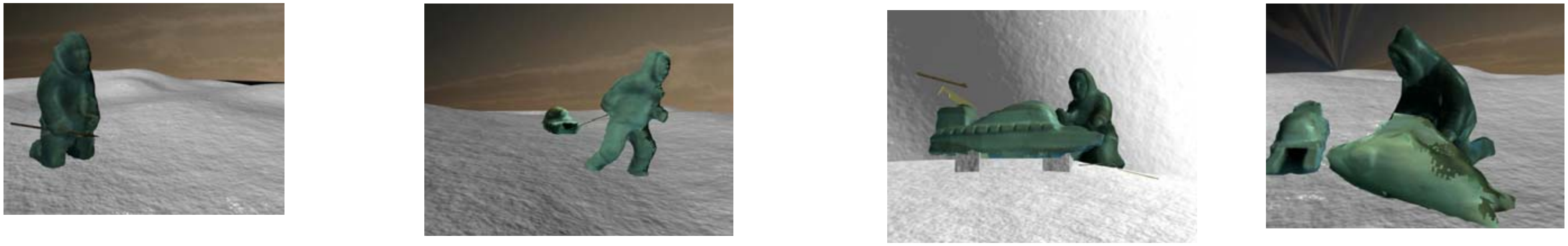
Application Case Study
Modeling Inuit Artifacts

Results:

1. A collection of 3D models of each component



2. Assembly of the individual models into animations and Internet web study material.



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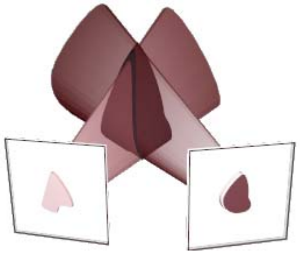
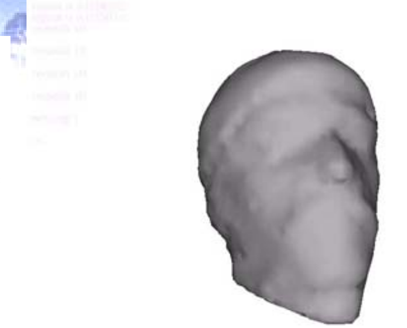
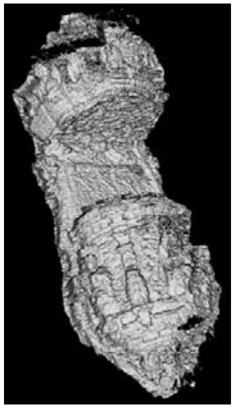
Preliminaries: Capturing **Macro** geometry:



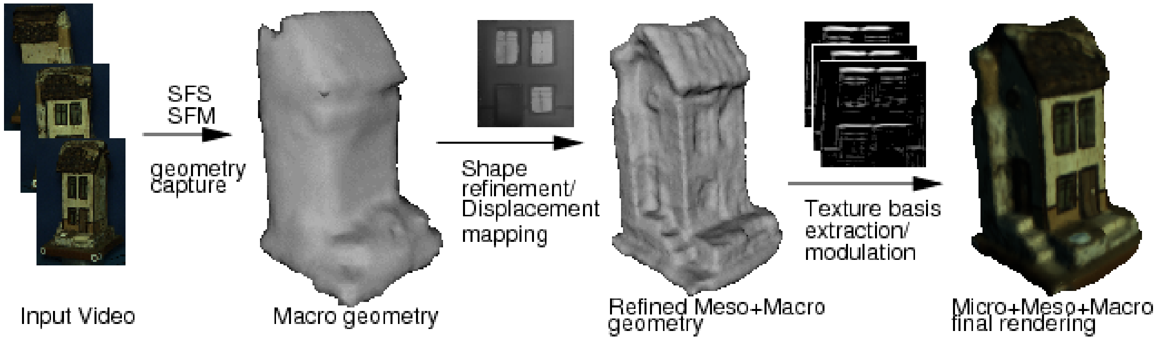


- Shape From Silhouette
  - Works for objects
  - Robust
  - Visual hull not true object surface
- Structure From Motion
  - Works for Scenes
  - Typically sparse
  - Sometimes fragile (no salient points in scene)
- (Dense “Stereo” -- Later)
  - Use as second refinement step

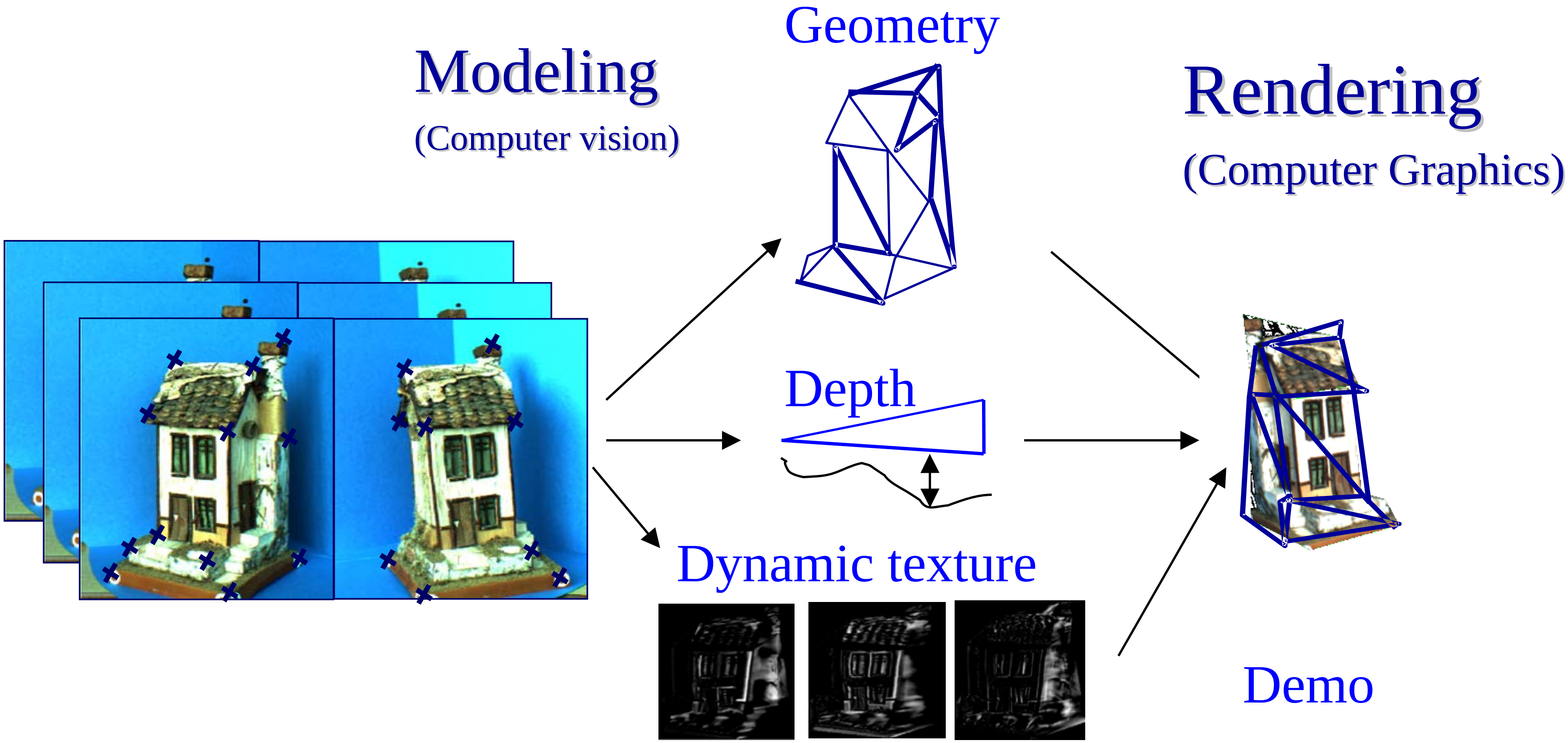


3-tier Macro, Meso, Micro model

- Multi-Tiered Models:
  - Commonly:
    - Two tiers: 3D Geometry and appearance (* texture mapping)
    - Used in graphics applications, recovered in Vision applications
  - Three-Tier
    - Macro scale: describes scene geometry (triangulated mesh)
    - Meso scale: fine scale geometric detail (displacement map)
    - Micro: fine scale geometry and reflectance (Texture basis)
  - Captured by sequential refinement



Geometry alone does not solve modeling!
Need: Multi-Scale Model



Modeling

(Computer vision)

Geometry

Rendering

(Computer Graphics)

Depth

Dynamic texture

Demo

Multi-Scale model: **Macro** geometry, **Meso** depth, **Micro** texture

Three scales map naturally to CPU and GPU hardware layers

Key issue: Efficient memory access and processing

Speedup

1. Macro: Conventional geometry processing

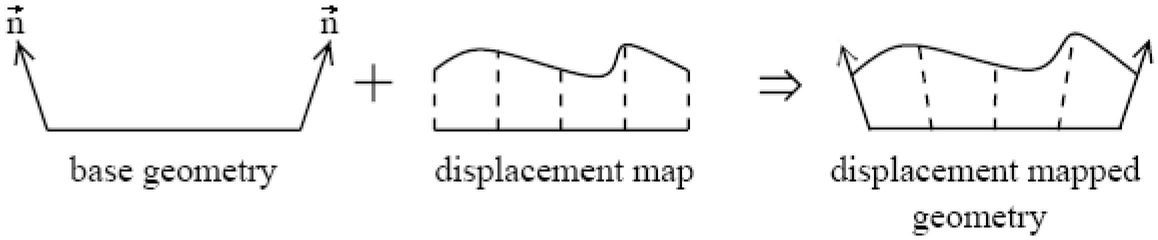
10x

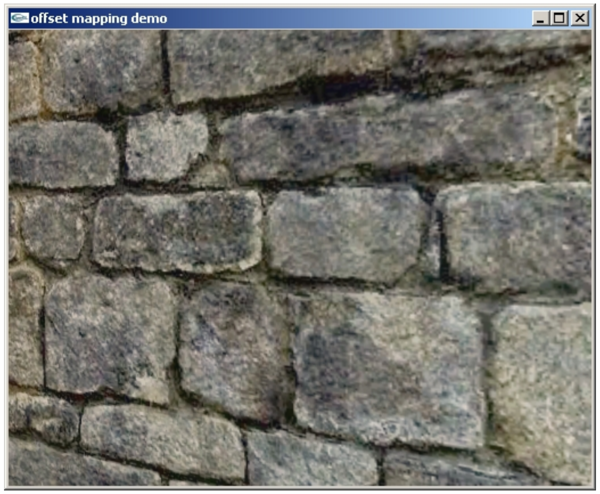
2. Meso: Pixel shader
   - Fixed code, variable data access

10x

3. Micro: Shader or Register comb.
   - Fixed code, fixed data access

2. **Meso** Structure:
Depth with respect to a plane





Flat texture

Displacement mapped

Computing **Meso** structure: Variational shape and reflectance

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Per-point cost function

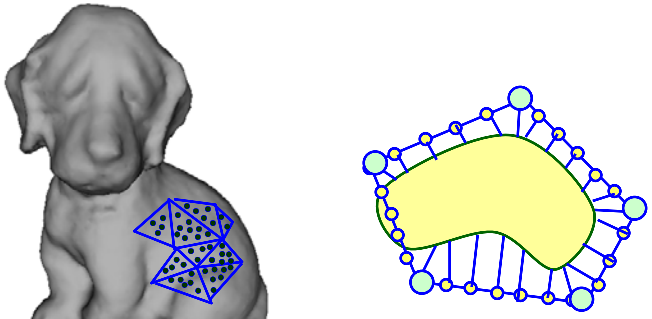
$$\Phi(\mathbf{X},\mathbf{n}) = \sum_i h(\mathbf{X},P_i)\left\| I_i(P_i(\mathbf{X})) - R(\mathbf{X},\mathbf{n},\mathbf{L}_i)\right\|$$

Visibility+sampling

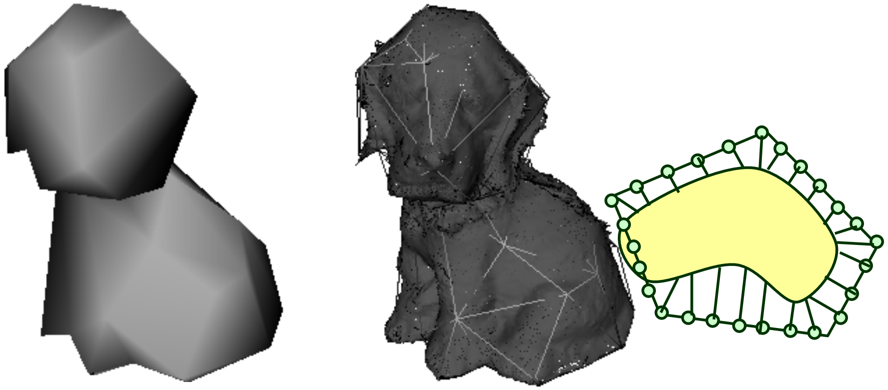
reflectance

$$\frac{\partial S}{\partial t} = \left(2\Phi k - \langle \nabla\Phi, \mathbf{n}\rangle\right)\mathbf{n}$$

Deformable mesh



Depth from Base



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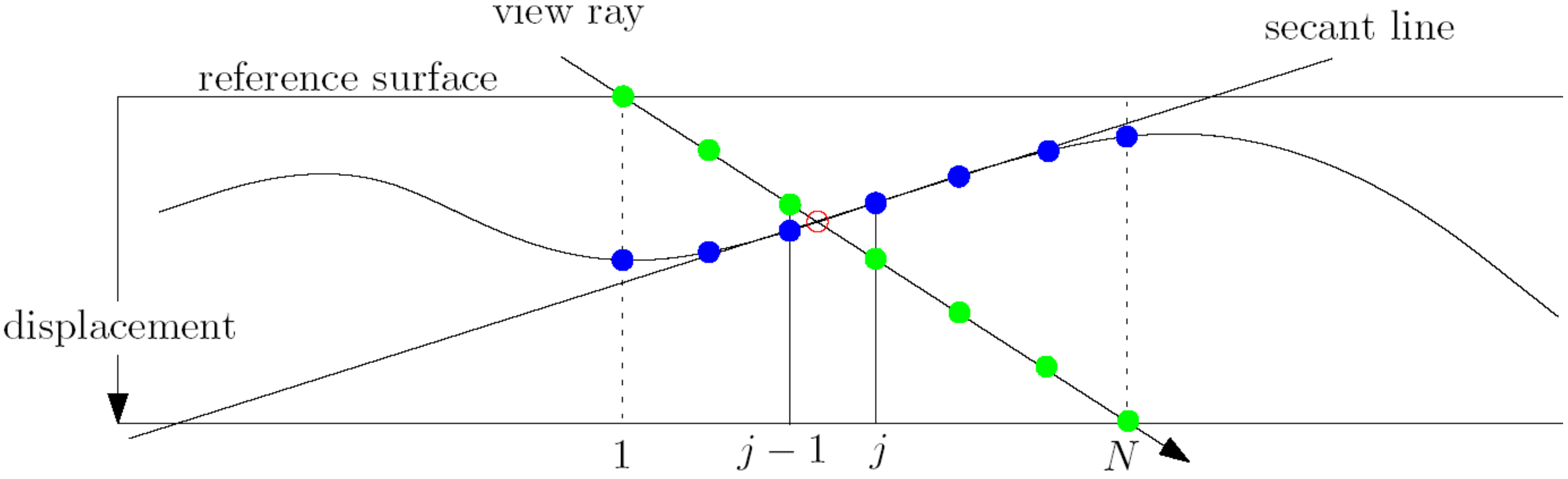
Rendering **Meso** Structure:

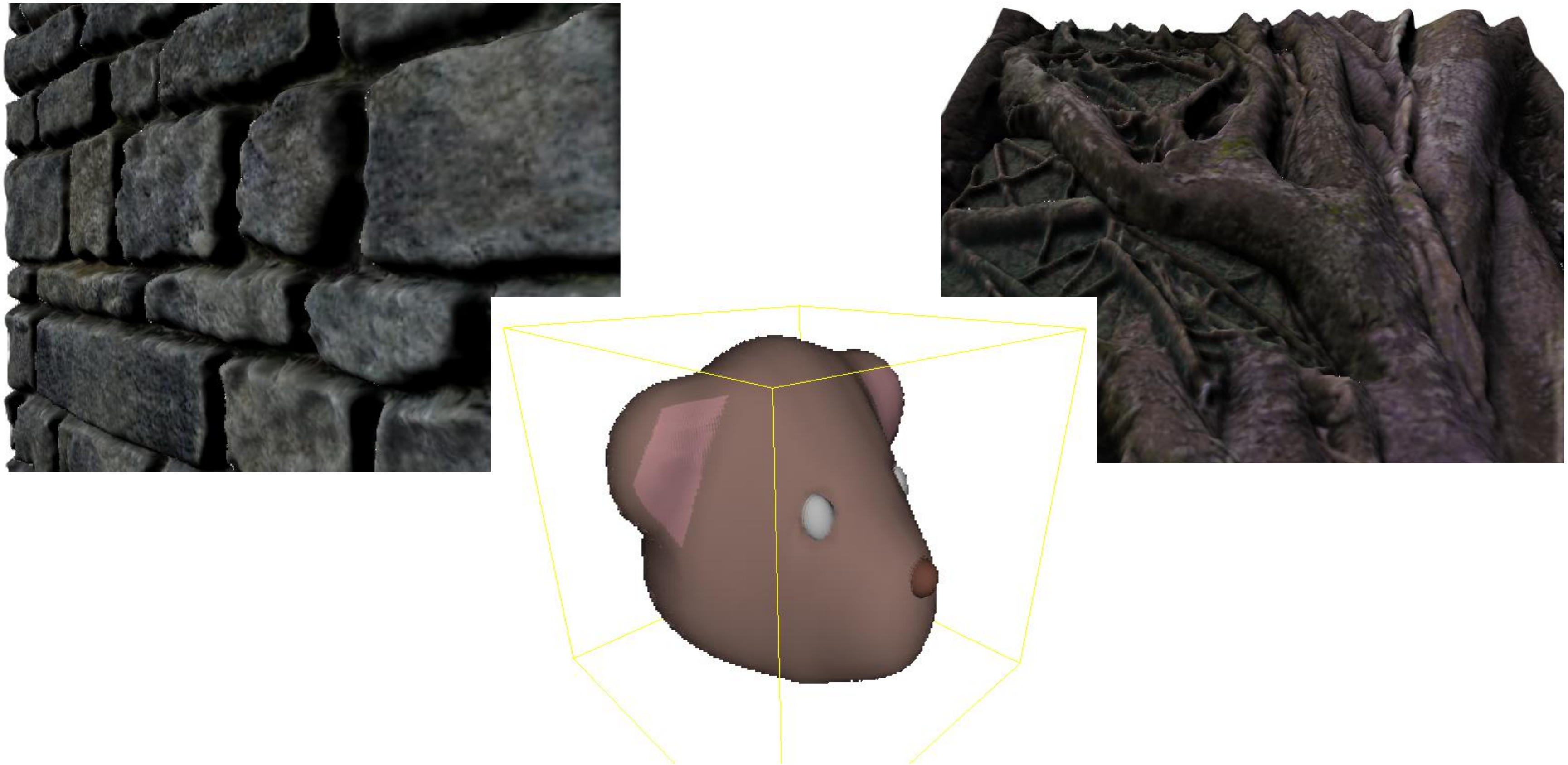
GPU: 83 pixel shader instructions



1. Sample d and ray at N (say15) points.
2. Find point location j of intersection
3. Approximate d with line, calculate intersection
4. Potentially iterate if needed for accuracy

Results:

Over 100 fps on consumer graphics cards



3. **Micro** structure:
Spatial texture basis

=> fixed execution and data access pattern

=> very fast implementation in graphics hardware

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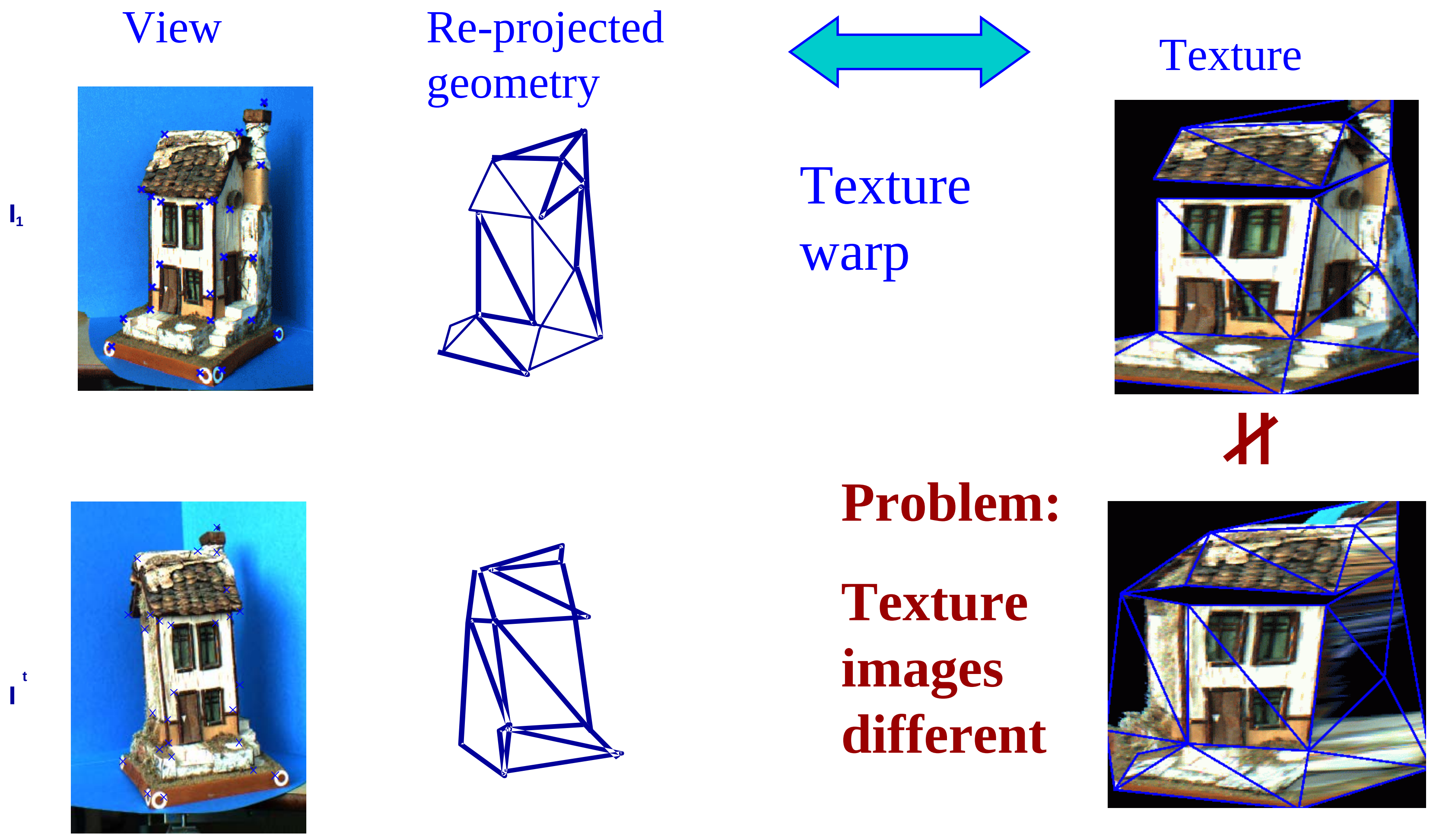
How/why do dynamic textures work?

3D geometry and texture warp map between views and texture images



Problem:

Texture images different

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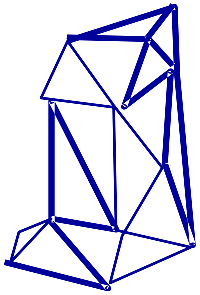
Sources of errors:

3D geometry and texture warp map between views and texture images

View

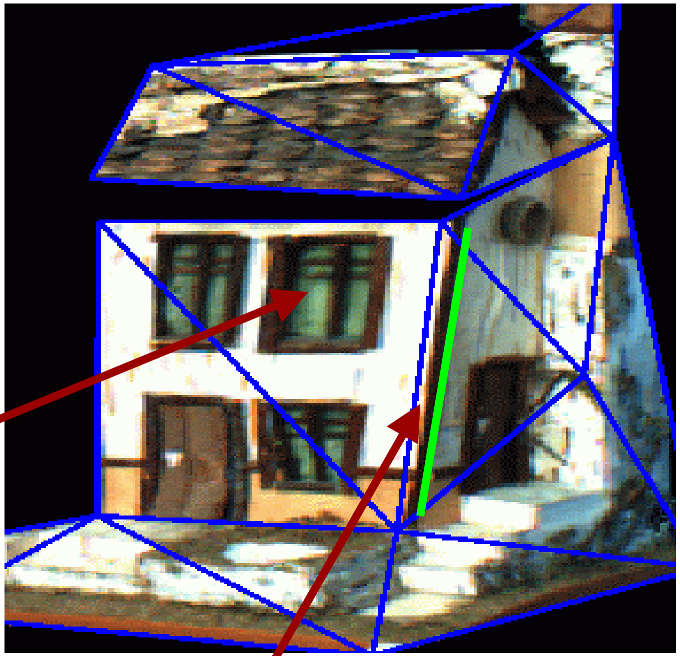
I_1

Re-projected geometry



Texture warp

Texture



2: Out of plane error:

Object surface /= texture plane

t

1: Planar error: Incorrect texture coordinates

Spatial basis intro

1. Moving sine wave can be modeled:

$$\begin{aligned} I(t) &= \sin(u + at) \\ &= \sin(u)\cos(at) + \cos(u)\sin(at) \\ &= \sin(u) y_1(t) + cos(u) y_2(t) \end{aligned}$$

Spatially fixed basis

2. Small image motion

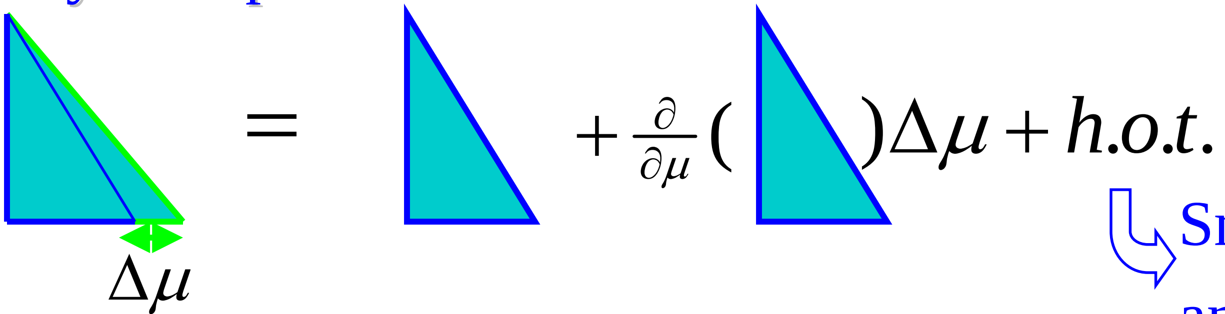
$$I = I_0 + \frac{\partial I}{\partial u}\Delta u + \frac{\partial I}{\partial v}\Delta v$$

Spatially fixed basis

Linear basis for spatio-temporal variation

On the object/texture plane:

- Variation resulting from small warp perturbations
- Taylor expansion:



Small if $\Delta\mu$ small and T_0 smooth

$$T(view) = T_0 + \underbrace{\frac{\partial}{\partial\mu} T_0 \Delta\mu}_{} + h.o.t.$$

Similarly: Can derive linear basis for out of plane and light variation!

Geometric spatio-temporal variability

Image "warp"

$$T(\mathbf{x}) = I(W(\mathbf{x}, \mu))$$

Image variability caused by an imperfect warp

$$\Delta T = I(W(\mathbf{x}, \mu + \Delta\mu)) - T_w$$

First order approximation

$$\Delta T = I(W(\mathbf{x}, \mu)) + \nabla T \frac{\partial W}{\partial \mu} - T_w = \nabla T \frac{\partial W}{\partial \mu}$$

Concrete examples

- Image plane
- Out of plane

Variability due to a planar projective warp (homography)

- Homography warp

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \mathcal{W}_h(\mathbf{x}_h, \mathbf{h}) = \frac{1}{1+h_7u+h_8v}\begin{bmatrix} h_1u & h_3v & h_5 \\ h_2u & h_4v & h_6 \end{bmatrix}$$

- Projective variability:

$$\Delta\mathbf{T}_h = \frac{1}{c_1}\left[\frac{\partial\mathbf{T}}{\partial u}, \frac{\partial\mathbf{T}}{\partial v}\right]\begin{bmatrix} u & 0 & v & 0 & 1 & 0 & -\frac{uc_2}{c_1} & -\frac{vc_2}{c_1} \\ 0 & u & 0 & v & 0 & 1 & -\frac{uc_3}{c_1} & -\frac{vc_3}{c_1} \end{bmatrix}\begin{bmatrix} \Delta h_1 \\ \vdots \\ \Delta h_8 \end{bmatrix}$$

$$= [\mathbf{B}_1 \ldots \mathbf{B}_8][y_1, \ldots, y_8]^T = B_h\mathbf{y}_h$$

- Where $c_1 = 1 + h_7u + h_8v$, $c_2 = h_1u + h_3v + h_5$

  and $c_3 = h_2u + h_4v + h_6$

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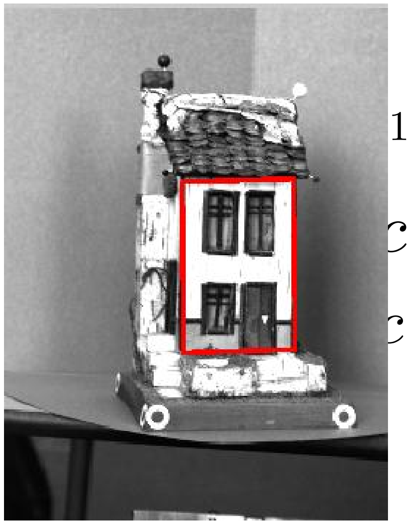
Variability due to a planar projective warp (homography)

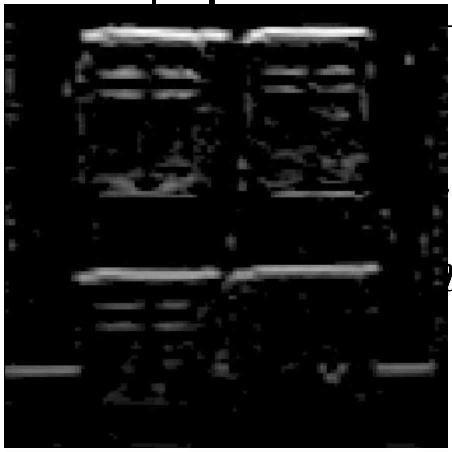
- Homography warp

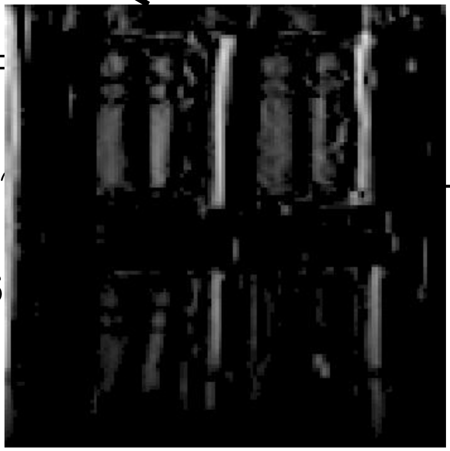
$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \mathcal{W}_h(\mathbf{x}_h, \mathbf{h}) = \frac{1}{1+h_7u+h_8v}\begin{bmatrix} h_1u & h_3v & h_5 \\ h_2u & h_4v & h_6 \end{bmatrix}$$

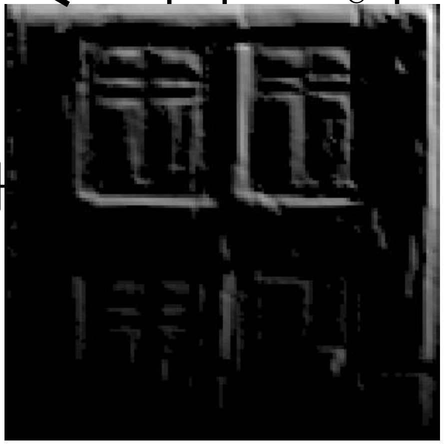
- Projective variability:

$$\Delta\mathbf{T}_h = \frac{1}{c_1}\left[\frac{\partial\mathbf{T}}{\partial u}, \frac{\partial\mathbf{T}}{\partial v}\right]\begin{bmatrix} u & 0 & v & 0 & 1 & 0 & -\frac{uc_2}{c_1} & -\frac{vc_2}{c_1} \\ 0 & u & 0 & v & 0 & 1 & -\frac{uc_3}{c_1} & -\frac{vc_3}{c_1} \end{bmatrix}\begin{bmatrix} \Delta h_1 \\ \vdots \\ \Delta h_8 \end{bmatrix}$$









Out-of-plane variability

- Let $r = [\alpha, \beta]$ angle for ray to scene point
- Pre-warp texture plane rearrangement:

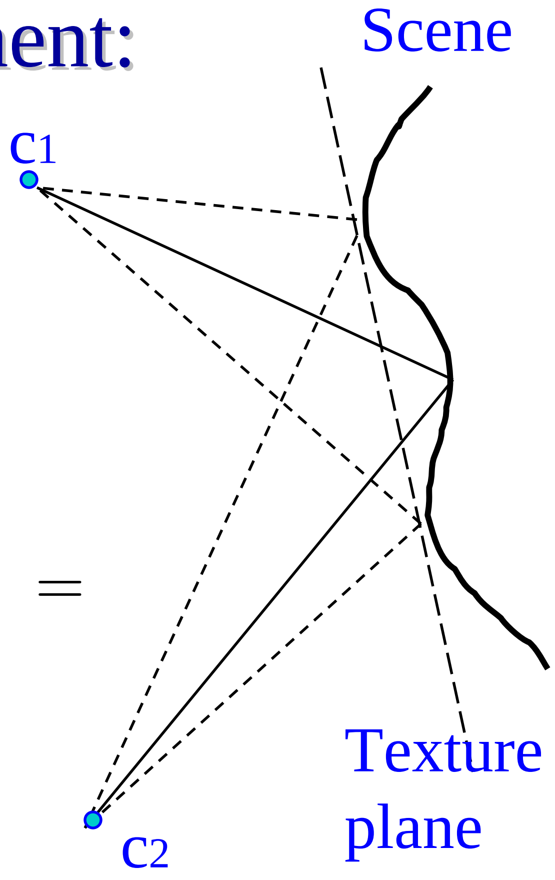
$$\begin{bmatrix}\delta u\\ \delta v\end{bmatrix} = \mathcal{W}_p(\mathbf{x},\mathbf{d}) = \mathbf{d}(\mathbf{u},\mathbf{v})\begin{bmatrix}\tan\alpha\\ \tan\beta\end{bmatrix}$$

Depth w.r.t. model facet

- Texture basis

$$\Delta\mathbf{T_p} = \mathbf{d}(\mathbf{u},\mathbf{v})\left[\frac{\partial\mathbf{T}}{\partial\mathbf{u}},\frac{\partial\mathbf{T}}{\partial\mathbf{v}}\right]\begin{bmatrix}\frac{1}{\cos^2\alpha} & \mathbf{0}\\ \mathbf{0} & \frac{1}{\cos^2\beta}\end{bmatrix}\begin{bmatrix}\boldsymbol{\Delta}\alpha\\ \boldsymbol{\Delta}\beta\end{bmatrix} =$$

$$= \mathbf{B_p}\mathbf{y_p}$$



Photometric variation

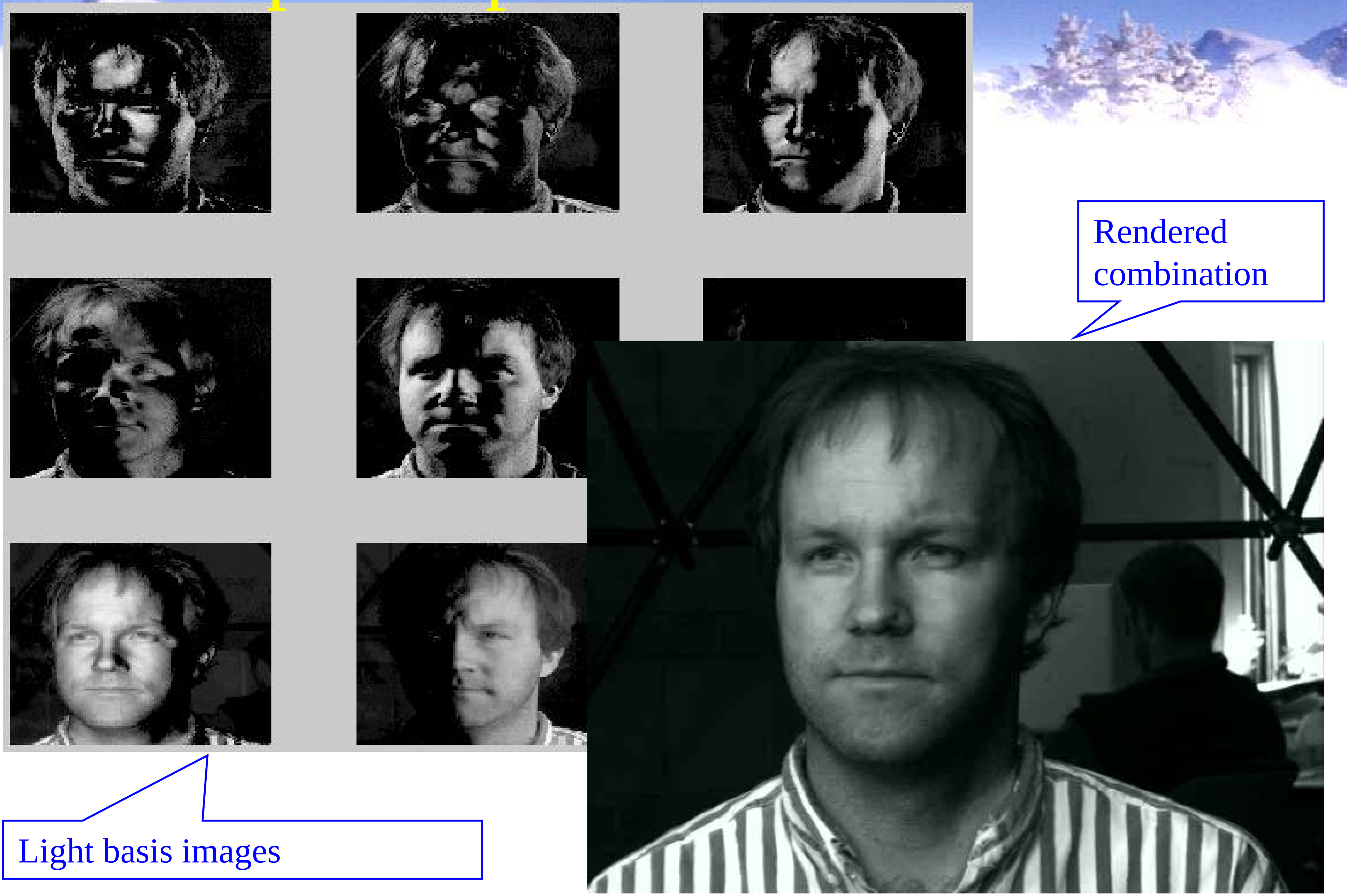
Analytic formula for irradiance for a convex Lambertian object under distant illumination (with attached shadows) - spherical harmonics

[Barsi and Jacobs, Ramamoorthi and Hanrahan 2001]

$$T(\alpha,\beta,\theta,\phi) \approx \sum_{l=0}^{2} \sum_{k=-l}^{l} L_{lk}(\alpha,\beta) A_l Y_{lk}(\theta,\phi)$$

$$T = [B_1 \cdots B_9][L_1 \cdots L_9]^T$$

Example of photometric variation



Rendered combination

Light basis images

Composite variability

Similarly, composite texture intensity variability

$$\Delta \mathbf{T} = \Delta \mathbf{T}_s + \Delta \mathbf{T}_d + \Delta \mathbf{T}_l + \Delta \mathbf{T}_e$$

Planar Depth Light Res Err

Can be modeled as sum of basis

$$\Delta \mathbf{T} = \mathbf{B_s y_s} + \mathbf{B_d y_d} + \mathbf{B_l y_l} + \boldsymbol{\Delta} \mathbf{T_e}$$

$$= \mathbf{By} + \boldsymbol{\Delta} \mathbf{T_e}$$

How to compute?

From a 3D graphics model:

1. Texture intensity derivatives
2. Jacobian of warp or displacement function

- Results in about 20 components:
  - T_0
  - 8 for planar,
  - 2 out-of plane (parallax),
  - 3-9 light

From video:

- We can expect an approximately 20dim variation in the space of all input texture images.

=> Extract this subspace

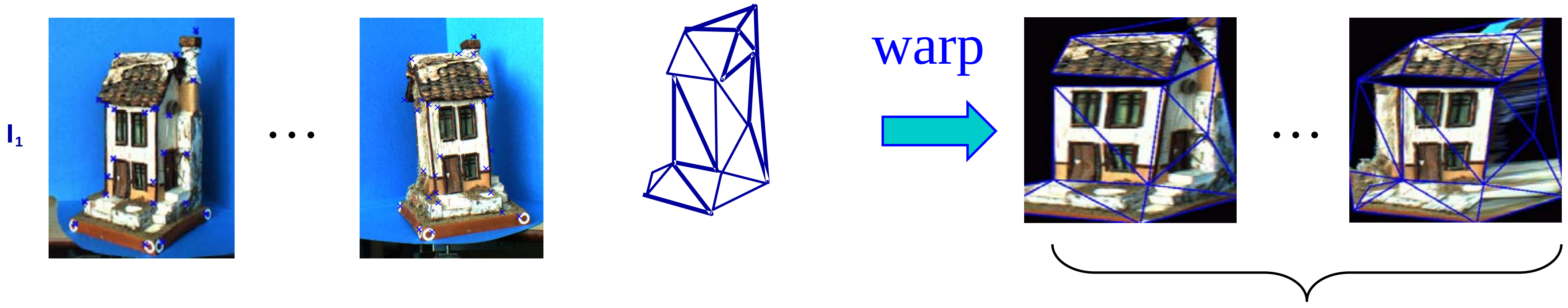
How to compute from images (cont)…

1. Take input video sequence, use SFS/SFM geometry to warp into texture space

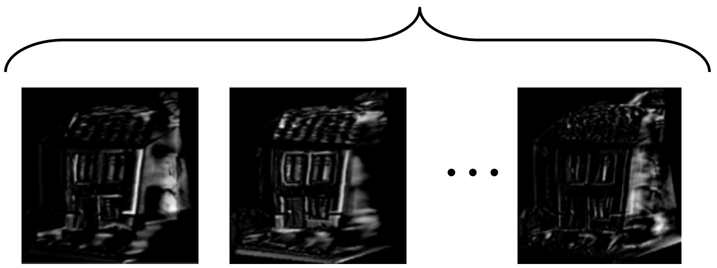
Input Images

Geometry

Texture warp



PCA



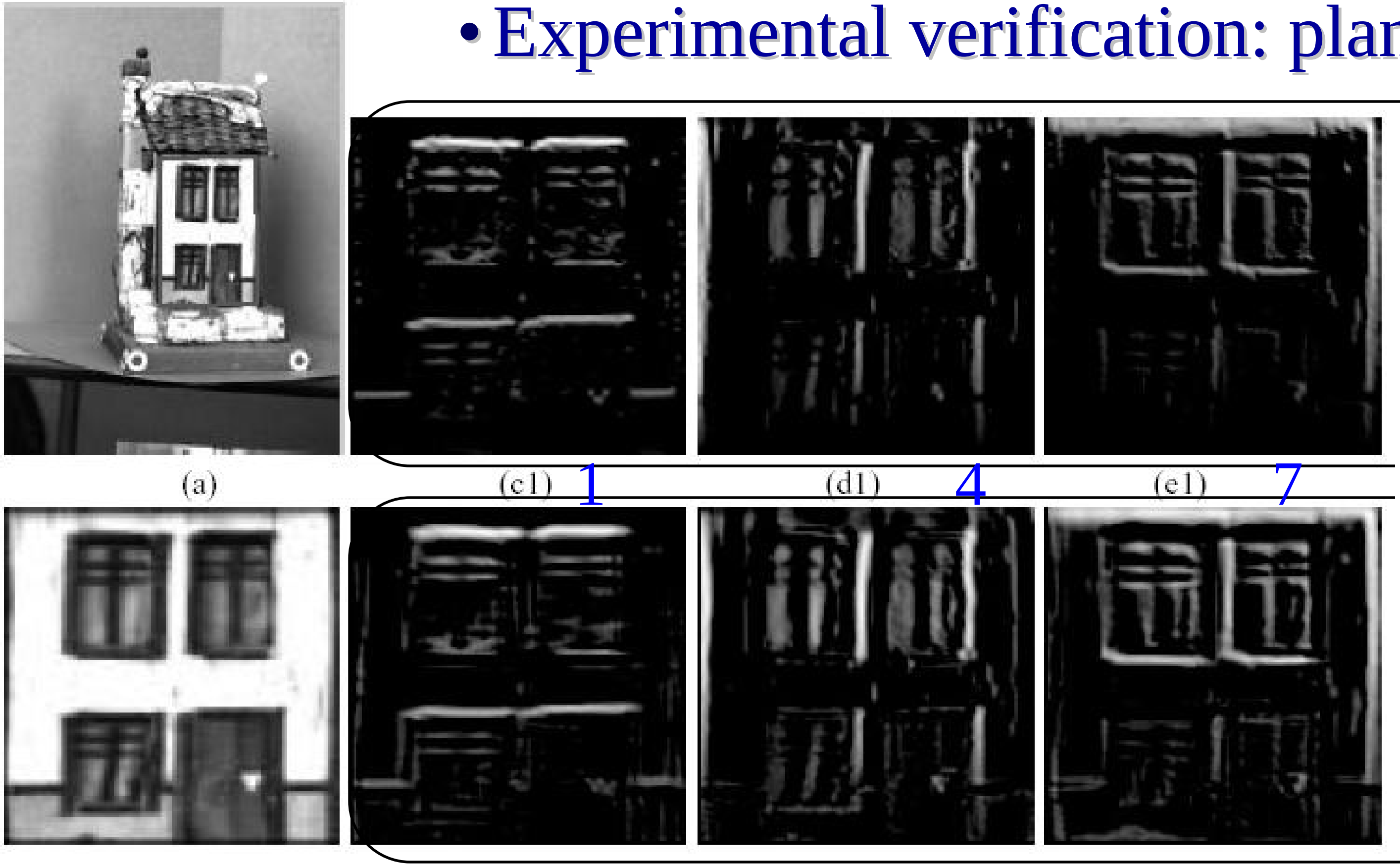
2. Extract a 20-dim subspace through PCA

TexDemo

Are analytic image derivatives and PCA basis the same?

- Same up to a linear transform!

- Experimental verification: planar homog



Derivatives

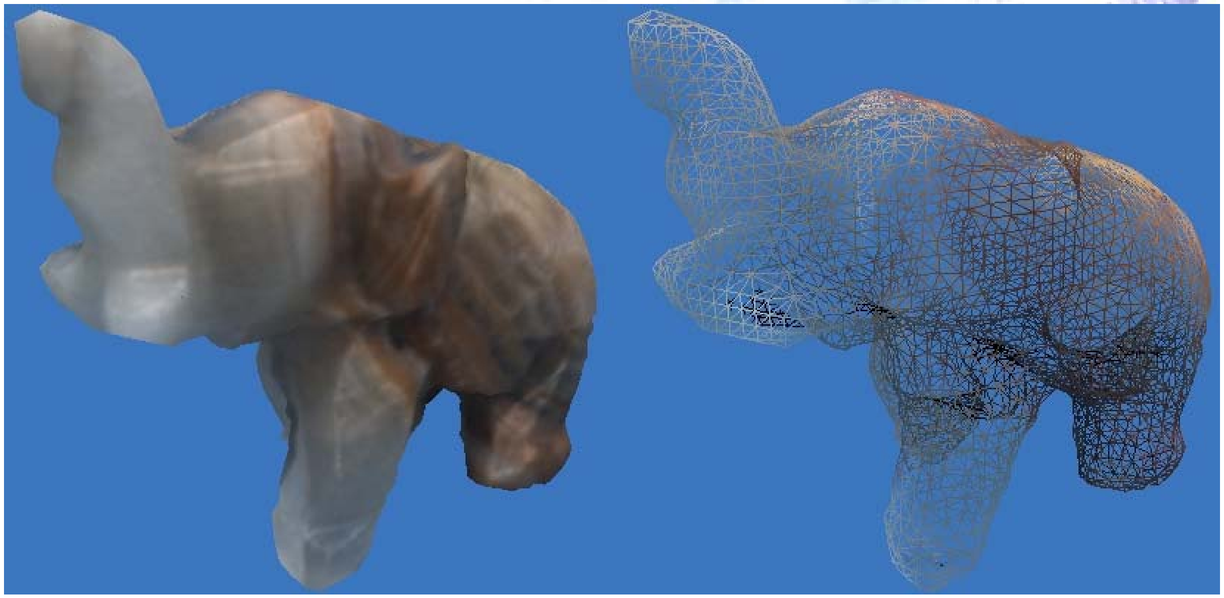
⇕

99% agreement

⇕

PCA

Example renderings from 3D models

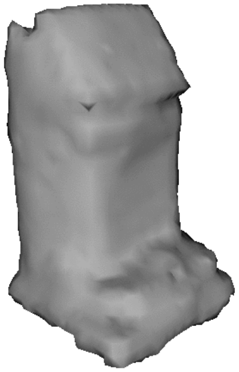


Recap: hierarchical model scale levels

1. Macro:

- SFM, SFS can generate coarse geometry but not detailed enough for realistic rendering
- Integrate tracking and structure computation

Scale: dozen pixels and up



2. Meso :

- Refine coarse geometry and acquire reflectance-variational surface evolution

Scale: 1-dozen pixels

3. Micro spatial basis :

- Represents appearance and corrects for small geometric texture errors limited by linearity of image Scale: 0-5 pixels

Comparison

1. Static texturing: (Many, e.g. Baumgartner et al. 3DSOM)
   - Average color projected to point.
   - Better: Pick color minimizing reprojection error over all input images

   Works when model geometry is close to ground truth and light simple
2. Viewdependent texture (Debevec et al)
   - Pick color from closest input photograph (or interpolate from nearest 3)

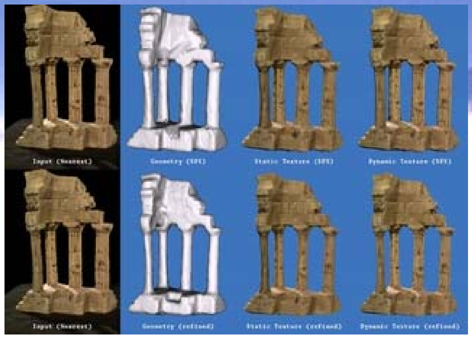
   Works when possible to store large numbers of images
3. Lumigraph / Surface light field (Buehler et al / Wood et al)
   - Store all ray colors (plenoptic function) intersecting a proxy surface

   Works if proxy surface close to true geometry
4. Dynamic texture (Ours: Jagersand '97/ Matusik / Ikeuchi99 /Vasilescu04...
   - Derive a Taylor expansion and represent derivatives of view dependency

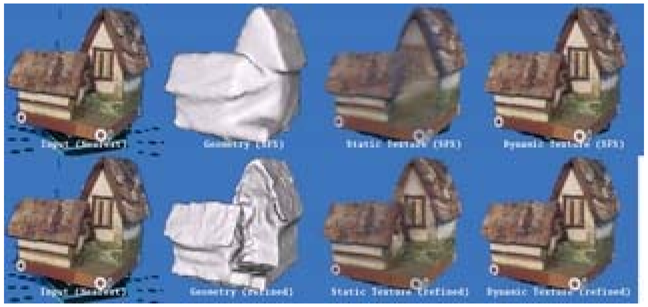
   Works for light and small (1-5 pixel) geometric displacements.

videos

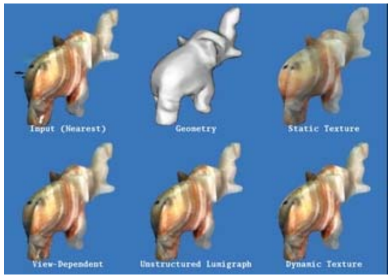
From Simple to Complex Scenes
4 test cases



1. Simple Geom: SFS alone ok



2. General Geom: SFS + Variational Shape and Reflectance fitting (+View dep texture)



3. Complex Light: Dynamic Texture / Lumigraph

4. Challenge for Computer Vision

From Simple to Complex Scenes
4 test cases

Martin Jagersand
U of Alberta

1. Simple Geom: SFS alone ok
2. General Geom: SFS + Variational Shape and Reflectance fitting (+View dep texture)
3. Complex Light: Dynamic Texture / Lumigraph
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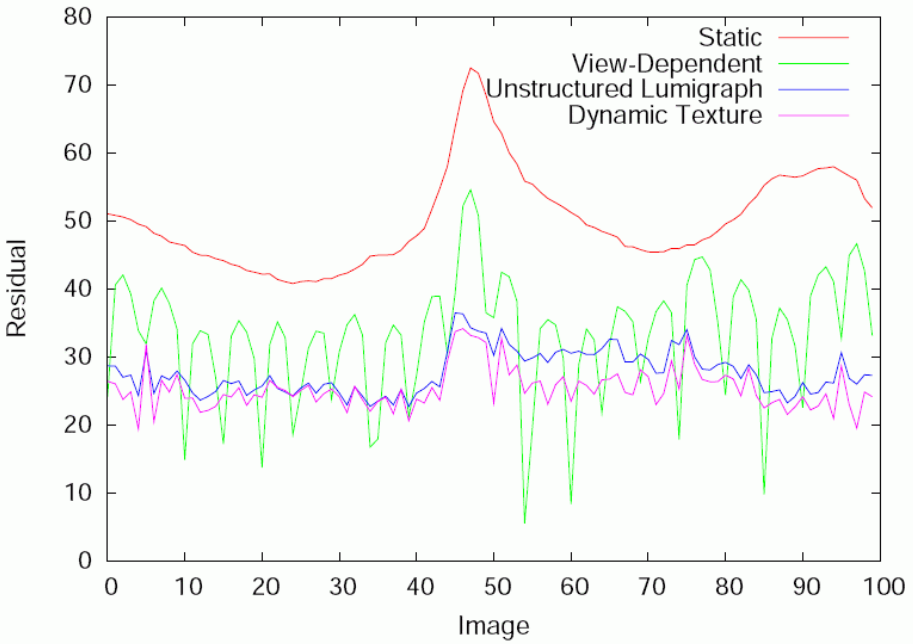
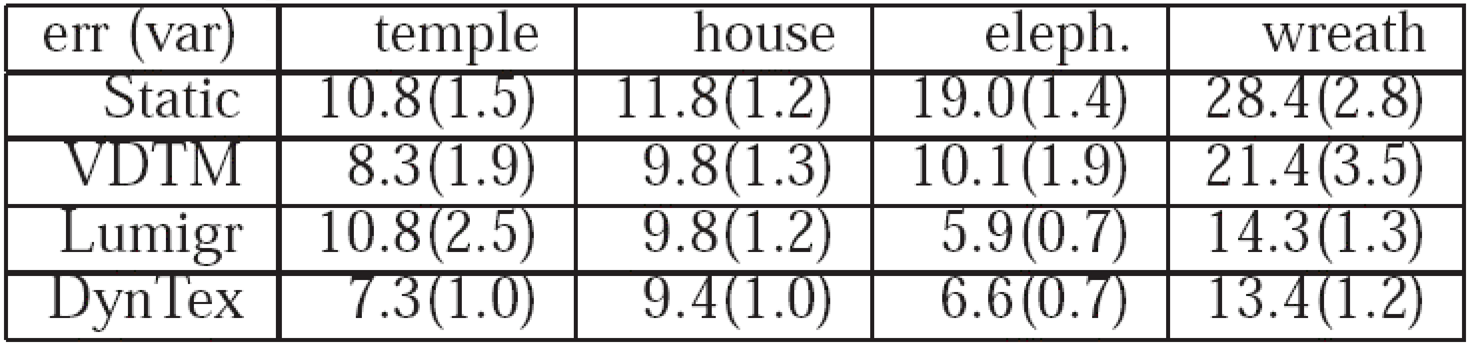




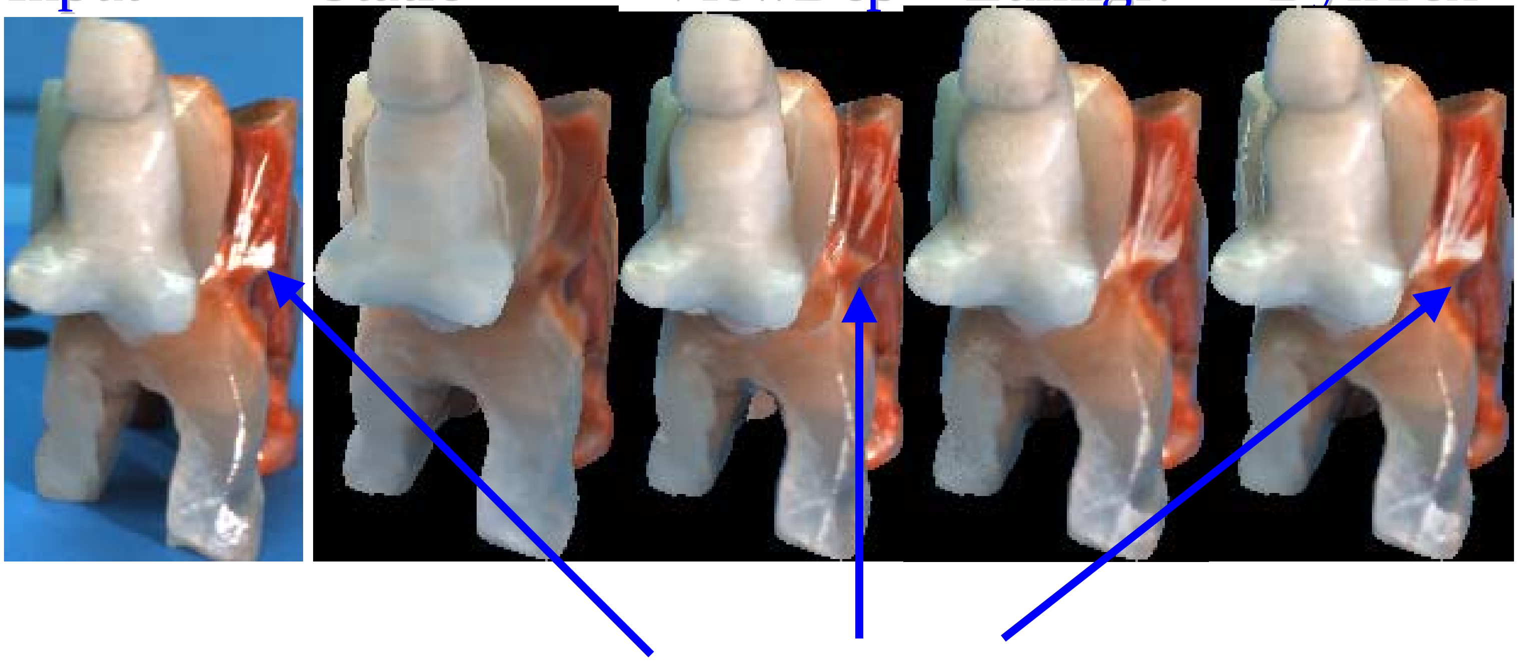
err (var)	temple	house	eleph.	wreath
Static	10.8(1.5)	11.8(1.2)	19.0(1.4)	28.4(2.8)
VDTM	8.3(1.9)	9.8(1.3)	10.1(1.9)	21.4(3.5)
Lumigr	10.8(2.5)	9.8(1.2)	5.9(0.7)	14.3(1.3)
DynTex	7.3(1.0)	9.4(1.0)	6.6(0.7)	13.4(1.2)

Table 1. Numerical texture errors and variance. %-scale.

Example of render differences

- Jade Elephant
  - Complex Reflectance (specularities and scattering)

Input Static ViewDep Lumigr. DynTex



Specular highlight

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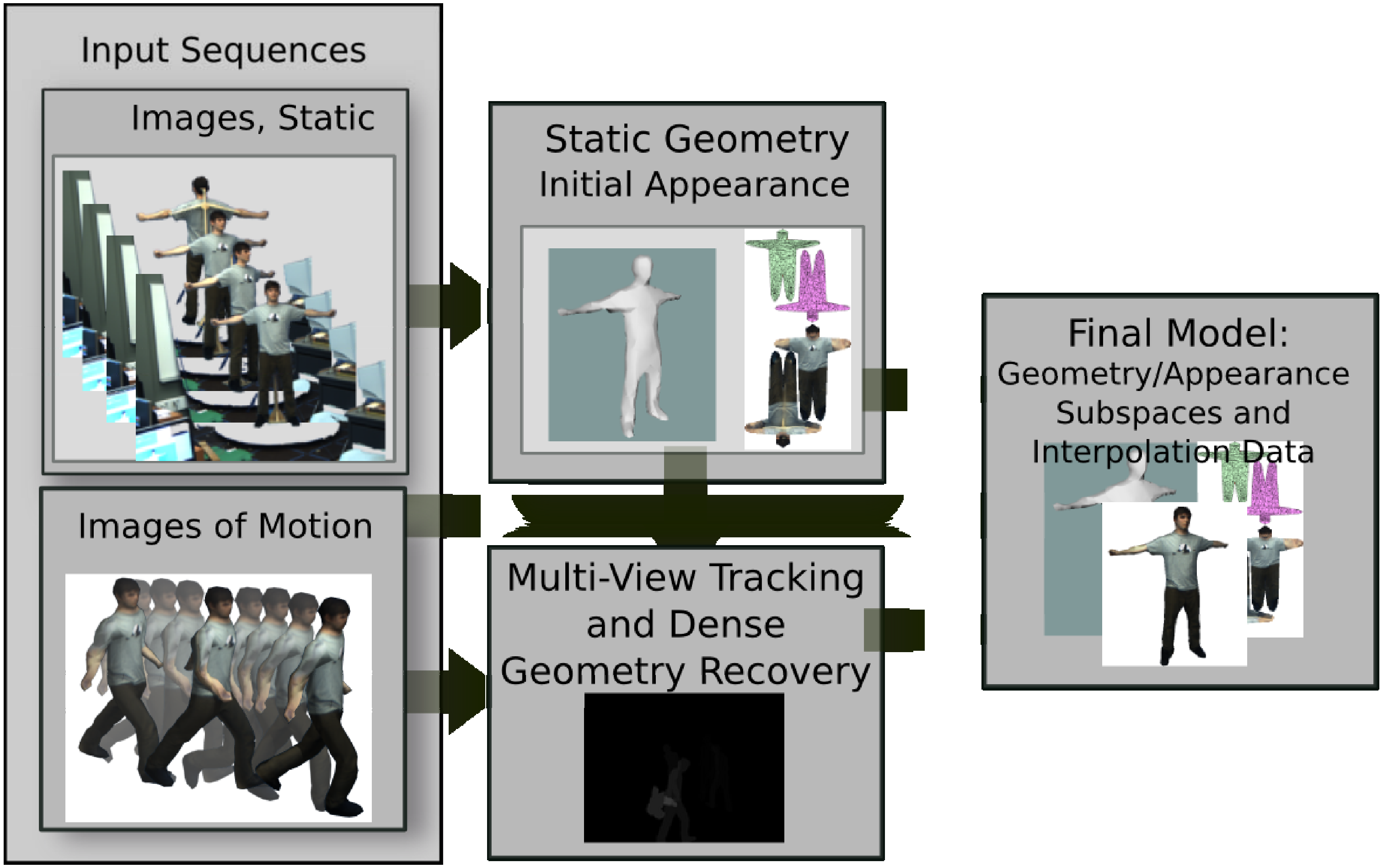
Capturing non-rigid animatable models

current PhD project, Neil Birkbeck



Input Sequences

Images, Static

Images of Motion

Static Geometry
Initial Appearance

Multi-View Tracking
and Dense
Geometry Recovery

Final Model:
Geometry/Appearance
Subspaces and
Interpolation Data

Questions?

More information:

- Downloadable renderer+models

www.cs.ualberta.ca/~vis/ibmr

- Capturing software + IEEE VR tutorial text

www.cs.ualberta.ca/~vis/VR2003tut

- Main references for this talk:

Jagersand et al “Three Tier Model” 3DPVT 2008 ….
Jagersand “Image-based Animation…” CVPR 1997

- More papers: www.cs.ualberta.ca/~jag

CAMERA-BASED
3D CAPTURE
SYSTEM

Video: see web page:

www.cs.ualberta.ca/~vis/ibmr/movies/capsys_1min.avi