PROJECT FLEXABLE

European Research Council
Established by the European Commission

Shape-from-Template

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Mathieu Perriollat, Daniel Pizarro, Richard Hartley, and others

Keynote given at ORASIS, Amiens, June 2015

ALCoV
I · S · I · T

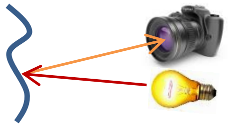
UdA

Primary Goal: Passive Single-Image 3D Reconstruction

Shape-from-Template

Shape-from-Template

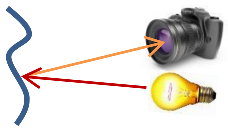
3D Reconstruction: to Recover 3D Shape from 2D Images



Escaping Criticism by del Caso, 1874

Model Town by Matt West, 2006

3D Reconstruction: Active Methods



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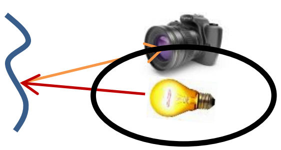
by Matt West, 2006



Structured lighting

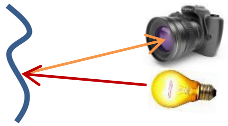
Image by Visnjic, 2010
Using Kinect

Dancing with invisible light
By Penven, 2010, using Kinect

Time-of-Flight

Reprinted from [Maier-Hein et al, MIA 2013]

3D Reconstruction: Passive Visual Cues



Escaping Criticism by
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Model Town
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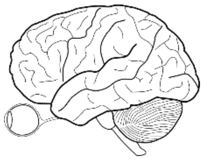
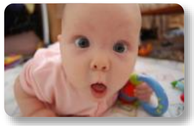
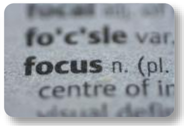
[Gibson ~ 1960 ; Marr ~ 1970]





Stereoscopy

Motion



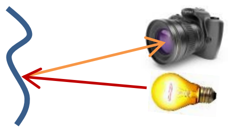
Blur

Occlusions

Shading

Texture

3D Reconstruction: Multiple Images



Escaping Criticism by del Caso, 1874

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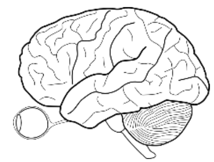


Stereoscopy

Motion

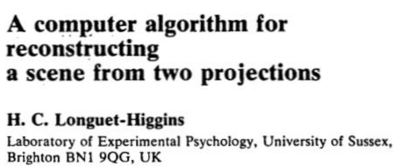
Blur

Occlusions

Shading

Texture

Example: Shape-from-Motion (SfM) for rigid scenes

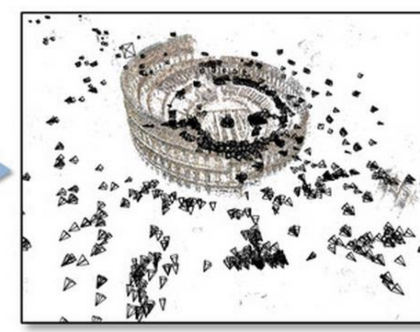


A computer algorithm for reconstructing a scene from two projections

H. C. Longuet-Higgins

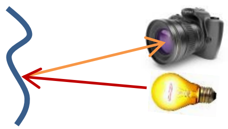
Laboratory of Experimental Psychology, University of Sussex, Brighton BN1 9QG, UK

[Longuet-Higgins, Nature 1981]



Reprinted from Bundler's website [Snavely et al, IJCV 2007]

3D Reconstruction: Single Image, Manually



Escaping Criticism by del Caso, 1874

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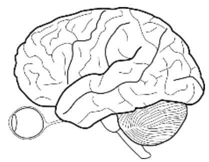
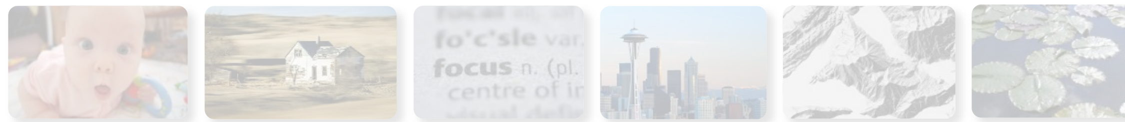
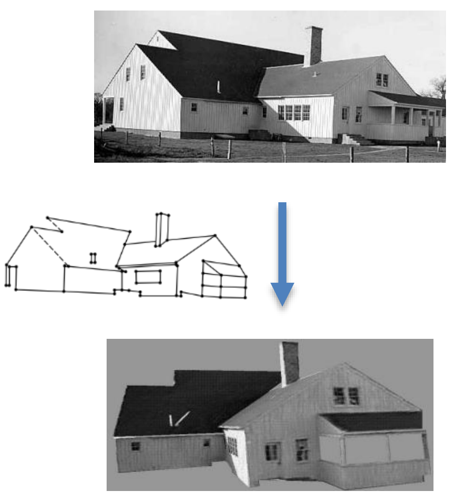
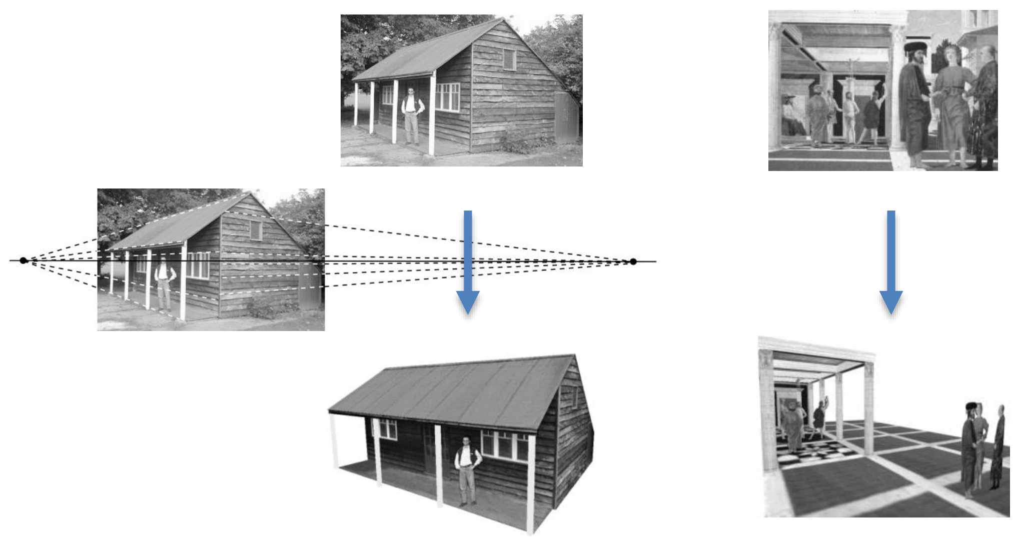




Stereoscopy | Motion | Blur | Occlusions | Shading | Texture

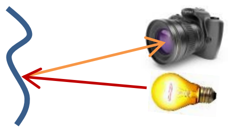


[Sturm et al, BMVC 1999]



[Criminisi et al, IJCV 2000]

3D Reconstruction: Single Image, Visual Cues



Escaping Criticism by del Caso, 1874

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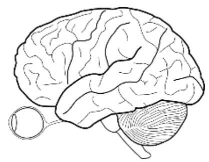
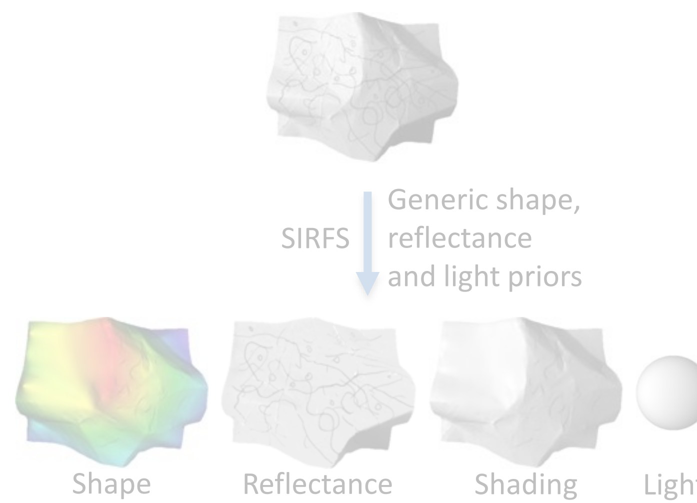


Stereoscopy | Motion | Blur | Occlusions | Shading | Texture

Example: Shape-from-Shading and extensions

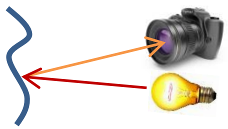
[Horn, MIT TR 1970]

[Breuß et al, SIAM JIS 2012]



[Barron et al, PAMI 2015]

3D Reconstruction: Single Image, Visual Cues



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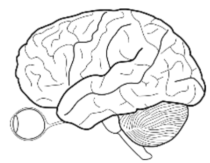


Stereoscopy

Motion

Blur

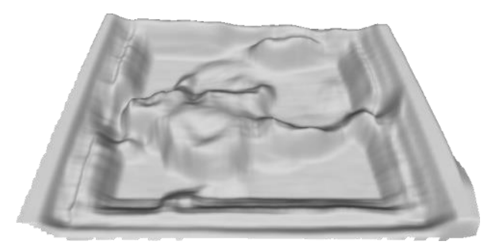
Occlusions

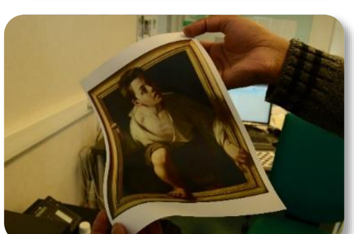
Shading

Texture

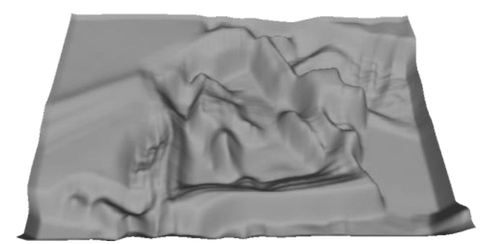
Defeating Shape-from-Shading

SfS →

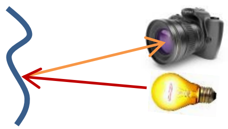




SfS →



3D Reconstruction: Visual Cues and Memory



Escaping Criticism by del Caso, 1874

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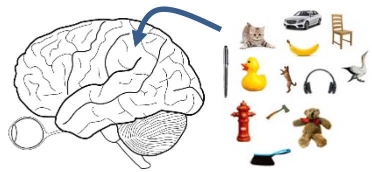
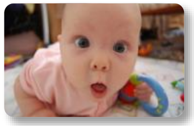
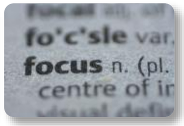
[Gibson ~ 1960 ; Marr ~ 1970]





Stereoscopy

Motion



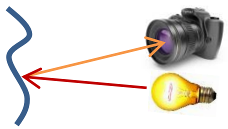
Blur

Occlusions

Shading

Texture

3D Reconstruction: Single Image, Visual Cues and Memory



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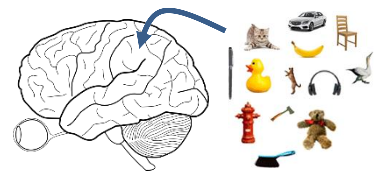


Stereoscopy

Motion

Blur

Occlusions

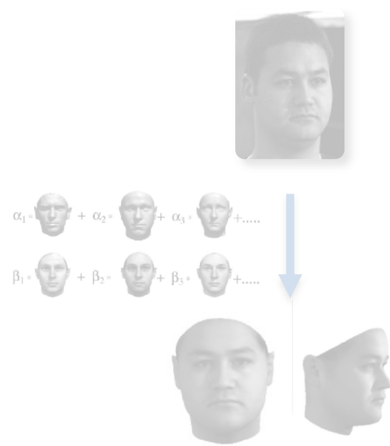
Shading

Texture

Automatic Photo Pop-up

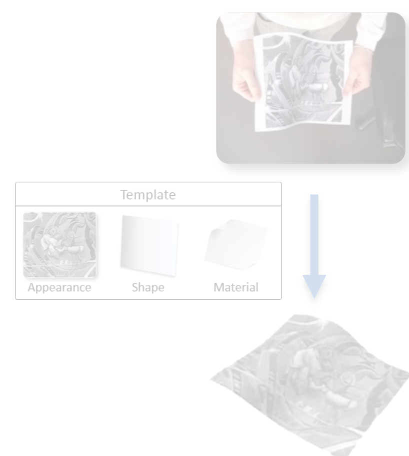
[Hoeim et al, SIGGRAPH 2005]

3DMM: 3D Morphable Models



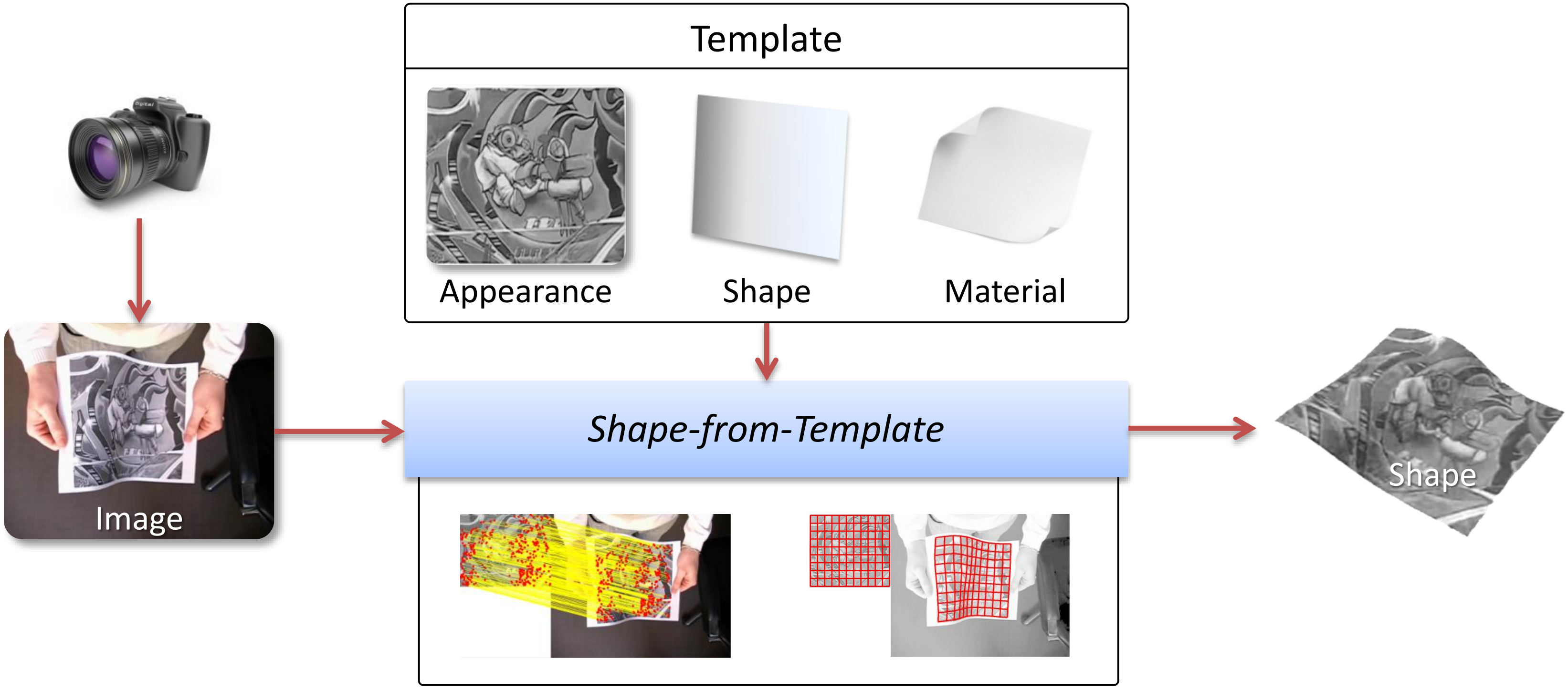
[Blanz et al, SIGGRAPH 1999]

Shape-from-Template

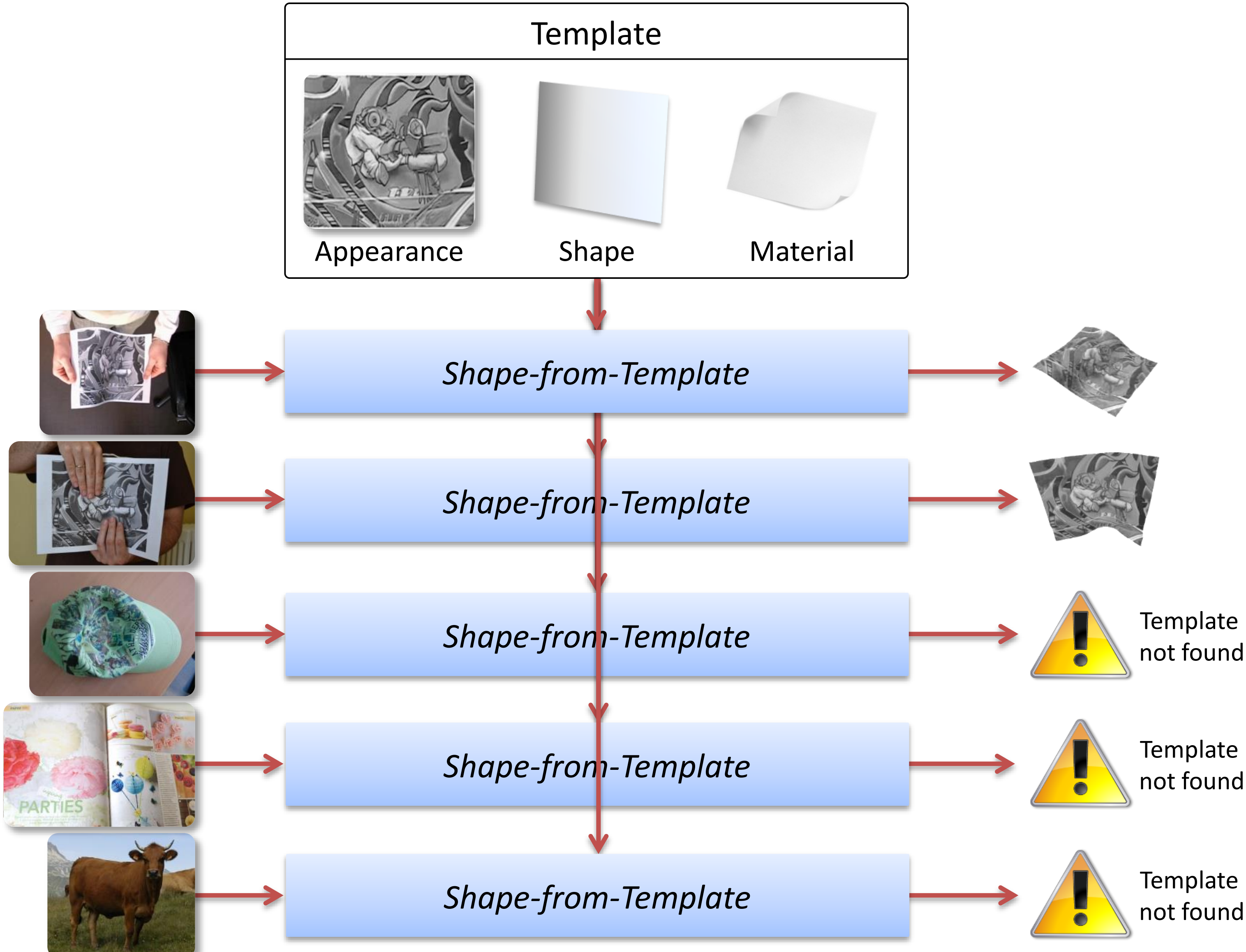


Shape-from-Template

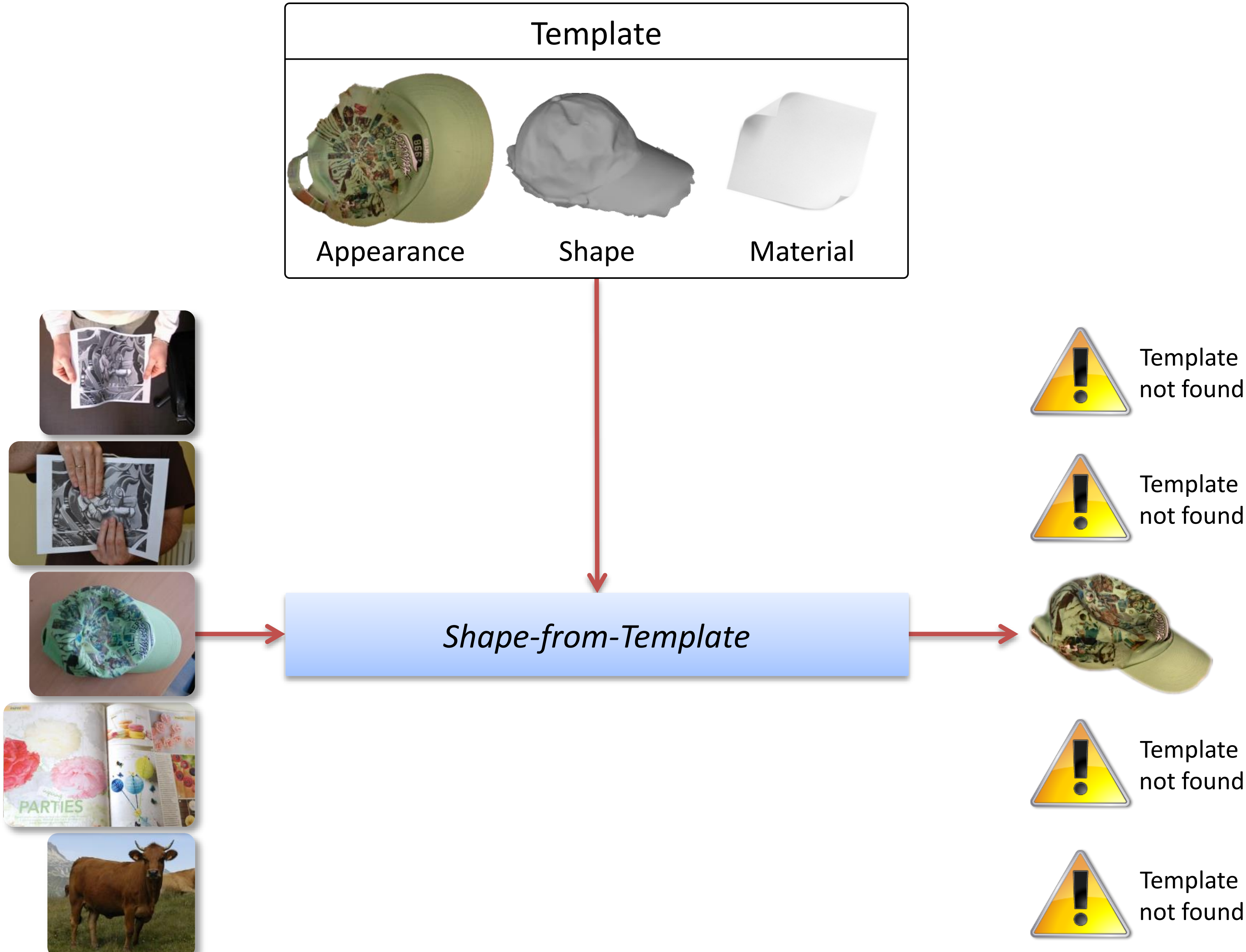
Early steps: [Salzmann et al, BMVC'05 ; Perriollat et al, BMVC'08]



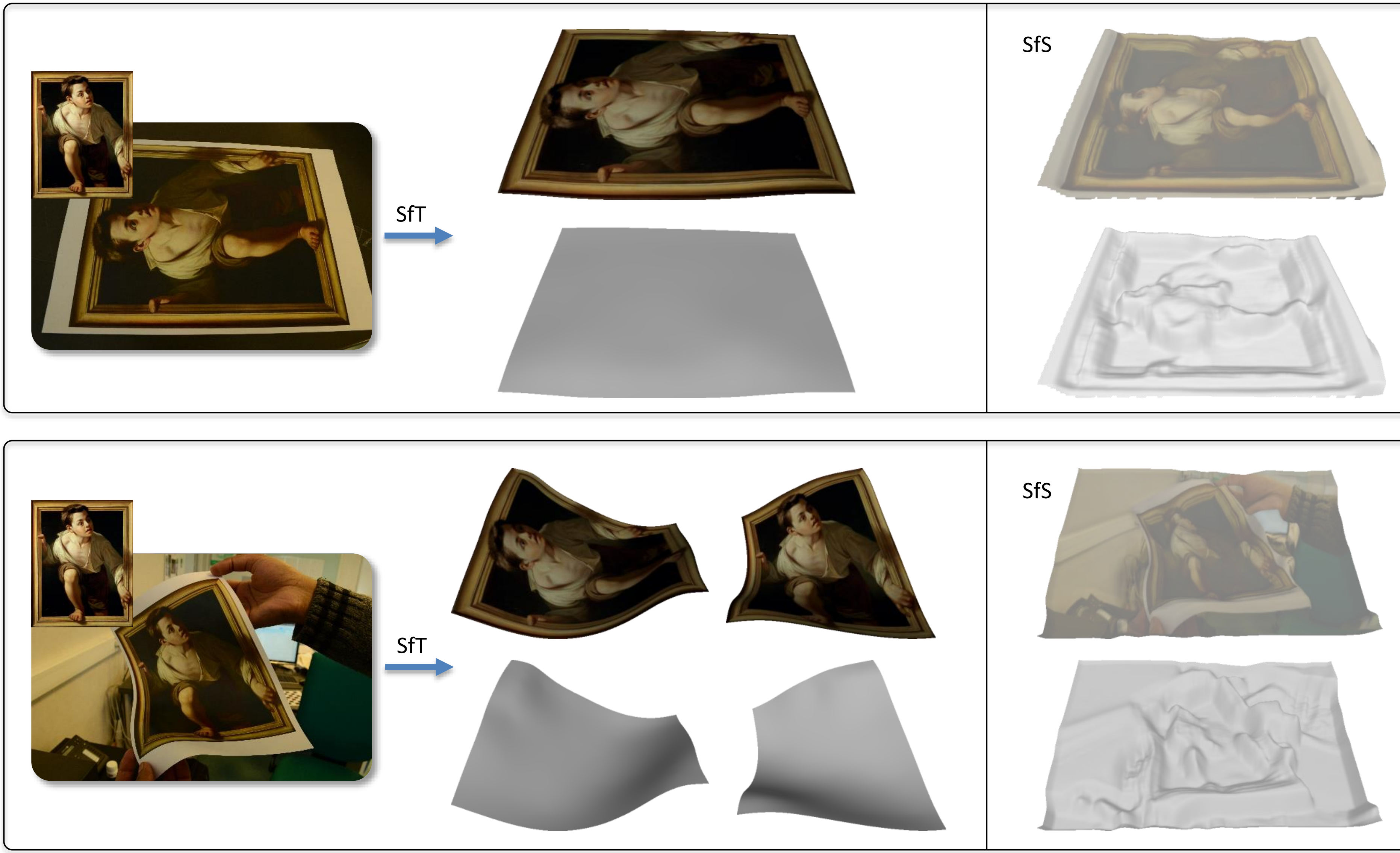
Shape-from-Template



Shape-from-Template

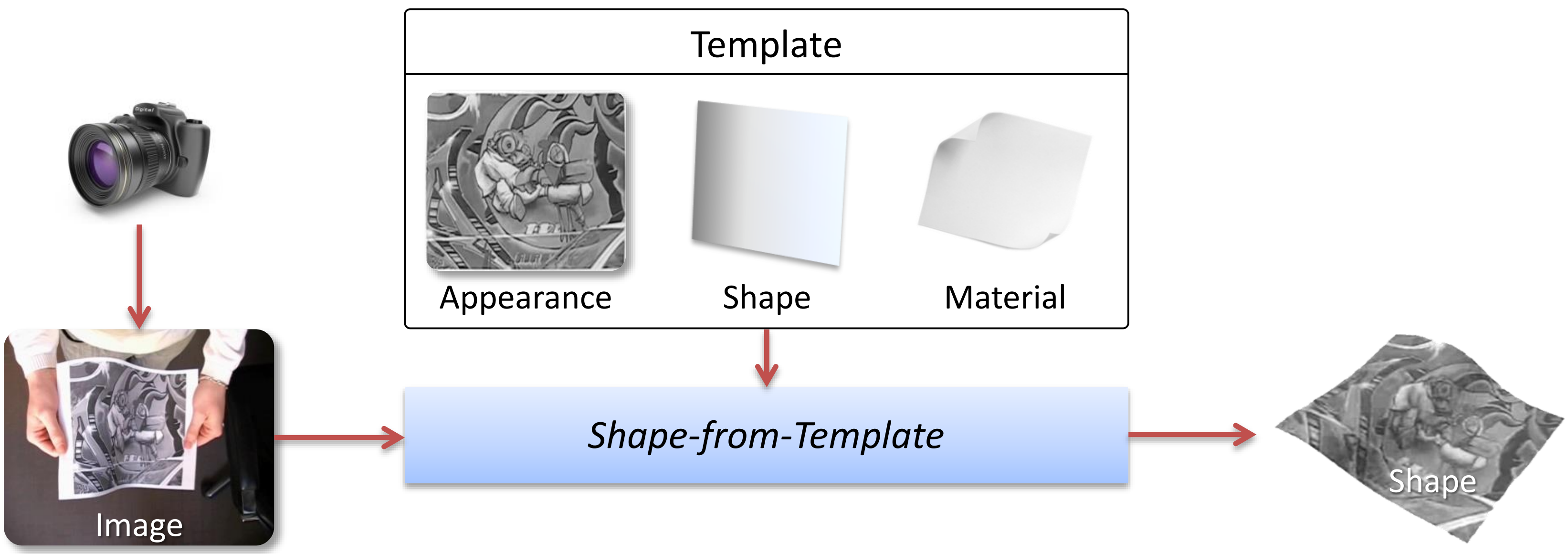


Shape-from-Template for Paintings



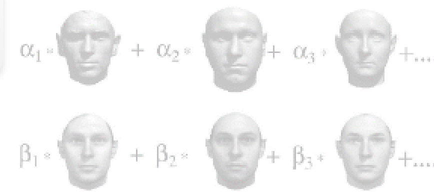
Shape-from-Template's Scope

- Passive, single-image
- Object-specific
- Known reference shape
- Matchable appearance
- Large shape space, simple physics-based deformation law



Large Shape Space, Simple Physics-Based Deformation Law

Small shape space



Template

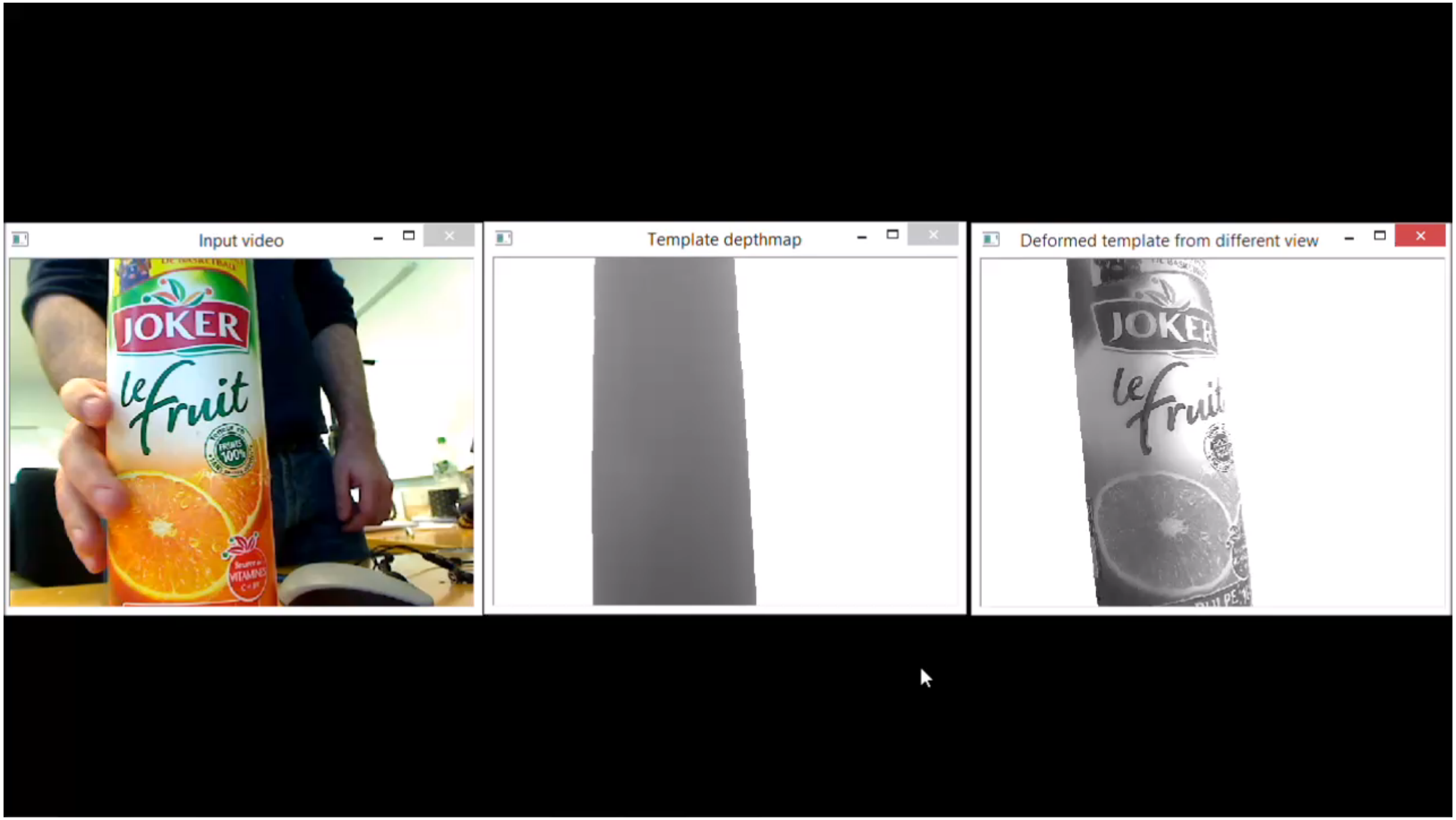
Appearance | Shape | Material

868 vertices, 1732 facets

Simple physics-based deformation law

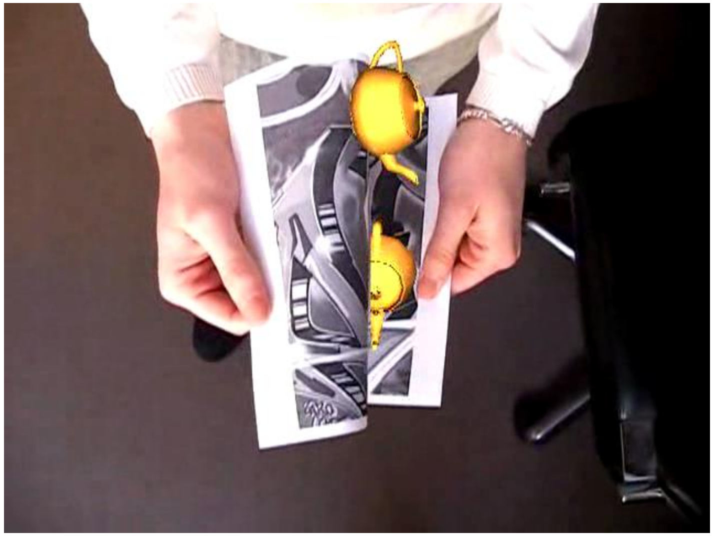
Large shape space

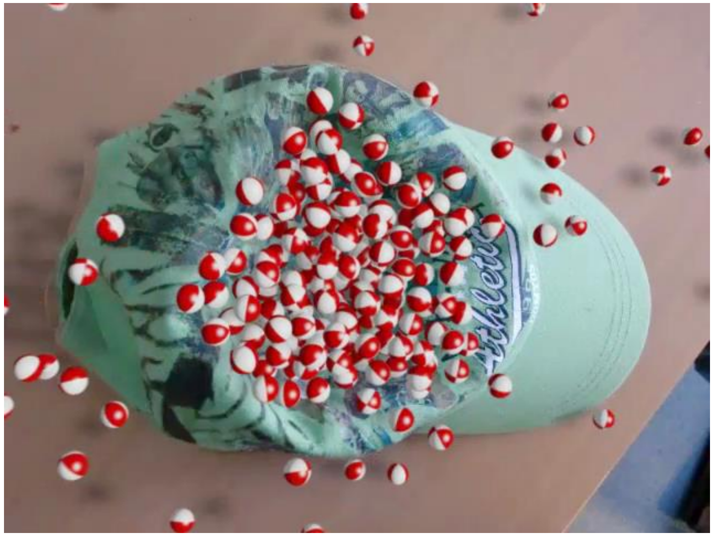
Real-Time Shape-from-Template

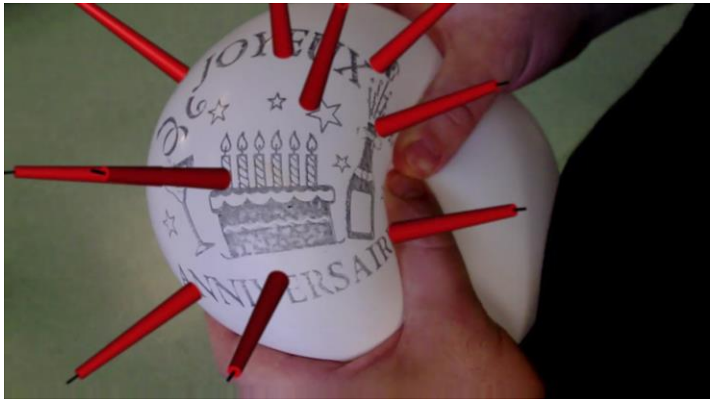


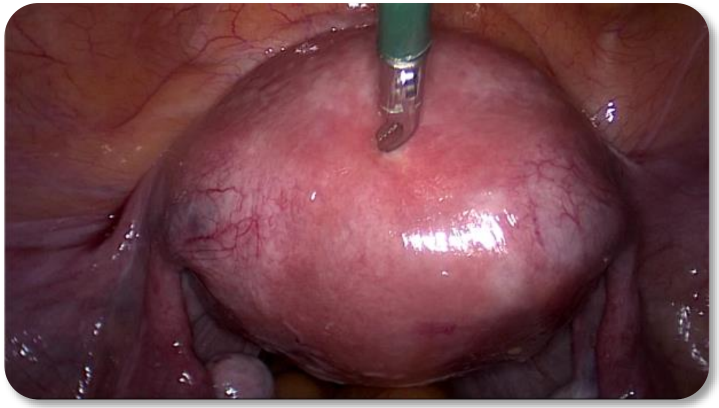
11 fps, Nvidia GTX 1500 cores

Application in Augmented Reality







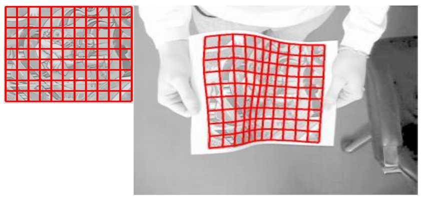


Application in Human-Computer Interaction

Lecture's Plan

$\varphi, \nabla\varphi$

1. **Modeling**



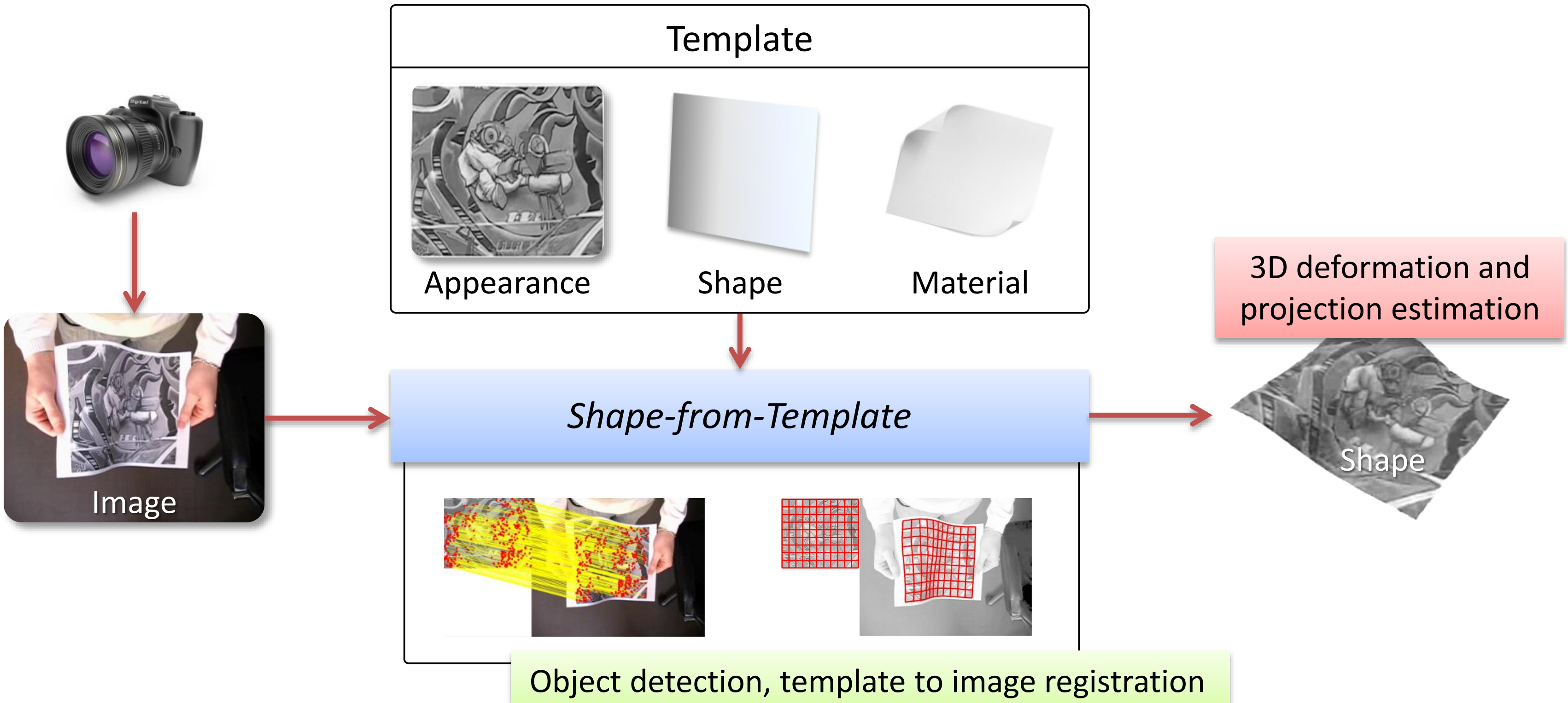
2. Registration

3. Reconstruction

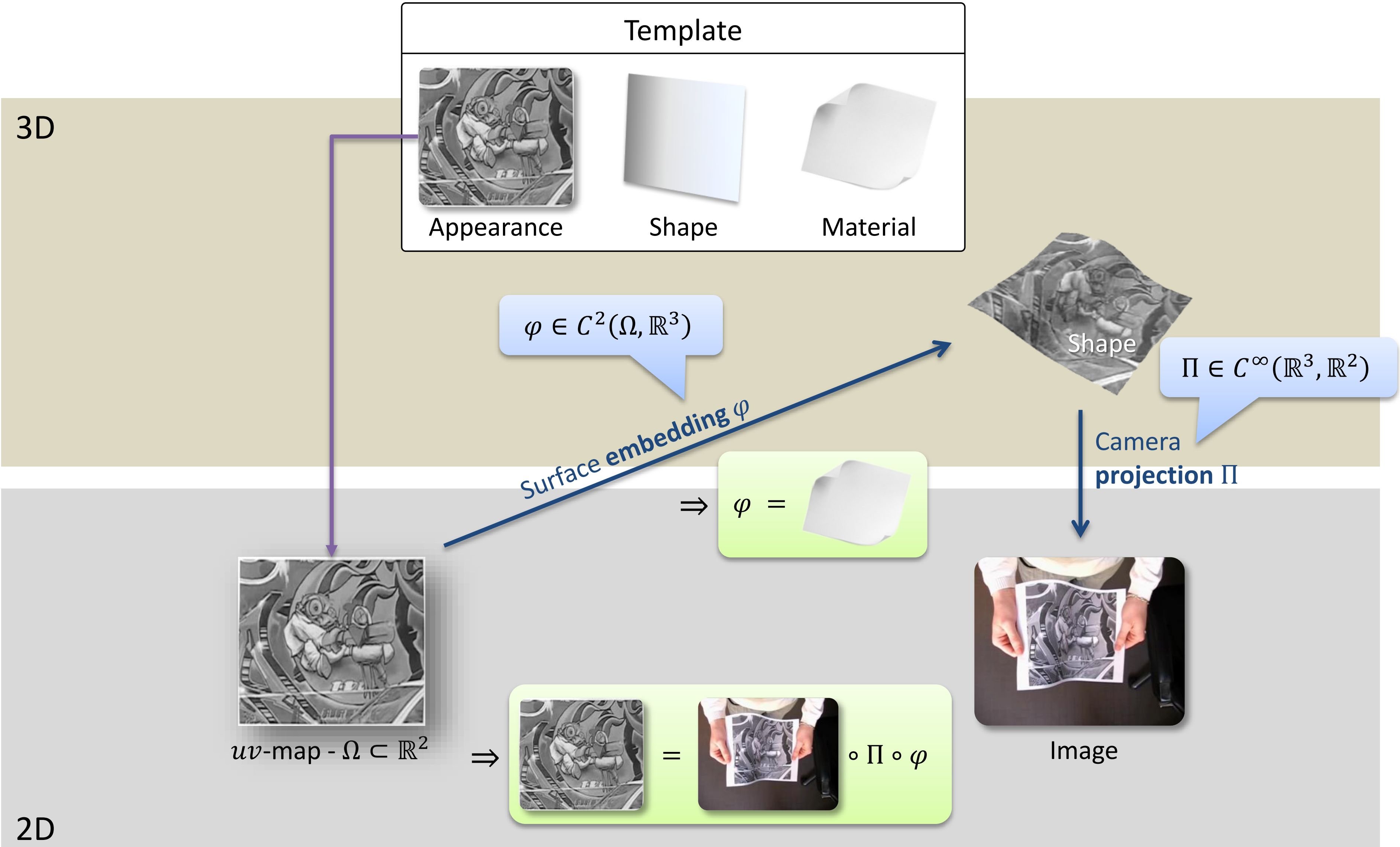
4. More examples, applications

5. Discussion, future work

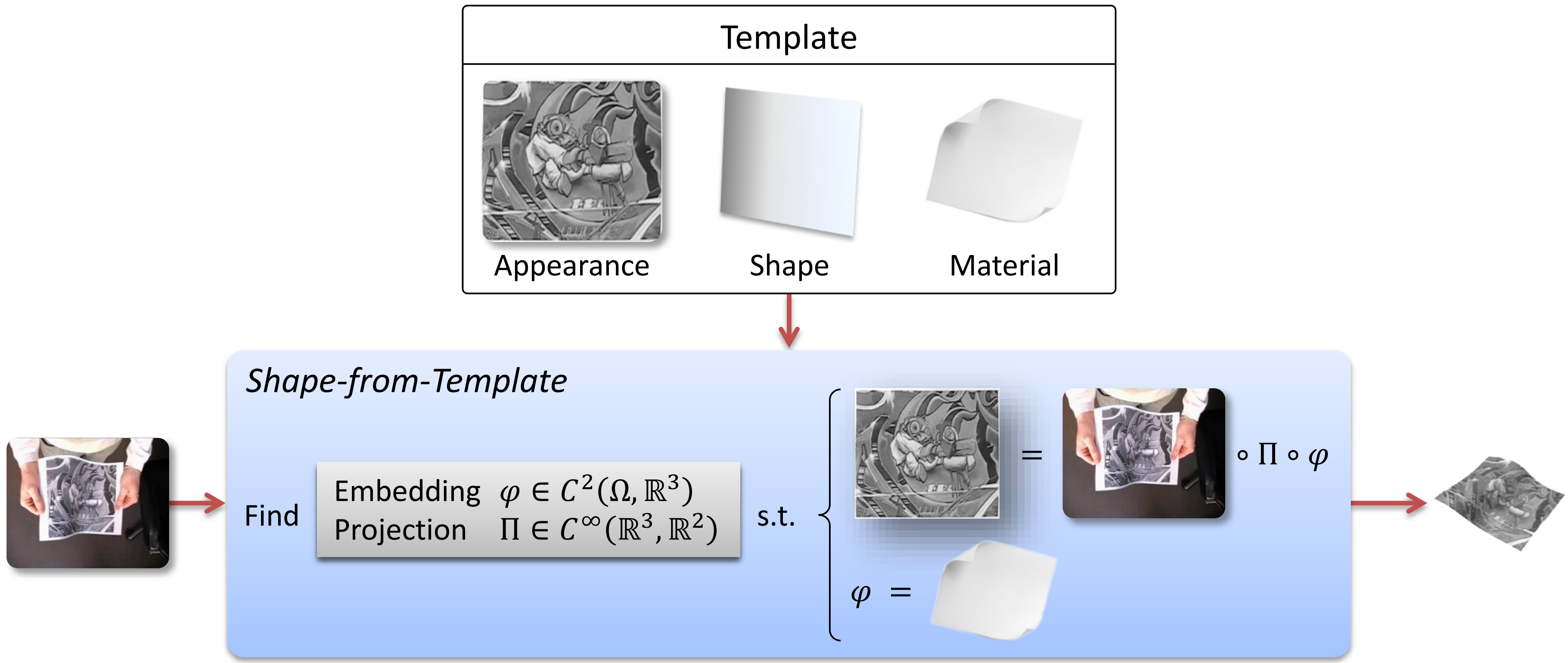
Shape-from-Template's Steps



Differential Geometric Setup

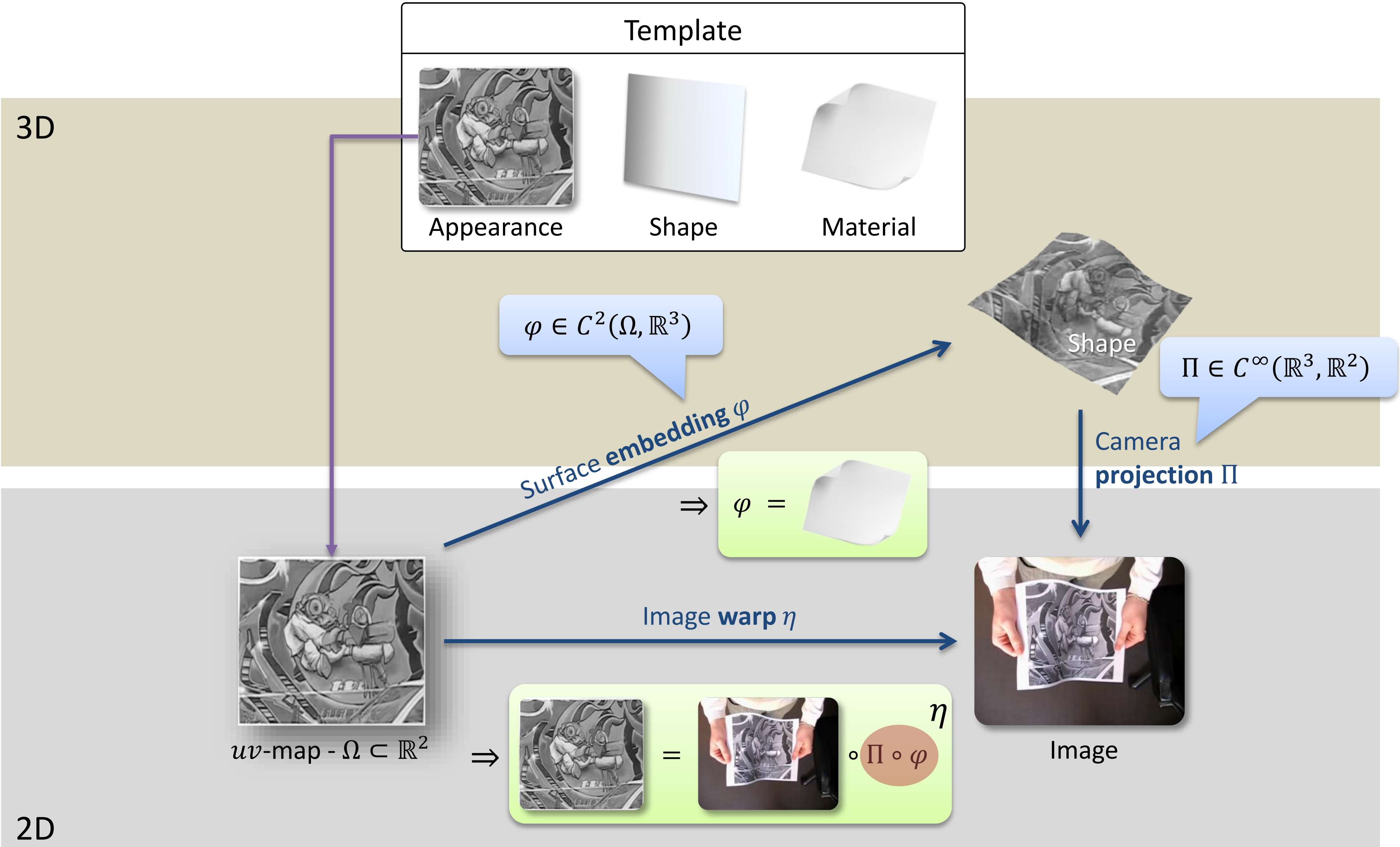


Differential Problem Statement

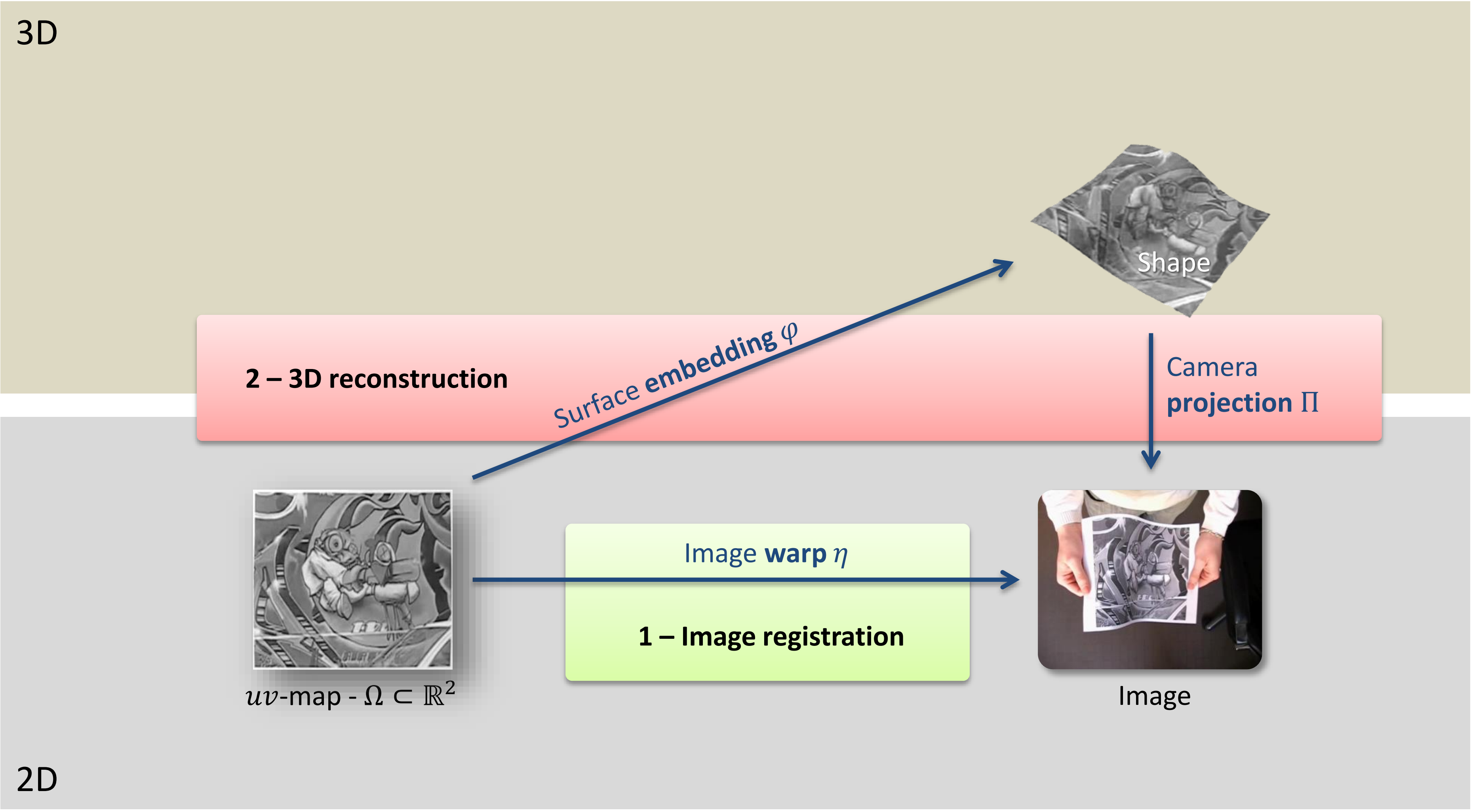


Non-convex variational problem

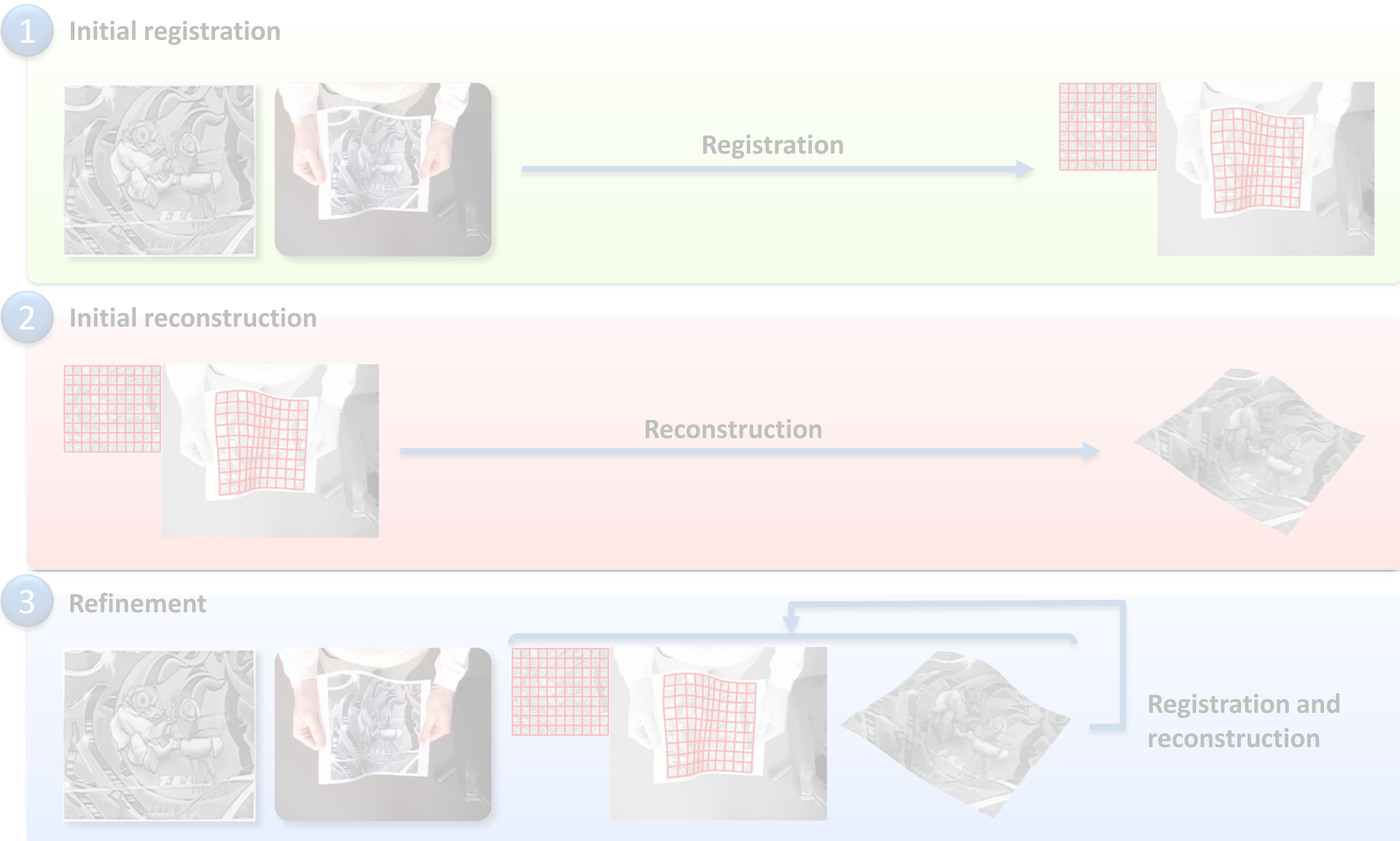
Differential Geometric Setup



Registration, Reconstruction



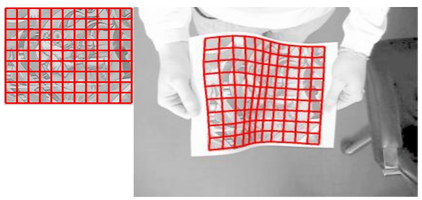
Shape-from-Template Workflow



Lecture’s Plan

$\varphi, \nabla\varphi$

1. Modeling



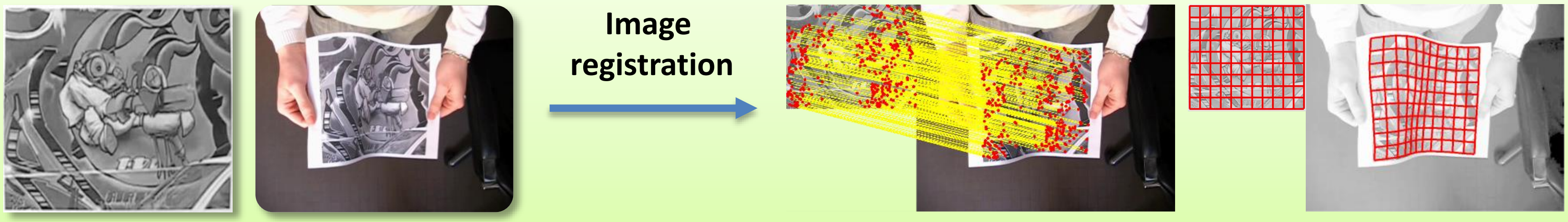
2. **Registration**

3. Reconstruction

4. More examples, applications

5. Discussion, future work

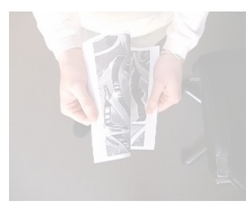
Image Registration: to Find Correspondences between Images



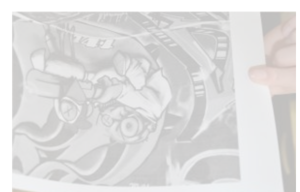
Absence

External occlusions

Self-occlusions



Wide-baseline



Need for dedicated methods inspired from optical flow and warp estimation

Registration: Feature-based vs Color-based

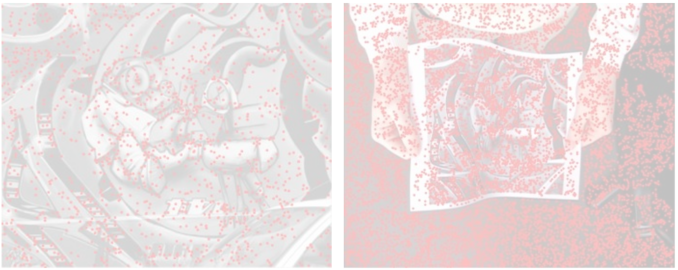
Absence

External occlusions

Self-occlusions

Wide-baseline

Feature-based



SIFT keypoints [Lowe, IJCV'04]

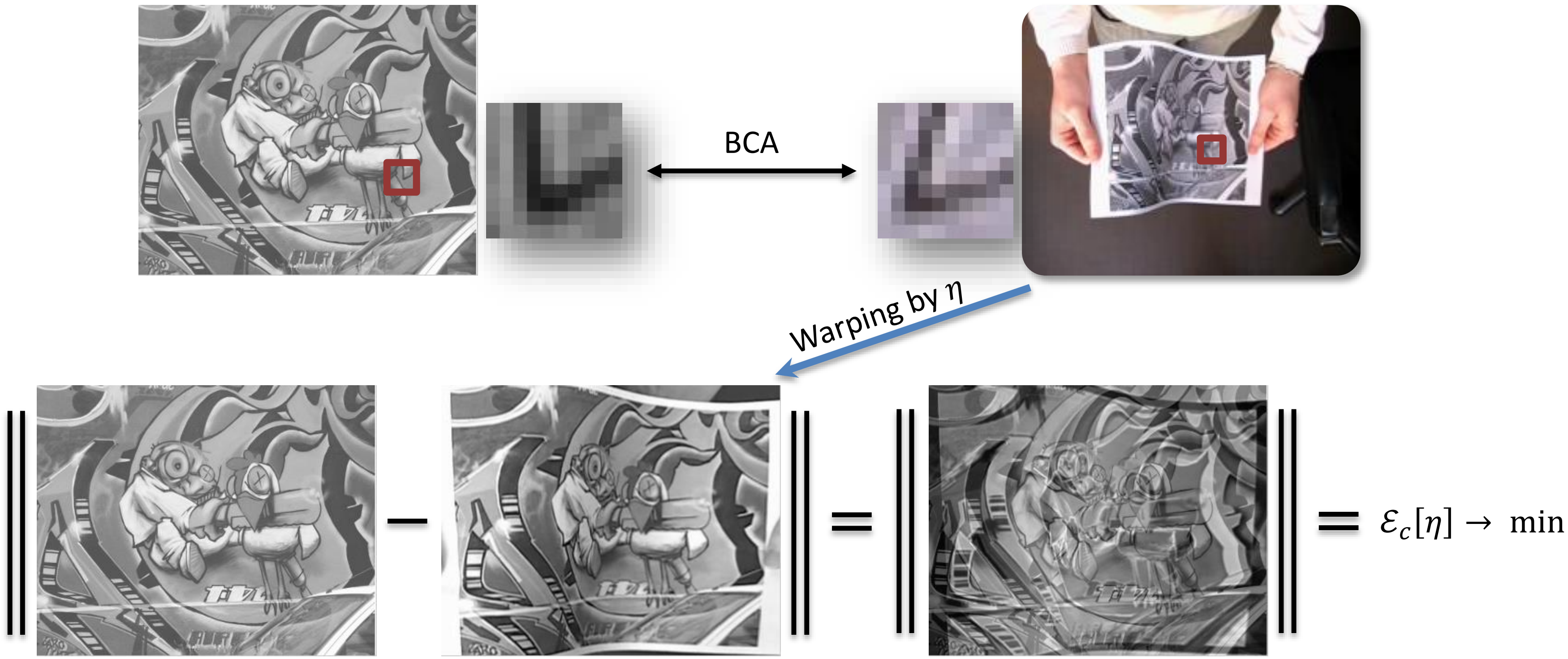
More convex

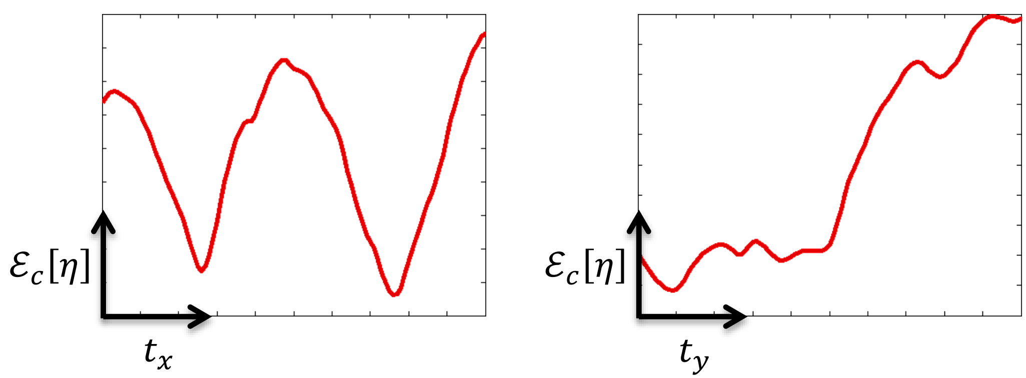
Color-based

SSD

More accurate

The Color-Based Formulation is Highly Nonconvex



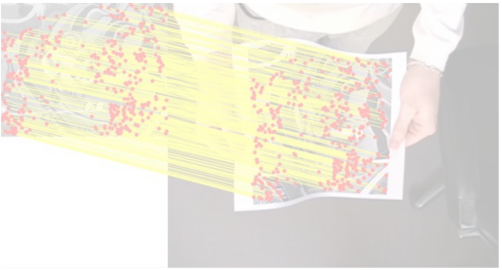


Accurate: a good thing to do

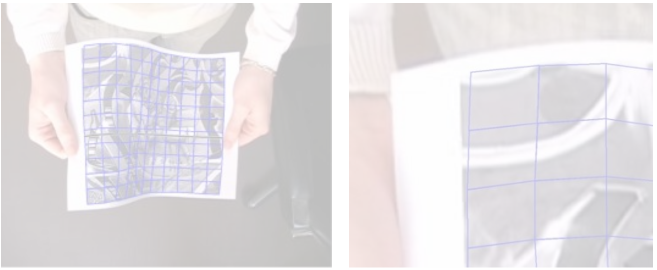
Nonconvex: requires initialization

Using Features to Initialize and Color to Refine

1 - Feature-based wide-baseline initialization



2 - Feature-based densification (convex)

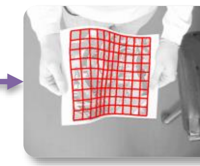


3 - Color-based refinement (non-convex)

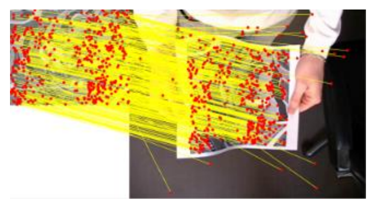
Image Registration, in a Nutshell

1 – Image registration

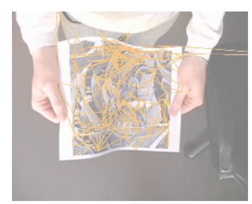
Find Warp $\eta \in C^2(\Omega, \mathbb{R}^2)$ s.t.  =  $\circ\, \eta$



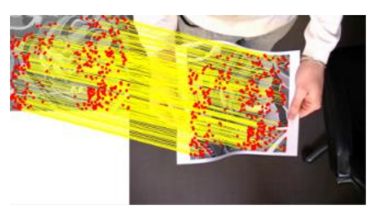
1 Putative keypoint matches
[Lowe, IJCV'04]



Densification with TPS
[Bookstein, PAMI'89]



2 Local consistency
[Pizarro et al, IJCV'12]



[Schmid et al, PAMI'97]

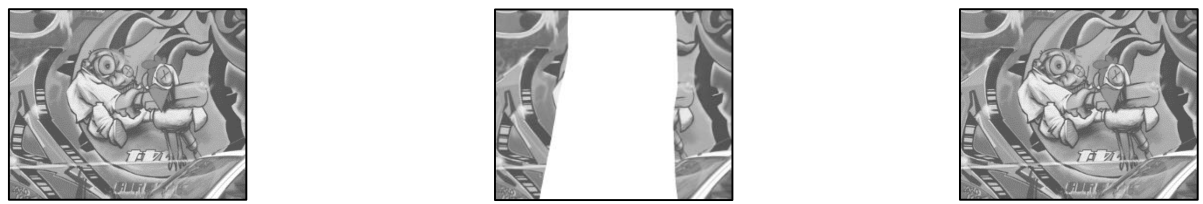
Template
not found

Image Registration, in a Nutshell

2 Local consistency
[Pizarro et al, IJCV'12]

3 Densification
[Bookstein, PAMI'89]

4 Partial self-occlusion detection
[Pizarro et al, IJCV'12]



5 Self-occlusion aware densification
[Pizarro et al, IJCV'12]

6 Color-based refinement
[Gay-Bellile et al, PAMI'10]

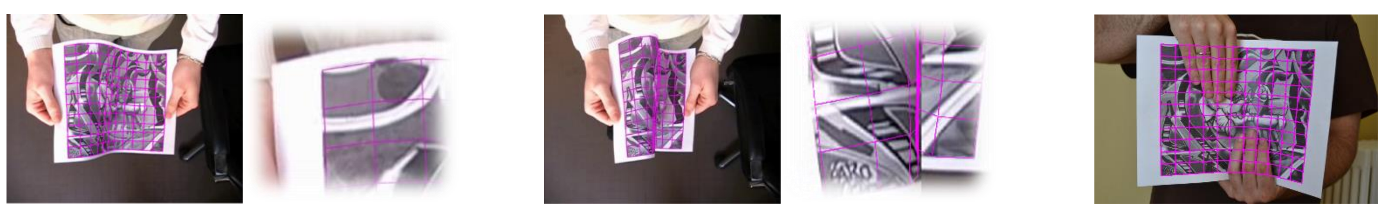


Image Registration, Results

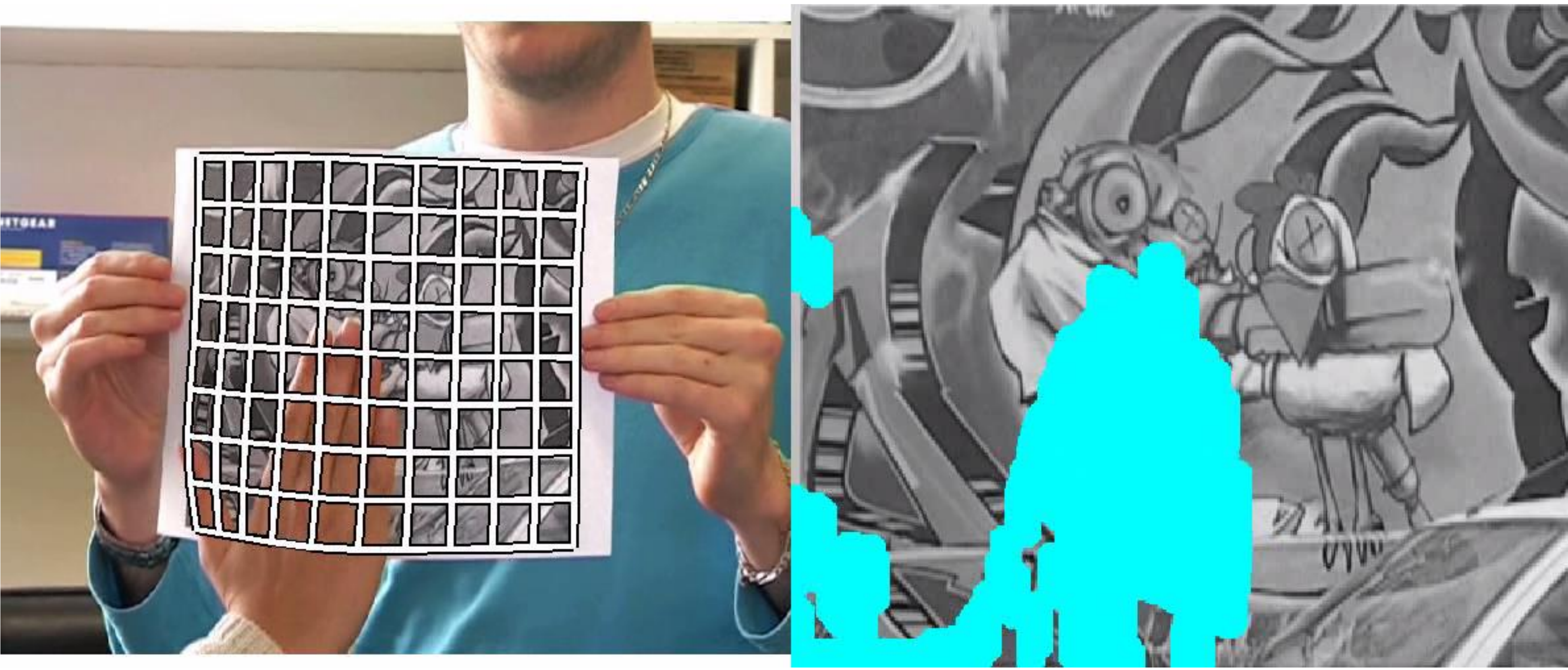
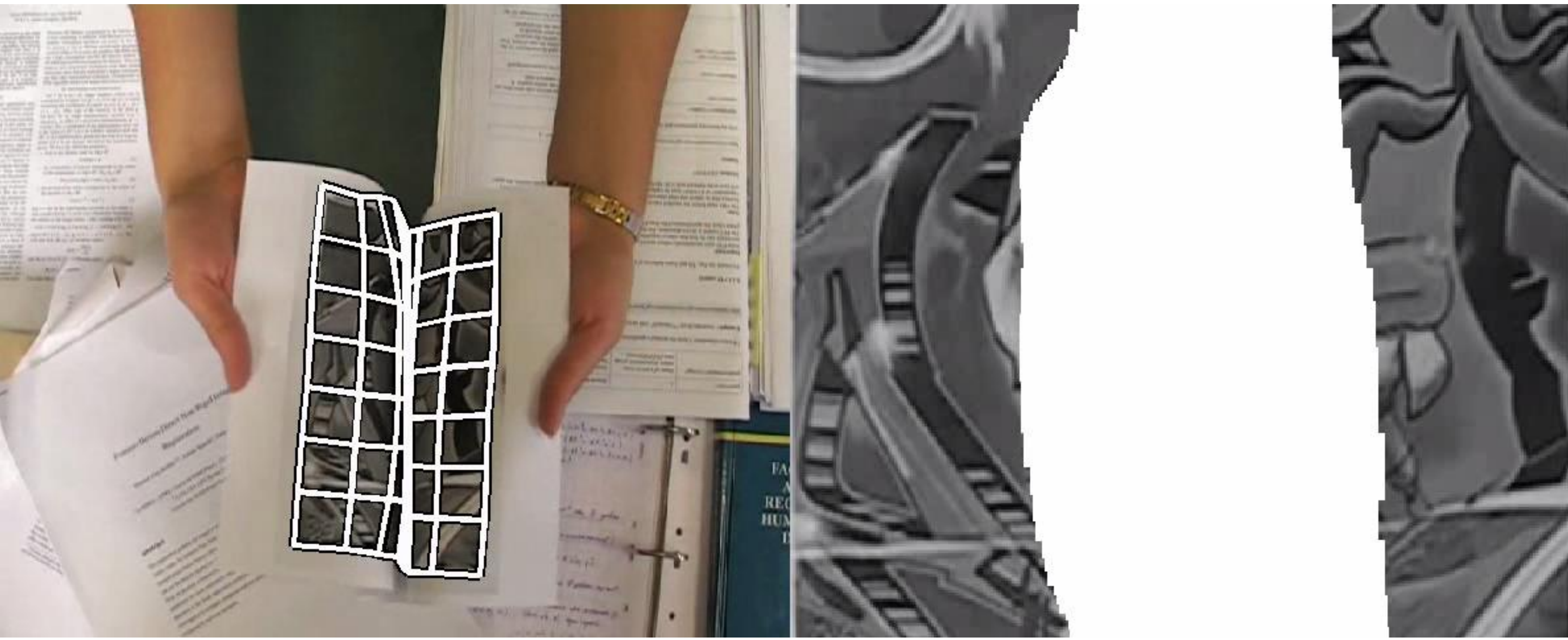


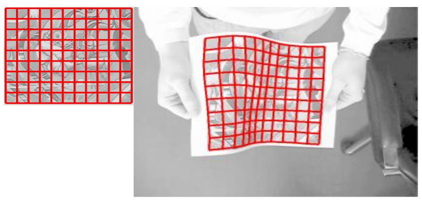
Image Registration, Results



Lecture's Plan

$\varphi, \nabla\varphi$

1. Modeling



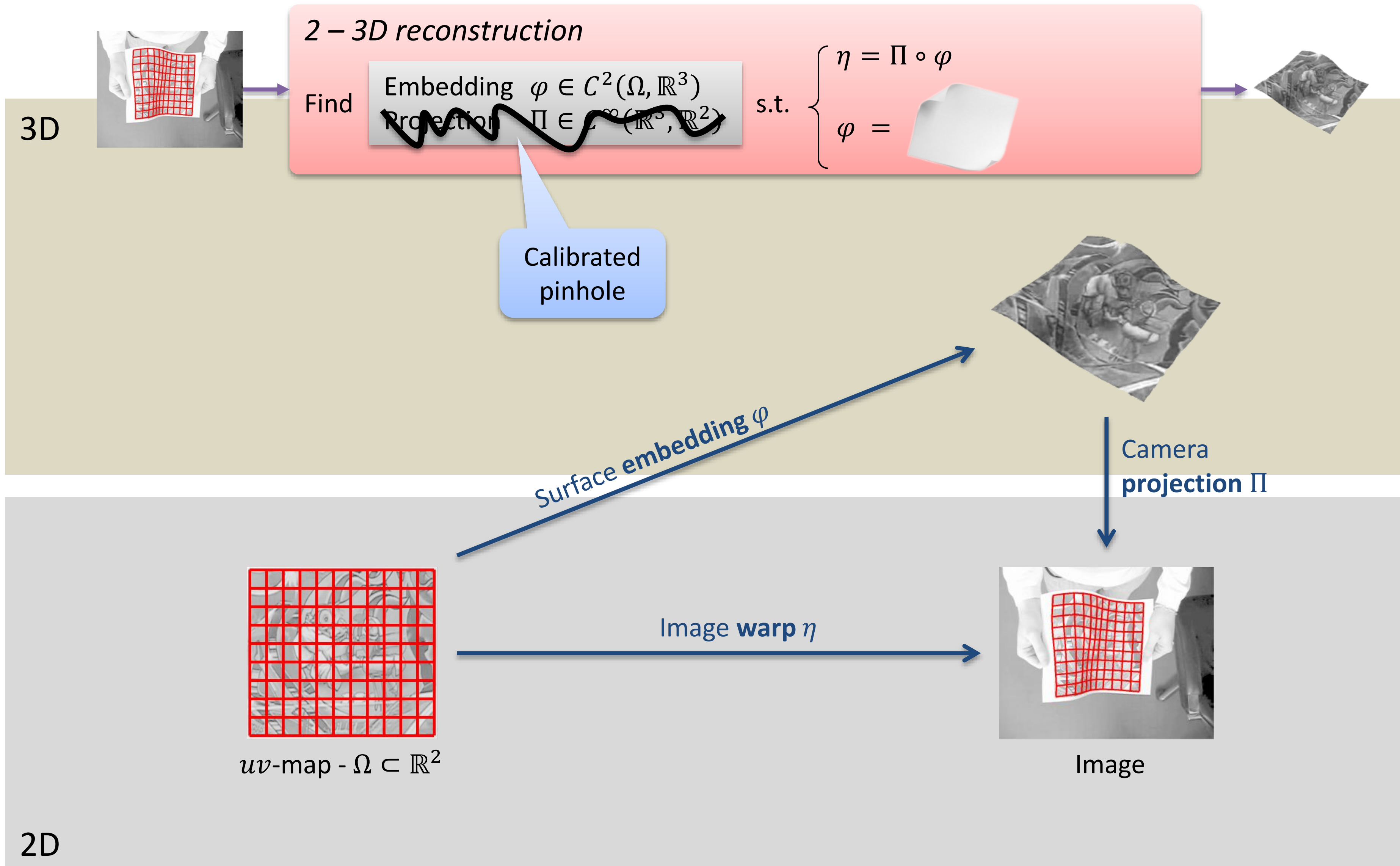
2. Registration

3. **Reconstruction**

4. More examples, applications

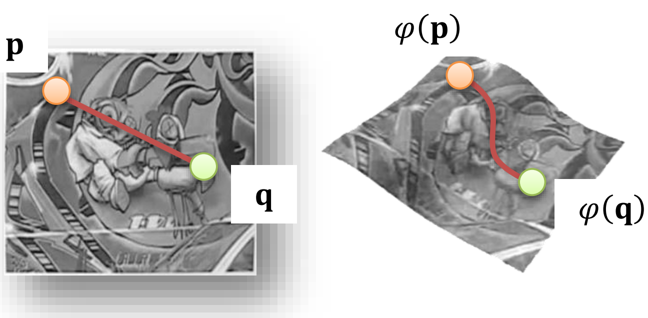
5. Discussion, future work

Step 2: 3D Reconstruction

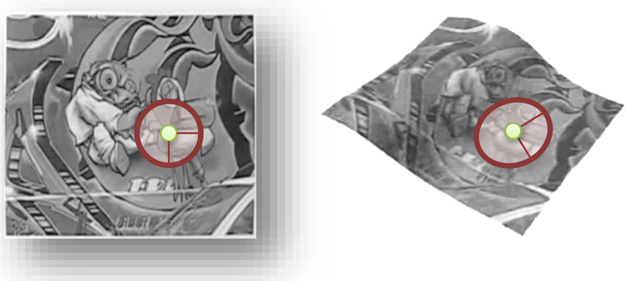


Thin-Shell Isometry

$\Rightarrow \varphi =$ 



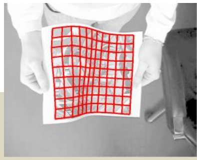
For φ continuous
$d(\mathbf{p},\mathbf{q}) = d_G(\varphi(\mathbf{p}),\varphi(\mathbf{q}))$ on Ω^2



For φ differentiable
$\nabla\varphi^\top\nabla\varphi = \mathrm{I}$ on Ω

[Perriollat et al, IJCV'11; Salzmann et al, PAMI'11]

Zeroth Order Methods



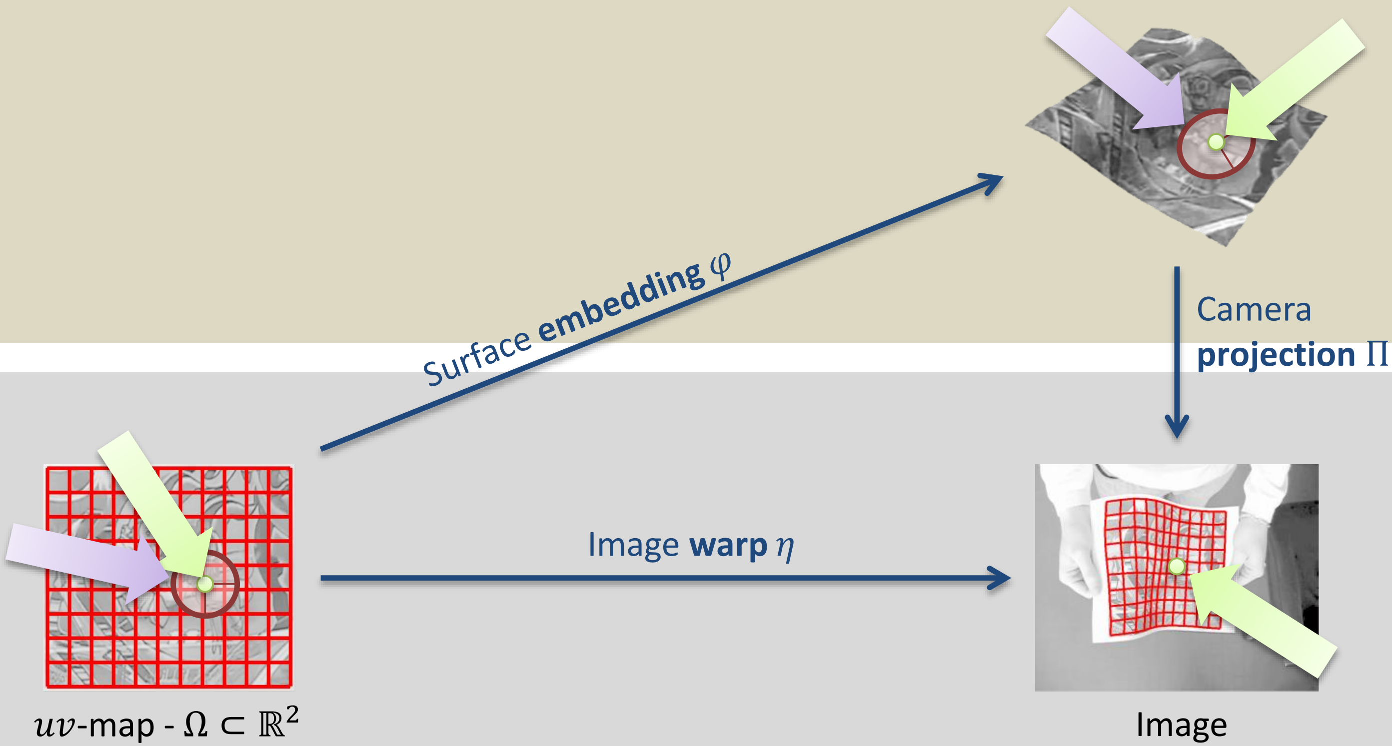
2 – 3D reconstruction

Find
Embedding $\varphi \in C^2(\Omega, \mathbb{R}^3)$
~~Projection $\Pi \in C^\infty(\mathbb{R}^3, \mathbb{R}^2)$~~
s.t.
$$\begin{cases} \eta = \Pi \circ \varphi \\ \nabla\varphi^\top \nabla\varphi = \mathrm{I} \end{cases}$$

Zeroth order reprojection

Isometry

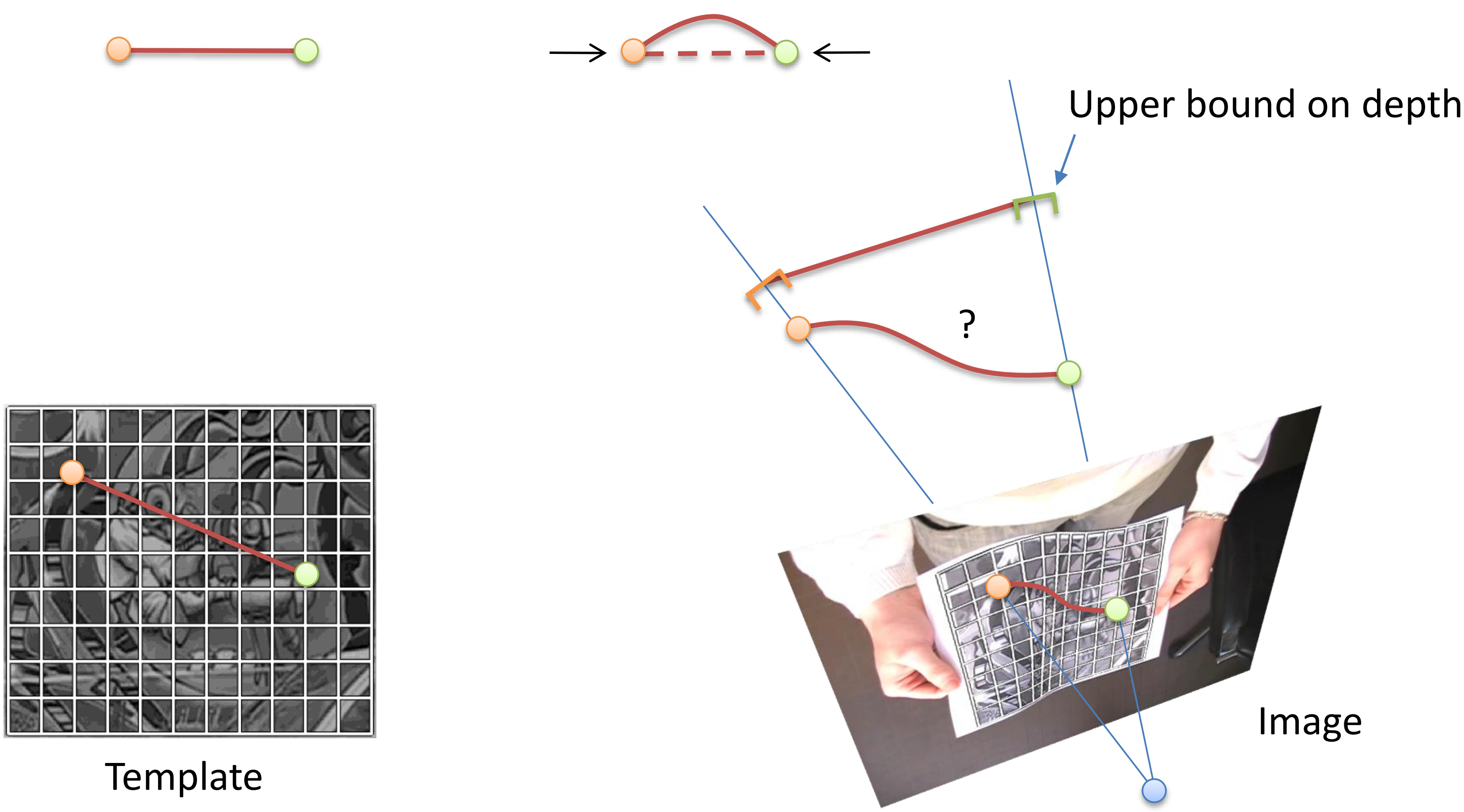
3D



2D

Main result: shape-wise solution of a convex relaxation
[Perriollat et al, IJCV'11; Salzmann et al, PAMI'11; Brunet et al, CVIU'14; Östlund et al, ECCV'12]

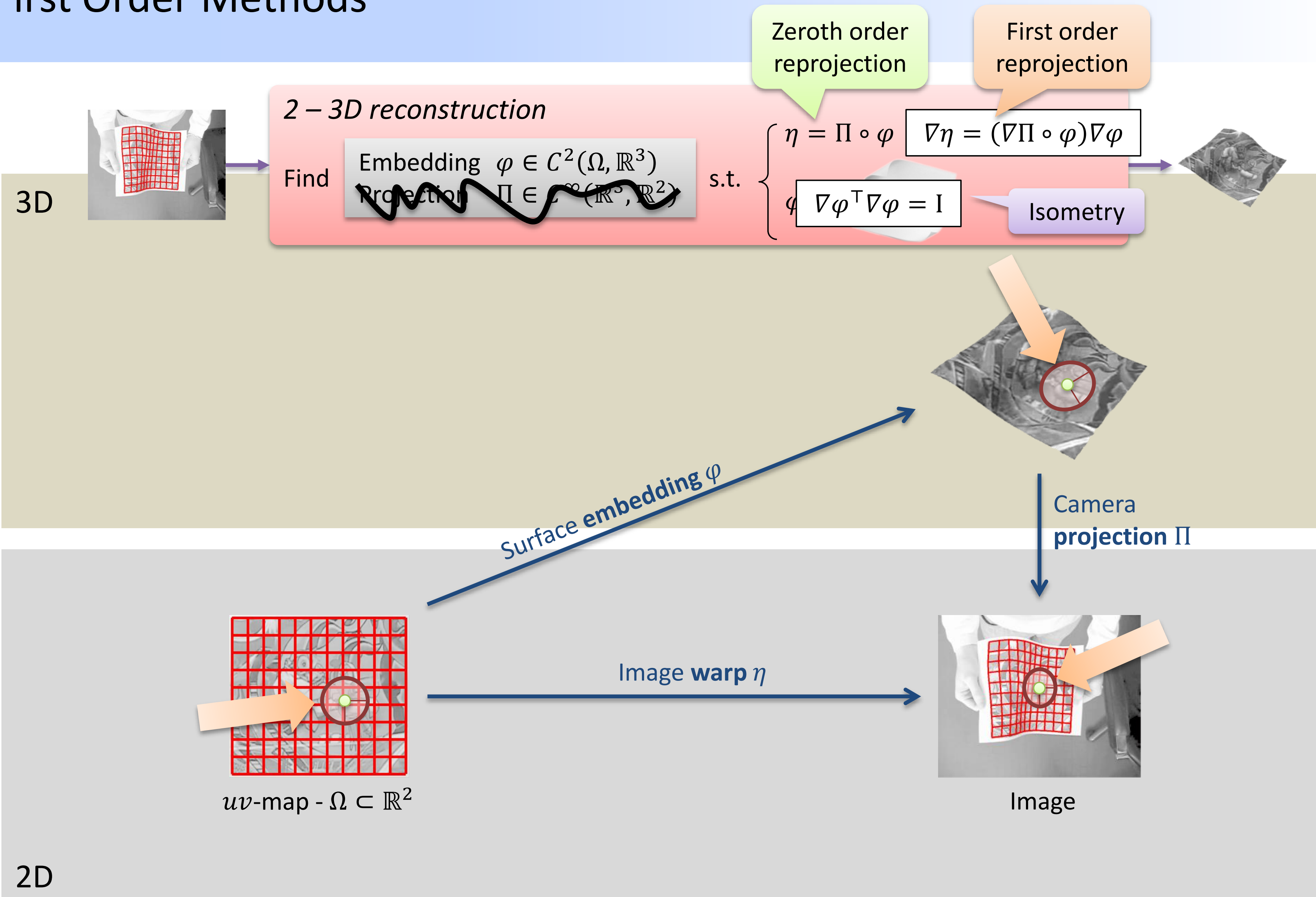
Zeroth Order Methods: Inextensibility Relaxation and the Maximum Depth Heuristic



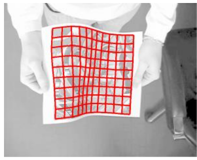
This translates to SOCP but does not extend to other types of deformation

[Bartoli et al, CVPR'12]

First Order Methods



First Order Methods



2 – 3D reconstruction

Find Embedding $\varphi \in C^2(\Omega, \mathbb{R}^3)$ ~~Projection $\Pi \in C^\infty(\mathbb{R}^3, \mathbb{R}^2)$~~ s.t.

$$\begin{cases} \eta = \Pi \circ \varphi & \boxed{\nabla\eta = (\nabla\Pi \circ \varphi)\nabla\varphi} \\ \boxed{\nabla\varphi^\top \nabla\varphi = \mathrm{I}} \end{cases}$$

Zeroth order reprojection

First order reprojection

Isometry

Let $\gamma \in C^1(\Omega, \mathbb{R})$ be the **depth function**

3D reconstruction is rewritten as a **first-order quadratic PDE system in $\boldsymbol{\gamma}$**

$$\|\tilde{\eta}\|_2^2 \nabla\gamma^\top \nabla\gamma + \gamma^2 \nabla\eta^\top \nabla\eta + \gamma(\nabla\gamma^\top \eta^\top \nabla\eta + \nabla\eta^\top \eta \nabla\gamma) = \mathrm{I}$$

Main result: exact point-wise non-holonomic solution

Implication: isometric Shape-from-Template is uniquely solvable in perspective imaging and solvable up to discrete ambiguities in affine imaging

[Bartoli et al, CVPR 2012, PAMI 2015]

First Order Methods

Isometric developable

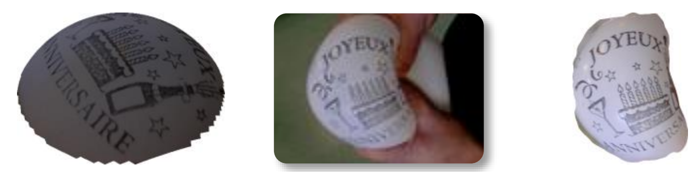
$$\|\tilde{\eta}\|_2^2 \nabla\gamma^\top \nabla\gamma + \gamma^2 \nabla\eta^\top \nabla\eta + \gamma(\nabla\gamma^\top \eta^\top \nabla\eta + \nabla\eta^\top \eta \nabla\gamma) = \mathrm{I}$$

Isometric non-developable object

$$\|\tilde{\eta}\|_2^2 \nabla\gamma^\top \nabla\gamma + \gamma^2 \nabla\eta^\top \nabla\eta + \gamma(\nabla\gamma^\top \eta^\top \nabla\eta + \nabla\eta^\top \eta \nabla\gamma) = \nabla\Delta^\top \nabla\Delta$$

Conformal

$$\|\tilde{\eta}\|_2^2 \nabla\gamma^\top \nabla\gamma + \gamma^2 \nabla\eta^\top \nabla\eta + \gamma(\nabla\gamma^\top \eta^\top \nabla\eta + \nabla\eta^\top \eta \nabla\gamma) = \nu \nabla\Delta^\top \nabla\Delta$$



Isometric (infinitesimal) weak-perspective

$$(\|\nabla\gamma\|_2^2 + \gamma^2) \nabla\eta \nabla\eta^\top + \alpha^2 \nabla\gamma^\top \nabla\gamma = \nu \nabla\Delta^\top \nabla\Delta$$

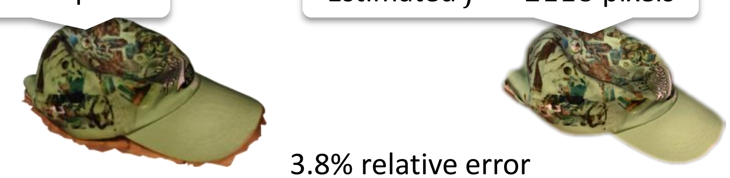
$f = 5870$ pixels

Isometric, unknown focal length

$$(f^2 \|\nabla\gamma\|_2^2 + \gamma^2) \nabla\eta \nabla\eta^\top + \alpha^2 \nabla\gamma^\top \nabla\gamma = \nu \nabla\Delta^\top \nabla\Delta$$

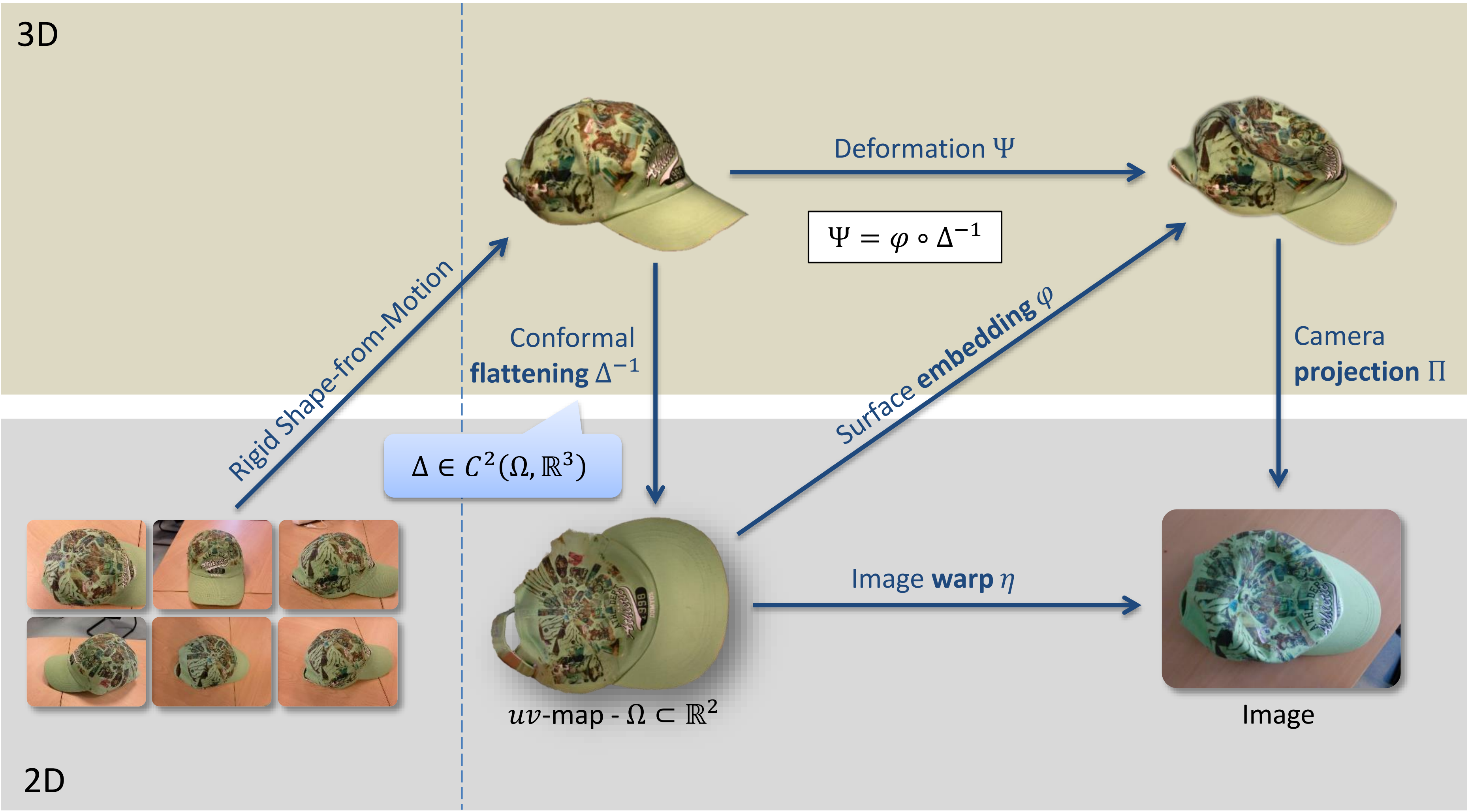
‘true’ $f = 2040$ pixels

Estimated $f = 2118$ pixels



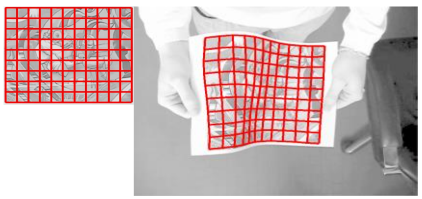
3.8% relative error

Non-flattenable Objects



Lecture’s Plan

$\varphi, \nabla\varphi$ 1. Modeling



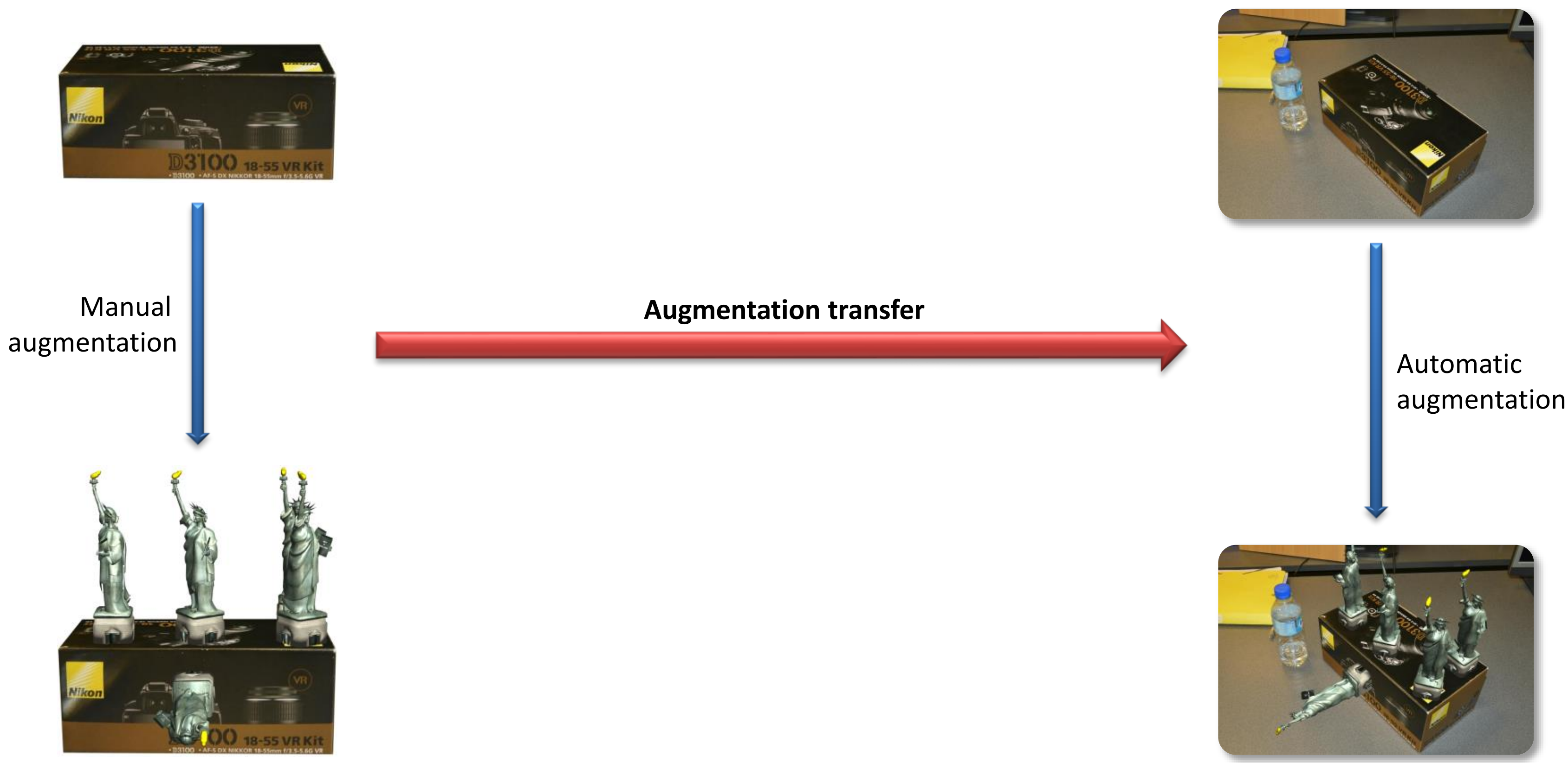
2. Registration

3. Reconstruction

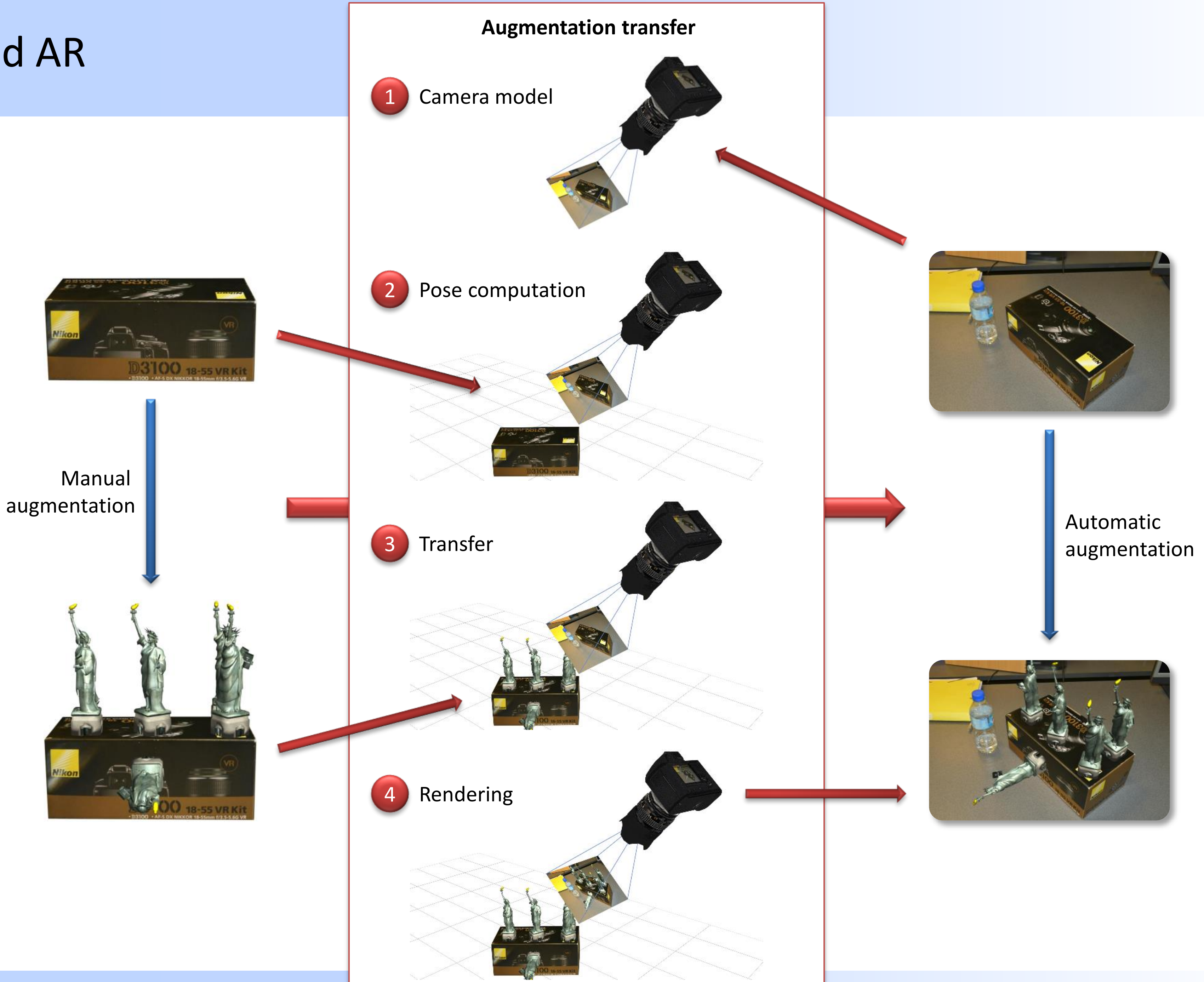
4. More examples, applications

5. Discussion, future work

Rigid AR

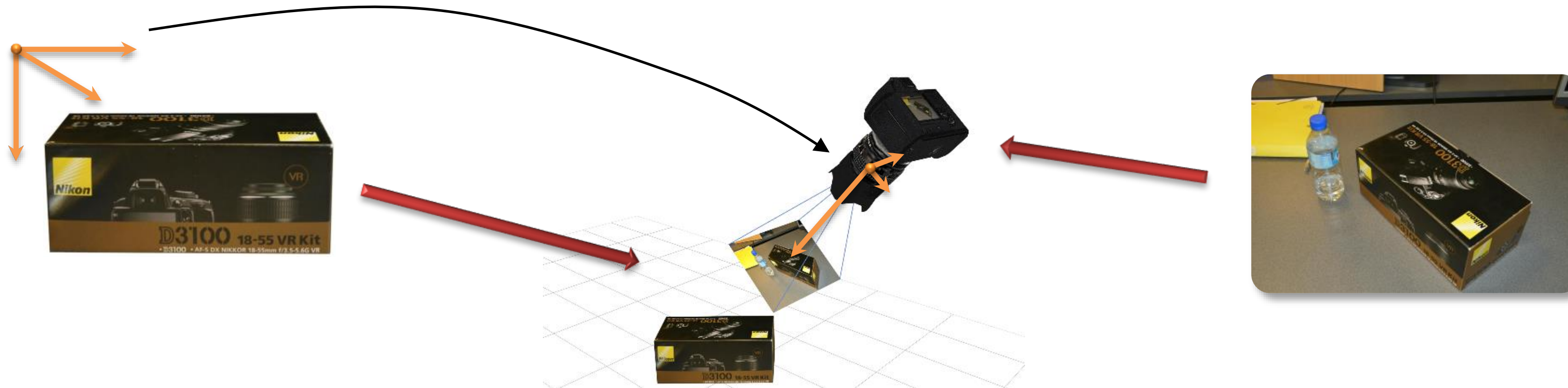

Nikon
D3100 18-55 VR Kit
Manual augmentation
Augmentation transfer
Automatic augmentation

Rigid AR


Augmentation transfer
1 Camera model
2 Pose computation
3 Transfer
4 Rendering
Manual augmentation
Automatic augmentation

Pose: 6 parameters

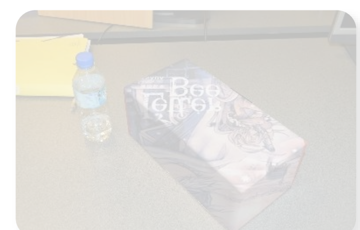
$$\mathbf{R} \in SO^3, \mathbf{t} \in \mathbb{R}^3$$



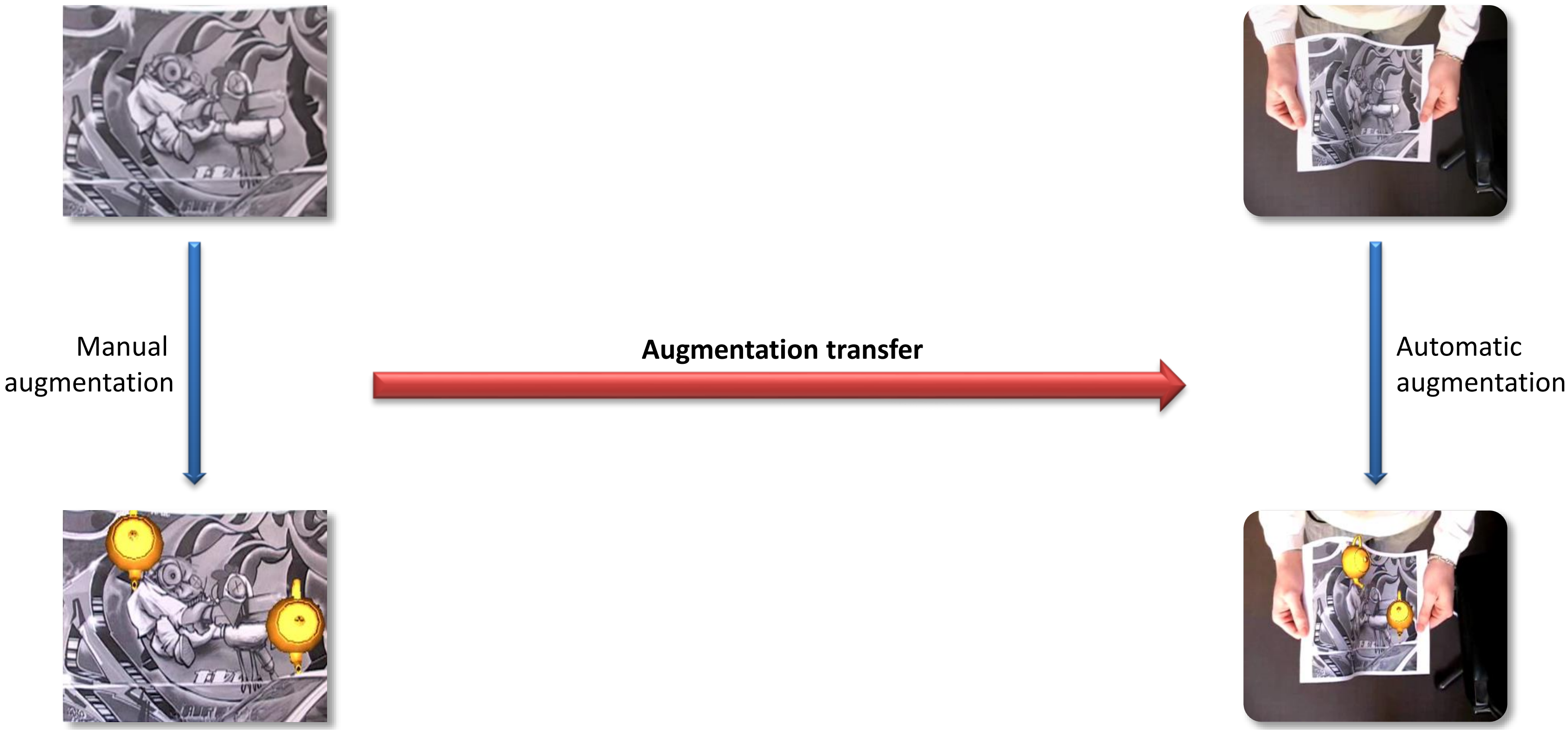
Computation tools:
- Keypoints
- Homographies
- RANSAC

Gives:
- Correspondence
- 3D shape

Facilitates:
- Retexturing
- Augmentation

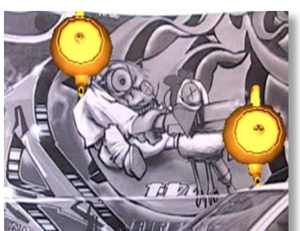


Deformable AR

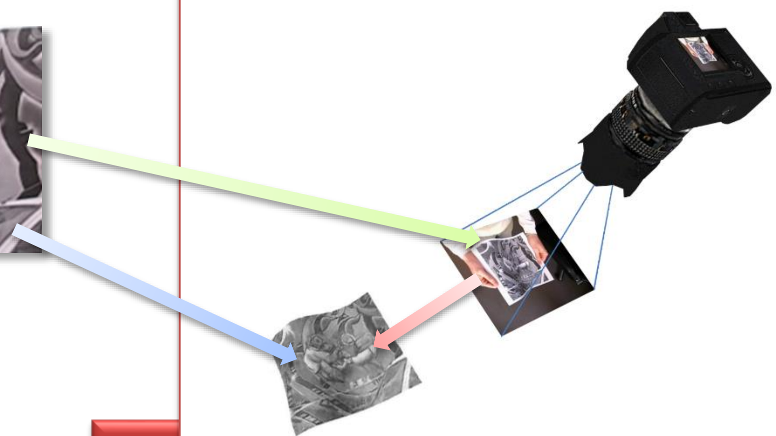


Deformable AR

Manual augmentation



Augmentation transfer

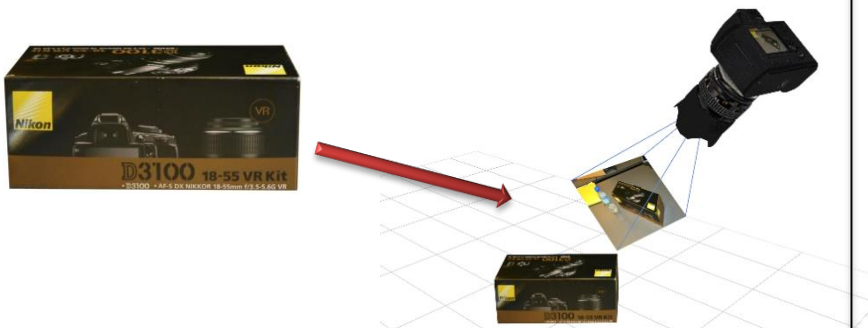


Automatic augmentation

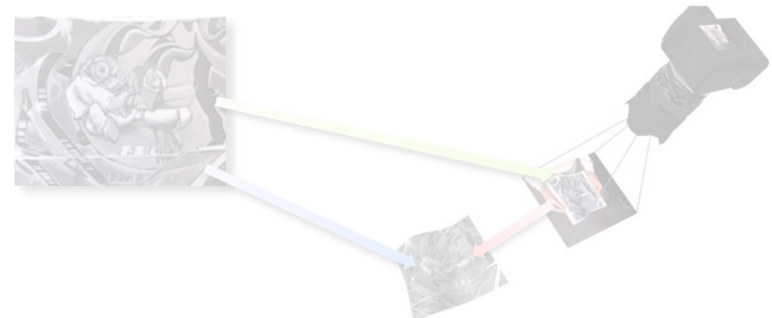
Problem 1: registration (aka matching, alignment)
Matching the fixed reference to the current frame

Problem 2: 3D reconstruction
Finding the object's shape for the current frame

Rigid vs Deformable AR

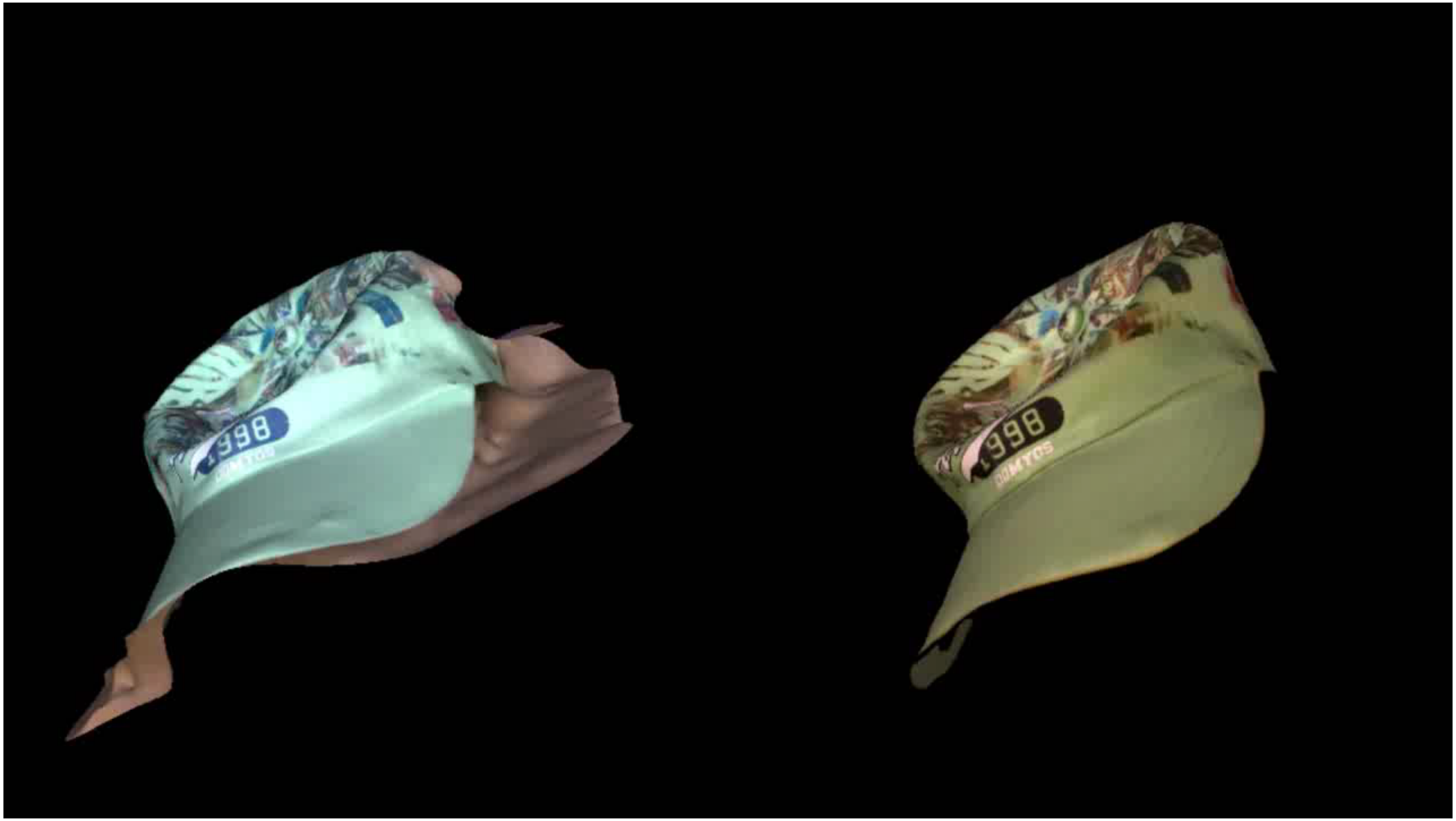


The 6 pose parameters is all we need



- Pose is not computable
- Registration and reconstruction are coupled but different
- They both have many parameters

Reconstruction

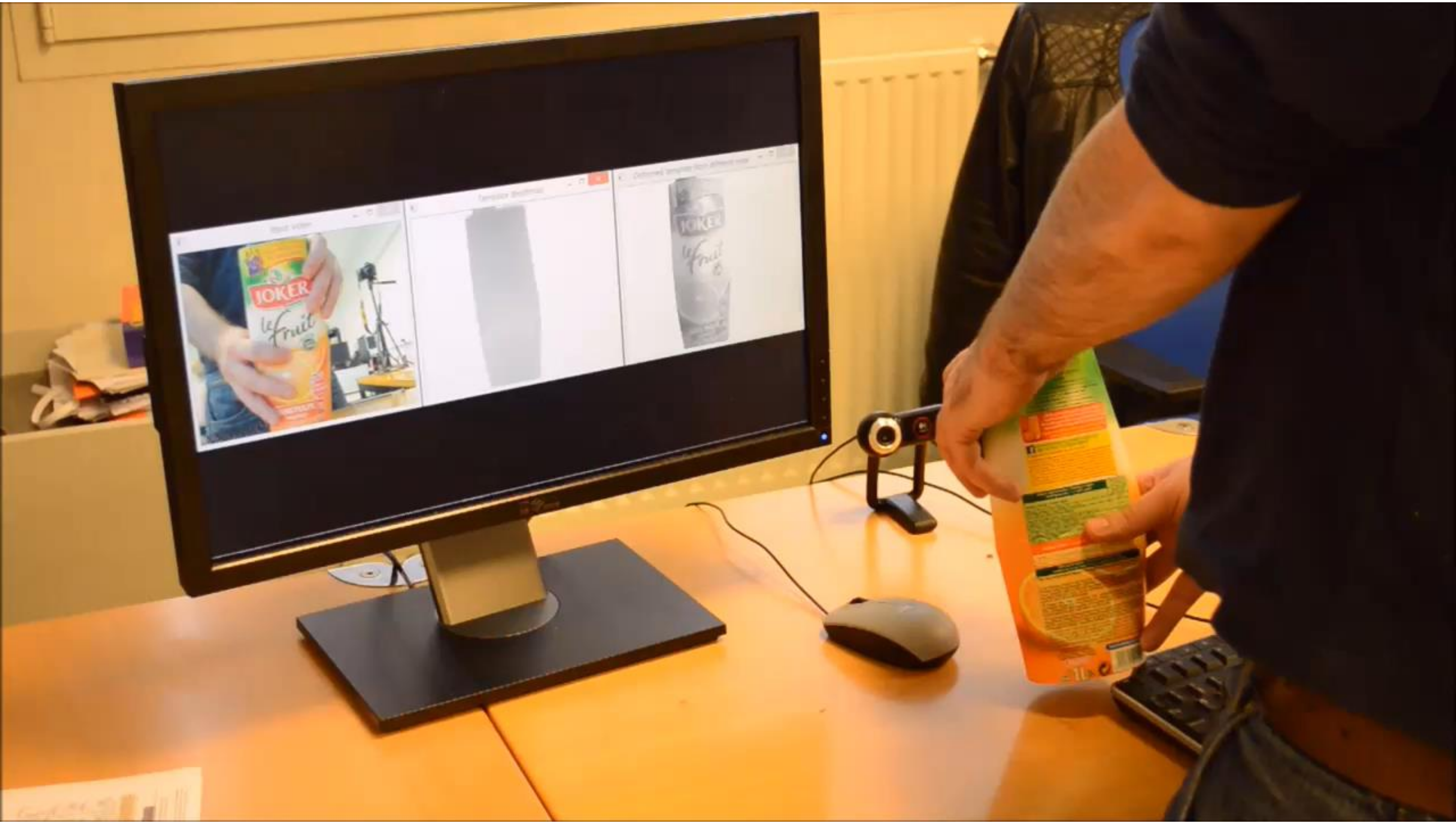


Ground-truth
(Rigid Shape-from-Motion)

Shape-from-Template

Augmentation

Real-Time Reconstruction

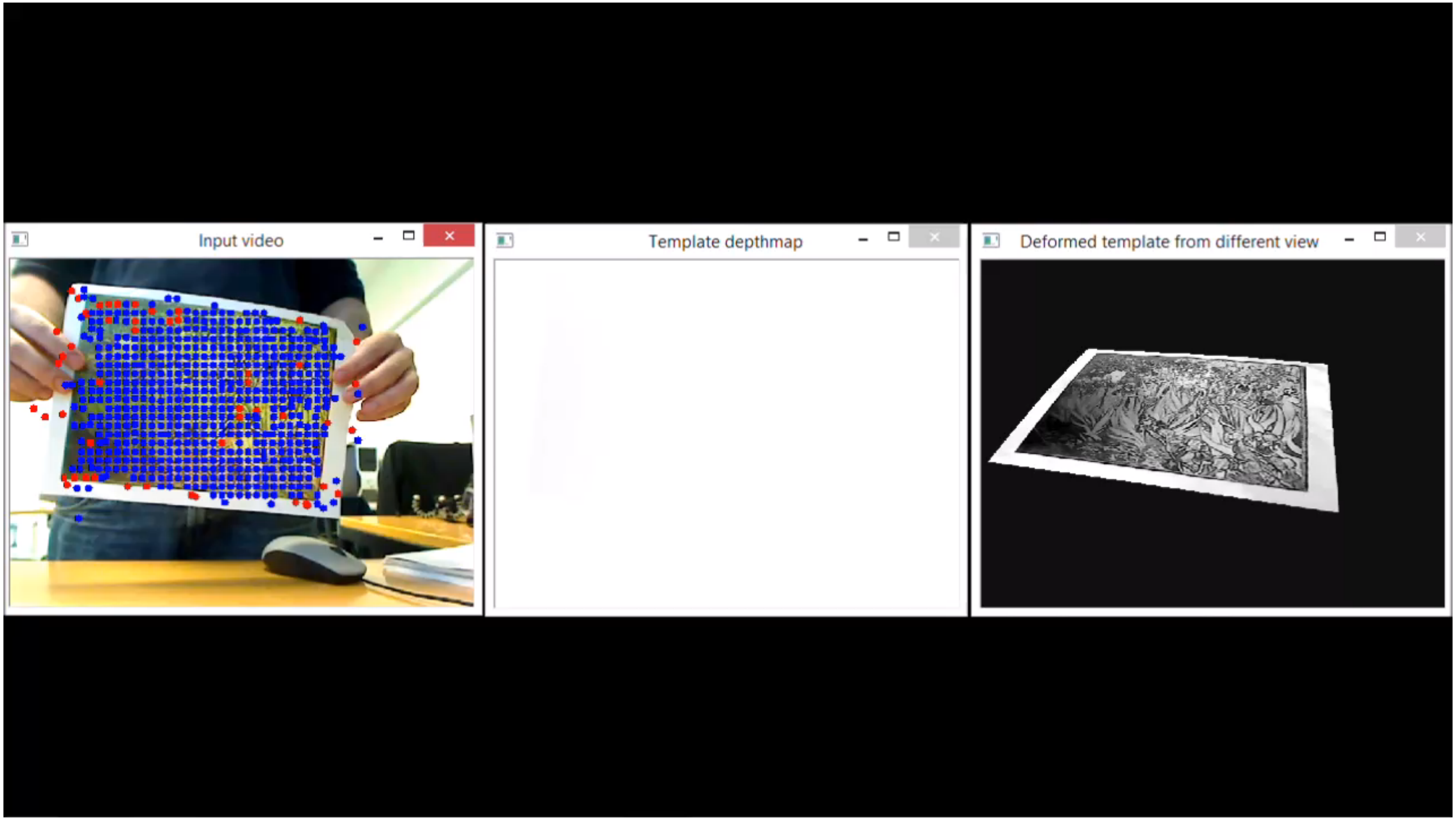


Human-Computer Interaction, Template

Material

256 vertices, 450 facets

Human-Computer Interaction



21 fps, Nvidia GTX 1500 cores

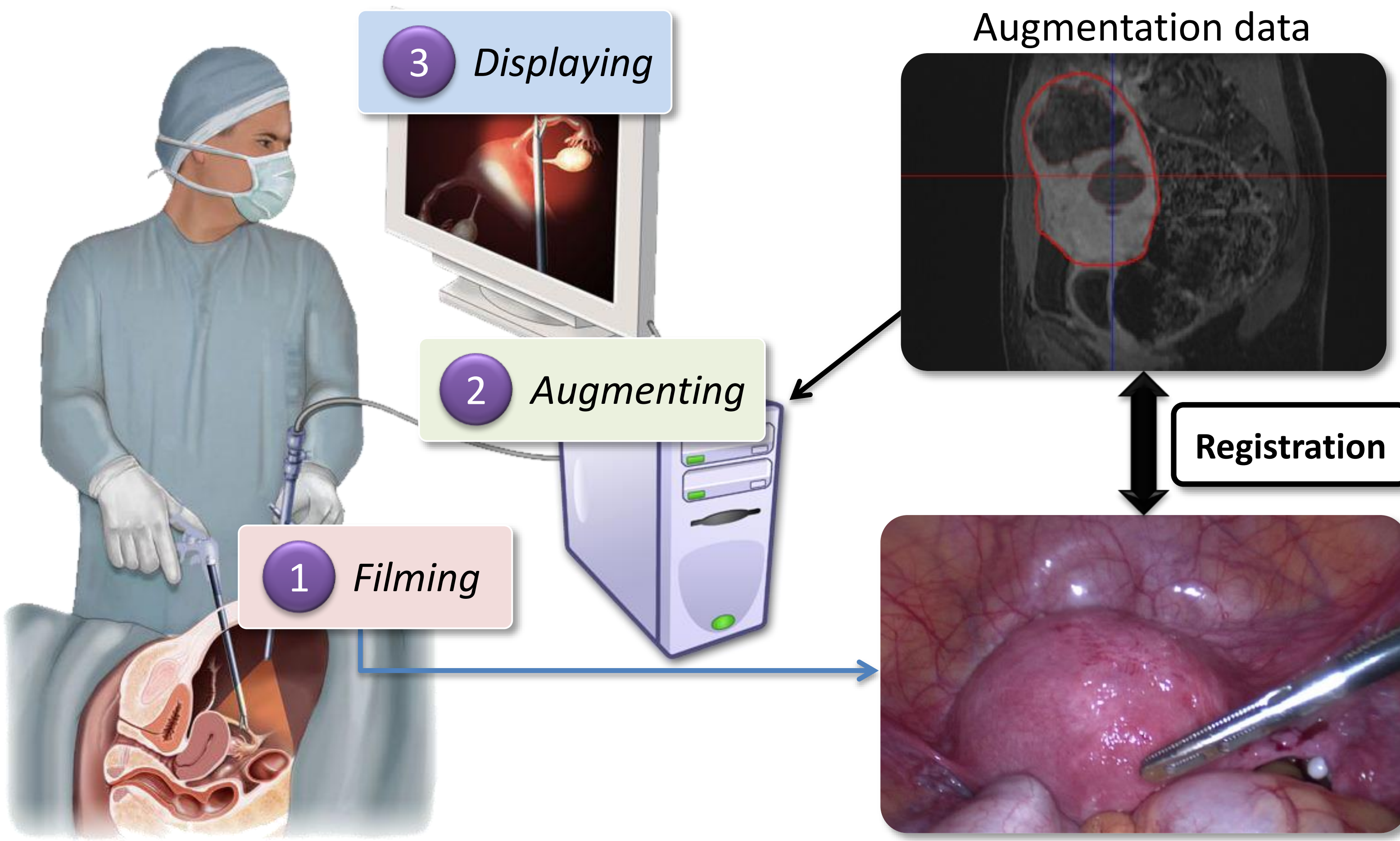
Human-Computer Interaction

Non-Isometric Deformation

Conformal deformation

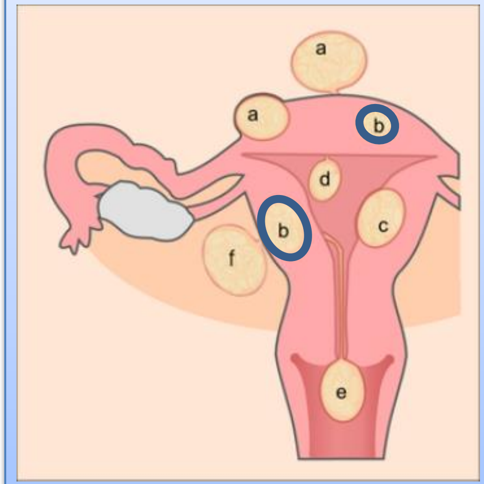
Linear elasticity [Malti et al, CVPR 2013, CVPR 2015 ; Haouchine et al, ISMAR 2014]
Learnt shape model and shading [Moreno et al, CVPR 2009]

Laparoscopic Augmented Reality

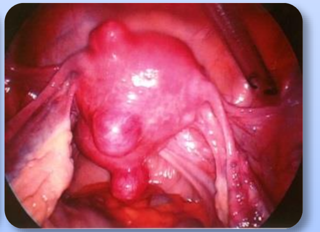


Uterine Fibroids or Myomas

Benign tumors from the myometrium

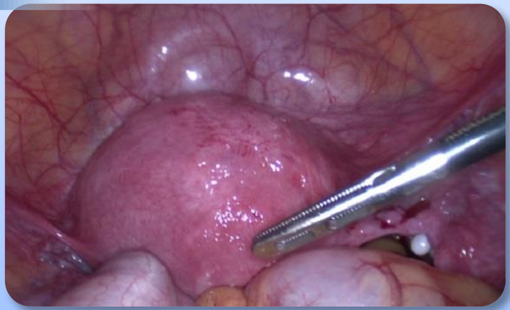


- Microscopic to extremely large size
- Often several of them

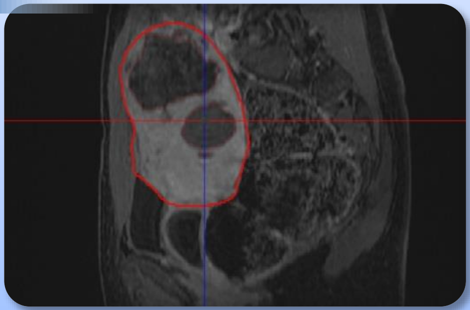


Intramural myomas (type b)

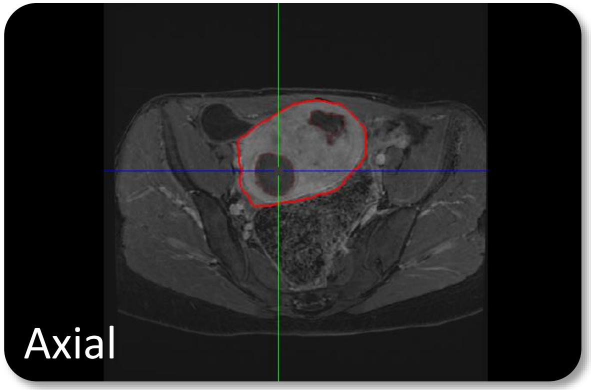
May be invisible in laparoscopy (and hysteroscopy)

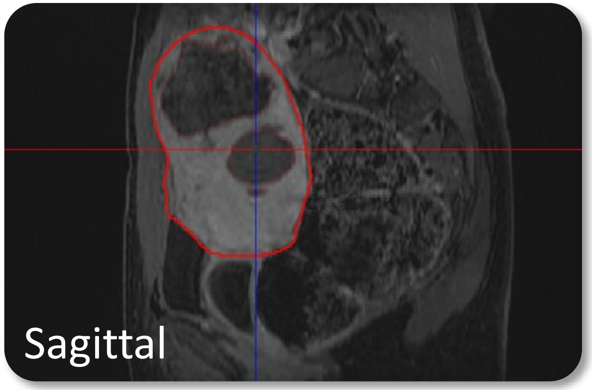


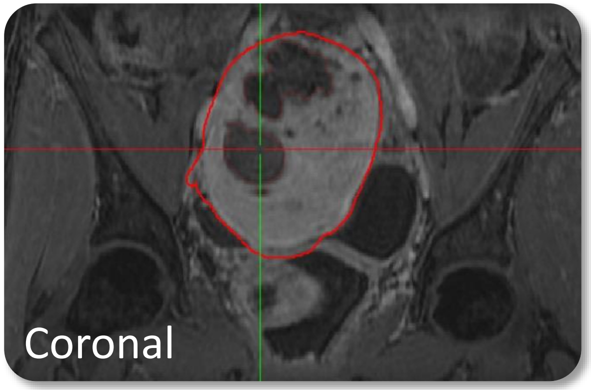
Clearly visible in MRI

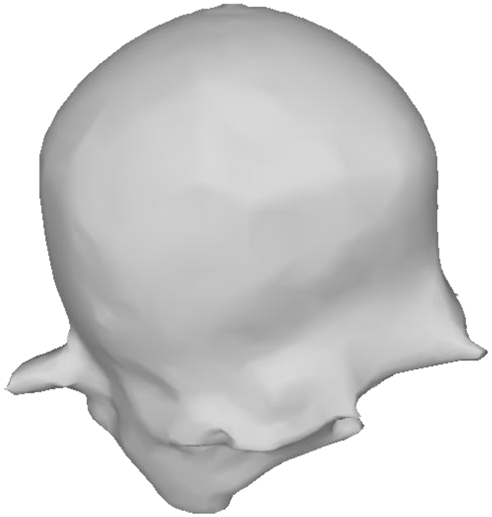


Preoperative MRI Preparation

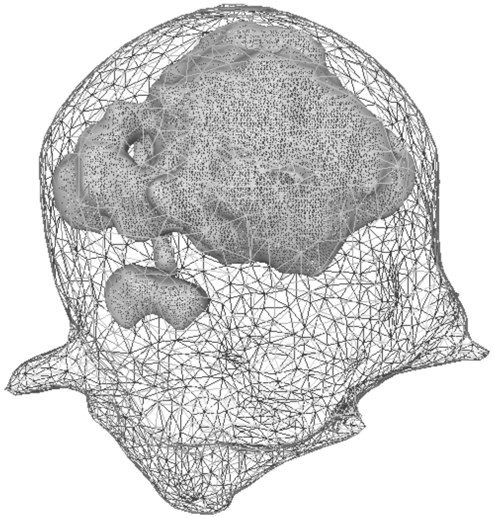




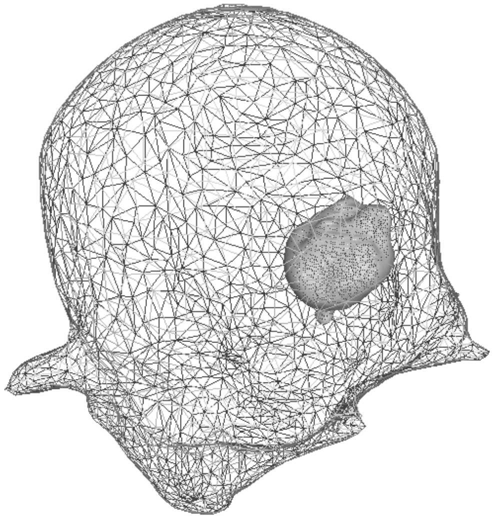




Uterus surface



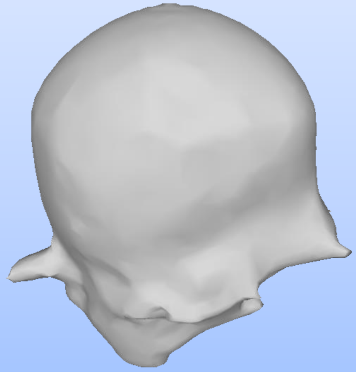
First fibroid



Second fibroid

Augmented Reality Framework

1 Registration

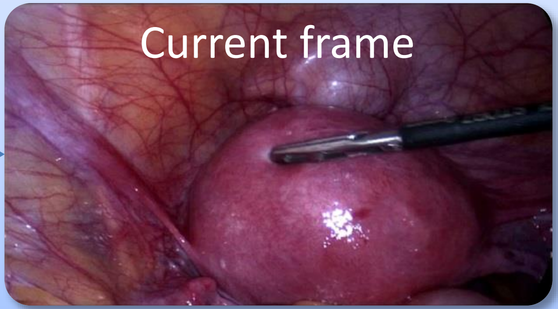


Requirements:

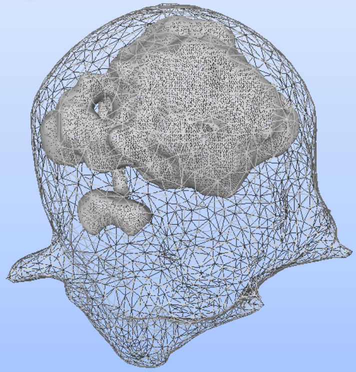
R1 – deformable　　R2 – multimodal

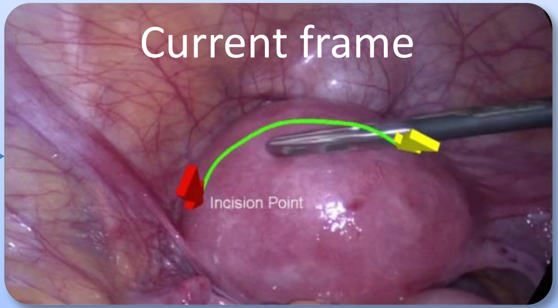
R3 – realtime　　R4 – automatic

Registration $\Phi_i : \mathbb{R}^3 \rightarrow \mathbb{R}^2$



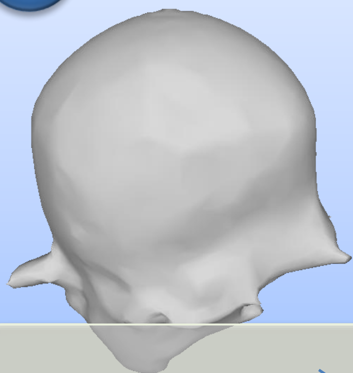
2 Augmentation



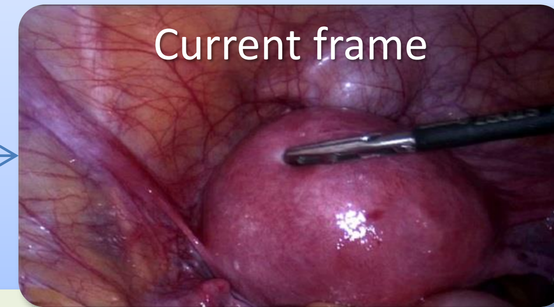


Two-Step Registration

1 Registration



Requirements:
R1 – deformable   R2 – multimodal
R3 – realtime   R4 – automatic



Registration $\Phi_i : \mathbb{R}^3 \rightarrow \mathbb{R}^2$

Relax requirements with $\Phi_i = \Gamma_i \circ \Gamma_0$

$\Gamma_0 : \mathbb{R}^3 \rightarrow \mathbb{R}^3$

$\Gamma_i : \mathbb{R}^3 \rightarrow \mathbb{R}^2$

Requirements: (R1), R3, R4

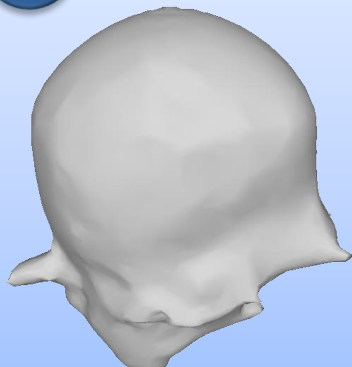
1a Preoperative to intraoperative reference

1b Intraoperative reference to current frame

[Collins et al, ISMAR 2014]

WBMTR (Wide-Baseline Multi-Texturemap Registration)

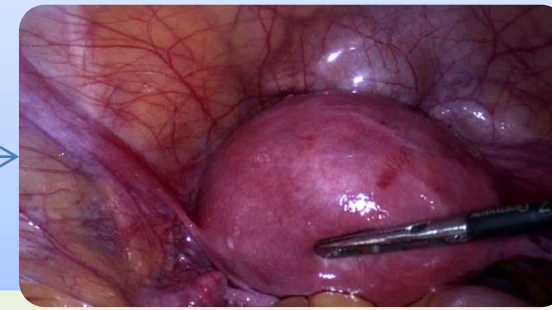
1 Registration



Requirements:

R1 – deformable | R2 – multimodal

R3 – realtime | R4 – automatic



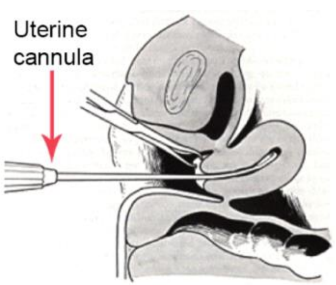
Registration $\Phi_i: \mathbb{R}^3 \rightarrow \mathbb{R}^2$

Relax requirements with $\Phi_i = \Gamma_i \circ \Gamma_0$

$\Gamma_0: \mathbb{R}^3 \rightarrow \mathbb{R}^3$

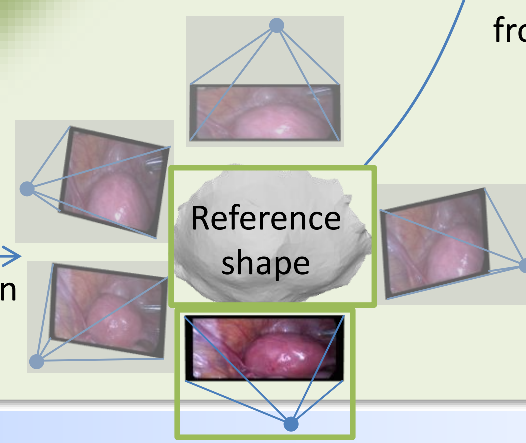
$\Gamma_i: \mathbb{R}^3 \rightarrow \mathbb{R}^2$

Pose with keypoints from best reference frame



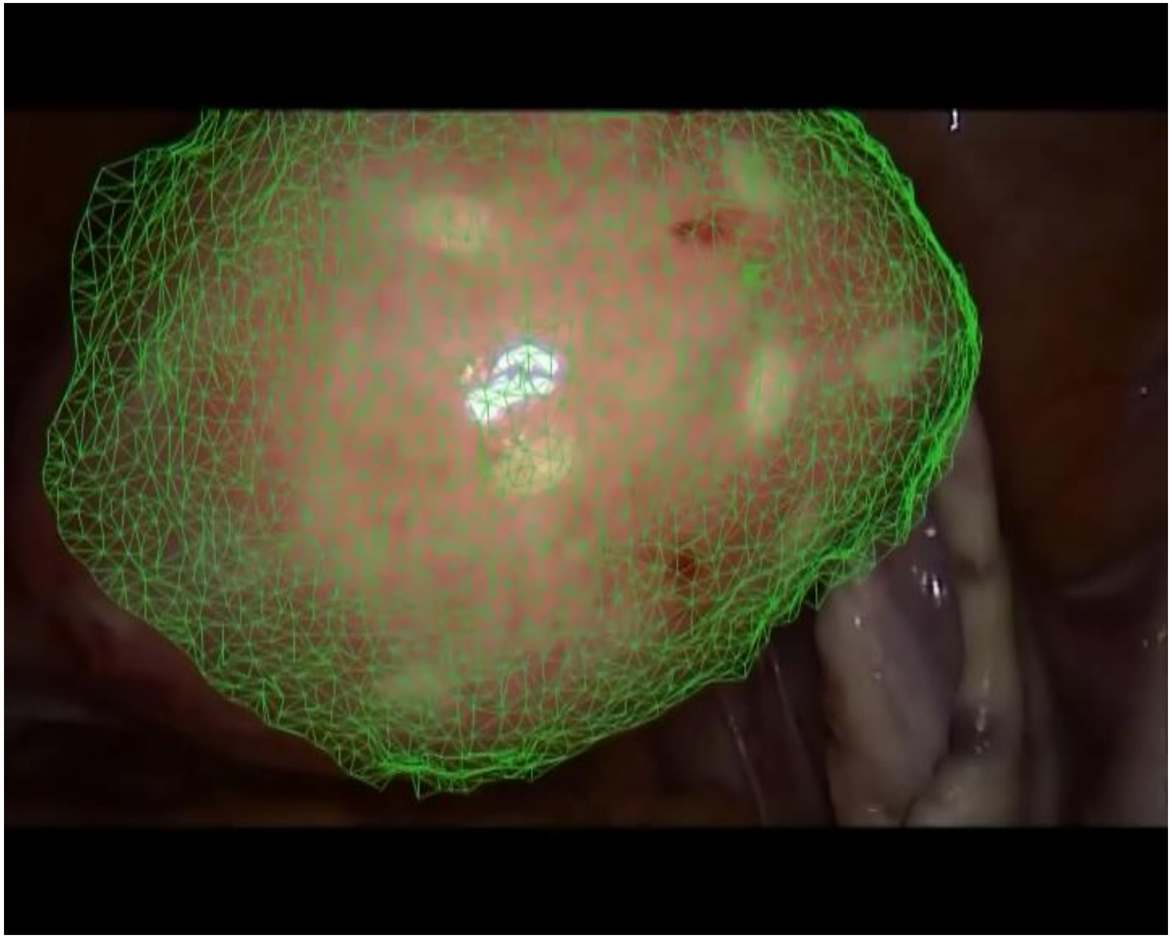
Reference frames

Shape-from-Motion

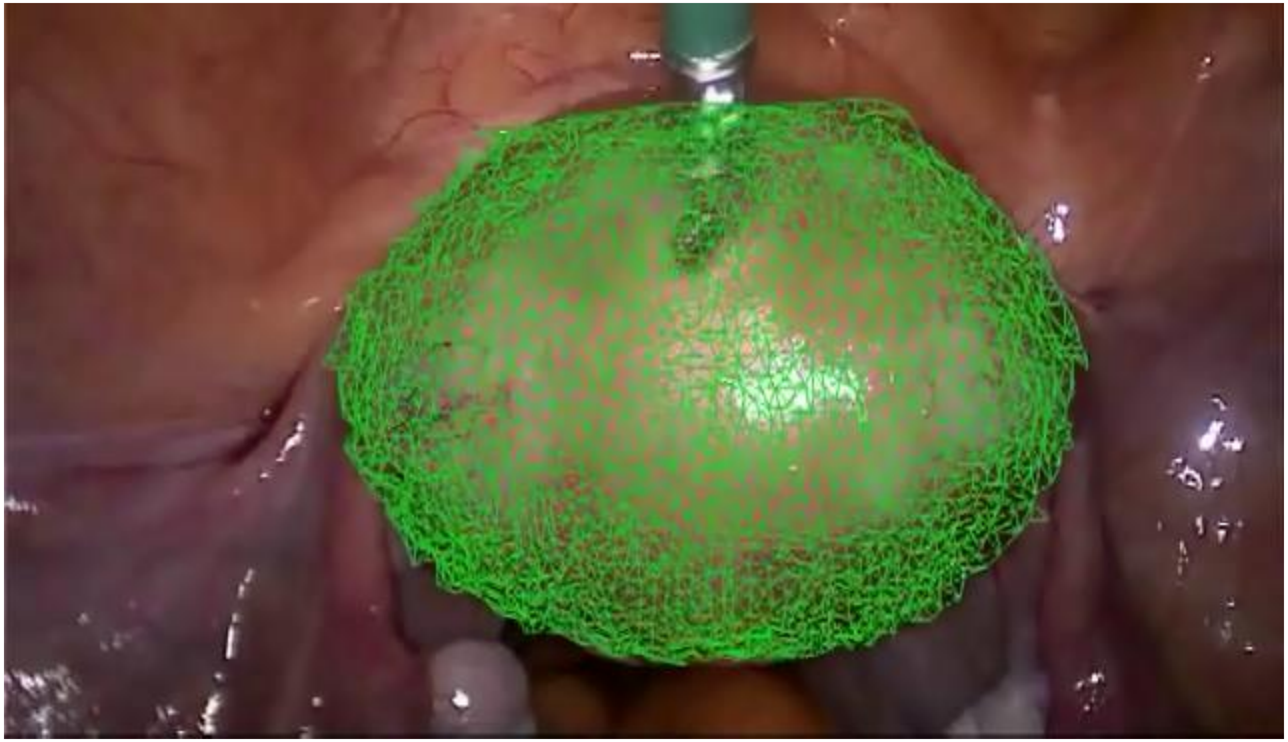


[Collins *et al*, MIAR@MICCAI'13]

WBMTR Registration Results

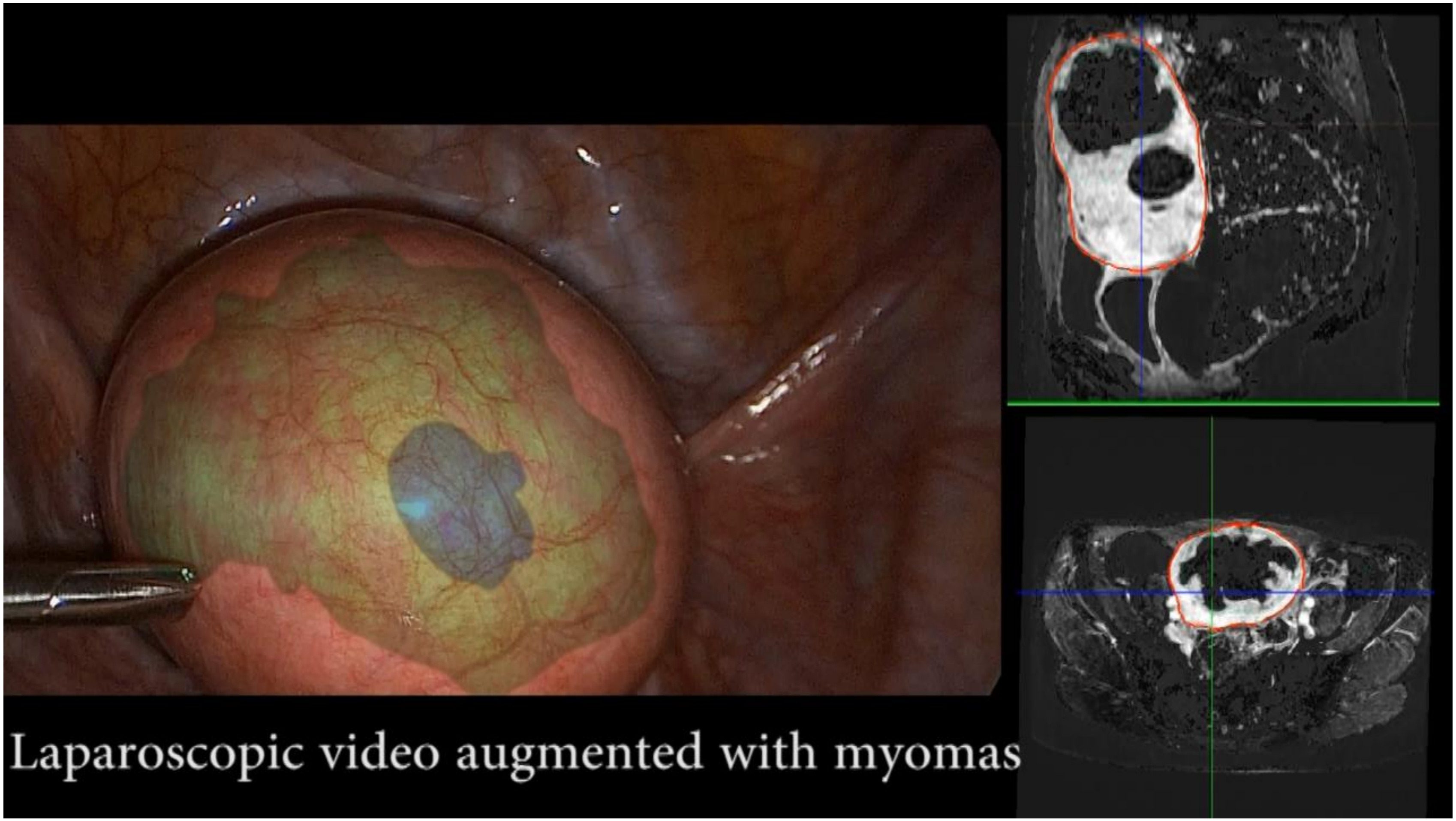


WBMTR Registration Results



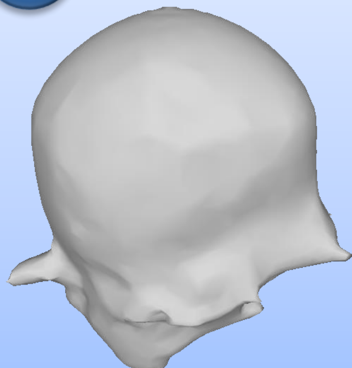
AR-Aided Laparoscopic Myomectomy: Phantom Results

AR-Aided Laparoscopic Myomectomy: Patient-data Results



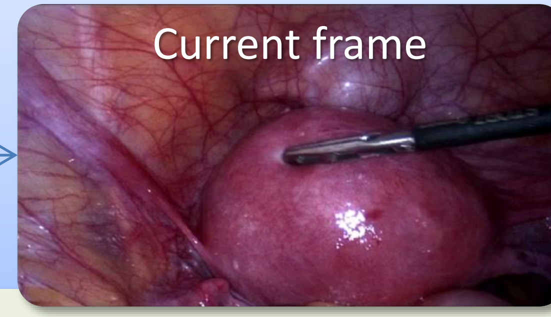
Generalizing Rigid Pose to Deformations

1 Registration



Requirements:

- R1 – deformable
- R2 – multimodal
- R3 – realtime
- R4 – automatic



Registration $\Phi_i: \mathbb{R}^3 \rightarrow \mathbb{R}^2$

Relax requirements with $\Phi_i = \Gamma_i \circ \Gamma_0$

Shape-from-Template

To recover Ψ_i (and Π)

$\Gamma_0: \mathbb{R}^3 \rightarrow \mathbb{R}^3$

$\Gamma_i: \mathbb{R}^3 \rightarrow \mathbb{R}^2$

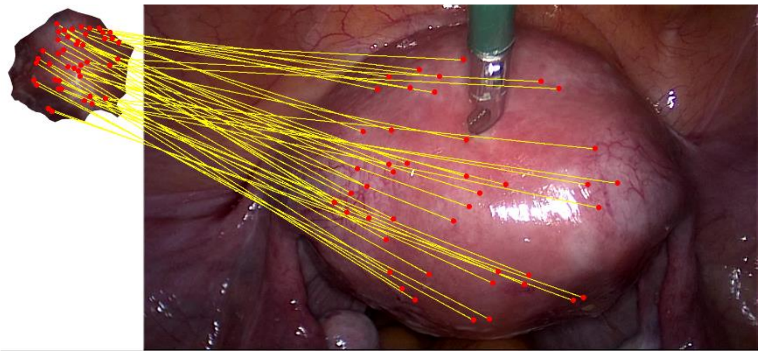
$\Pi: \mathbb{R}^3 \rightarrow \mathbb{R}^2$

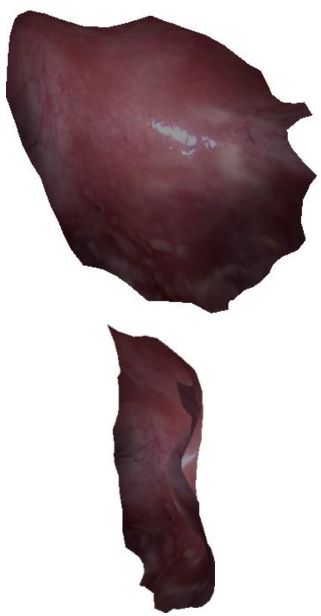
Projection

$\Psi_i: \mathbb{R}^3 \rightarrow \mathbb{R}^3$

Deformation

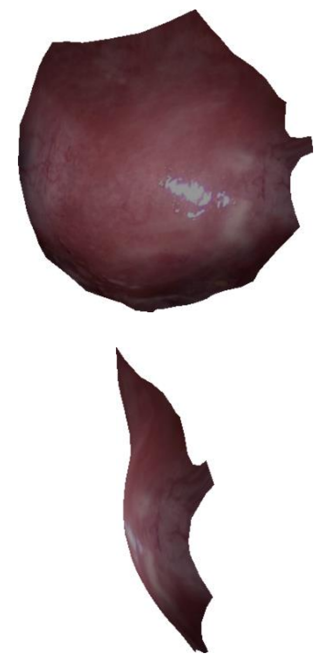
Uterine Shape-from-Template Results





Zeroth order, isometric
[Salzmann et al, PAMI'09]

First order, isometric

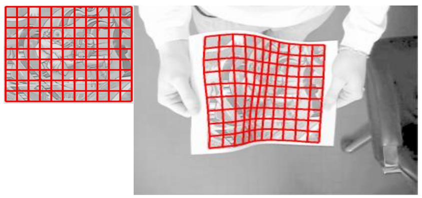


First order, conformal

Lecture's Plan

$\varphi, \nabla\varphi$

1. Modeling



2. Registration

3. Reconstruction

4. More examples, applications

5. Discussion, future work

Level of Difficulty

Rigid | **Deformable**

Isometric | Non-isometric

Difficulty

Isometry ≈ infinitesimal rigidity

Relationship to Plane Pose Estimation (PPE)

- Thin-shell isometric SfT
- First order methods ≈ Infinitesimal Plane Pose Estimation (IPPE)

- PPE has a rich history related to P3P and homography estimation
- P3P has up to 4 solutions [Fischler et al, PAMI 1981]
- PnP with $n > 3$ has a single solution if imaging is not affine but this is often unstable

- IPPE solves PPE by using the plane homography as warp [Collins et al, IJCV 2014]
- It has advantages
  - Simplicity and speed (eigenvalues and eigenvectors of a 2×2 matrix)
  - Stability (always returns 2 solutions)

More Complex Scenes – Use Detection and Recognition

Scene level

High dimensional shape space

Detection

Recognition

Object level

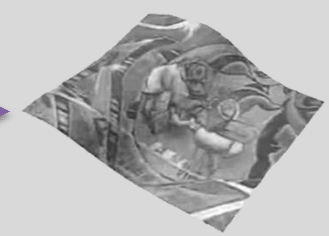
Faces

Low dimensional shape space

3D Morphable Face Model
[Blanz and Vetter, PAMI 2003]

Newspapers

High dimensional shape space
but simple deformation model



Shape-from-Template

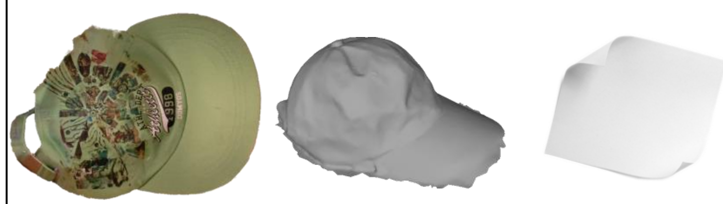
Some Extensions and Code

Multiobject Shape-from-Template [Alcantarilla et al, BMVC 2012]

Template 1

Appearance Shape Material

Template 2



Appearance Shape Material

etc.

Stable implementation [Chhatkuli et al, CVPR 2014]

Use the normal, not the depth, in the local solution

For code, see http://isit.u-clermont1.fr/~ab/Research

Ongoing and Future Work

- Handle *many* objects – thousands, millions, …
- Non-isometric deformations – solvability, boundary conditions
- Weakly textured objects, combining with shading [Moreno et al, ECCV 2010]

NRSfM: Non-Rigid Shape-from-Motion

- No template, but more images
- Shape is solvable for three images with an isometric deformation

[Chhatkuli et al, BMVC 2014]

Shape-from-Template

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ALCoV-ISIT, Clermont-Ferrand

with Florent Brunet, Toby Collins, Vincent Gay-Bellile, Abed Malti,
Mathieu Perriollat, Daniel Pizarro, Richard Hartley, and others

Keynote given at ORASIS, Amiens, June 2015