ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Dynamic 2D/3D Registration

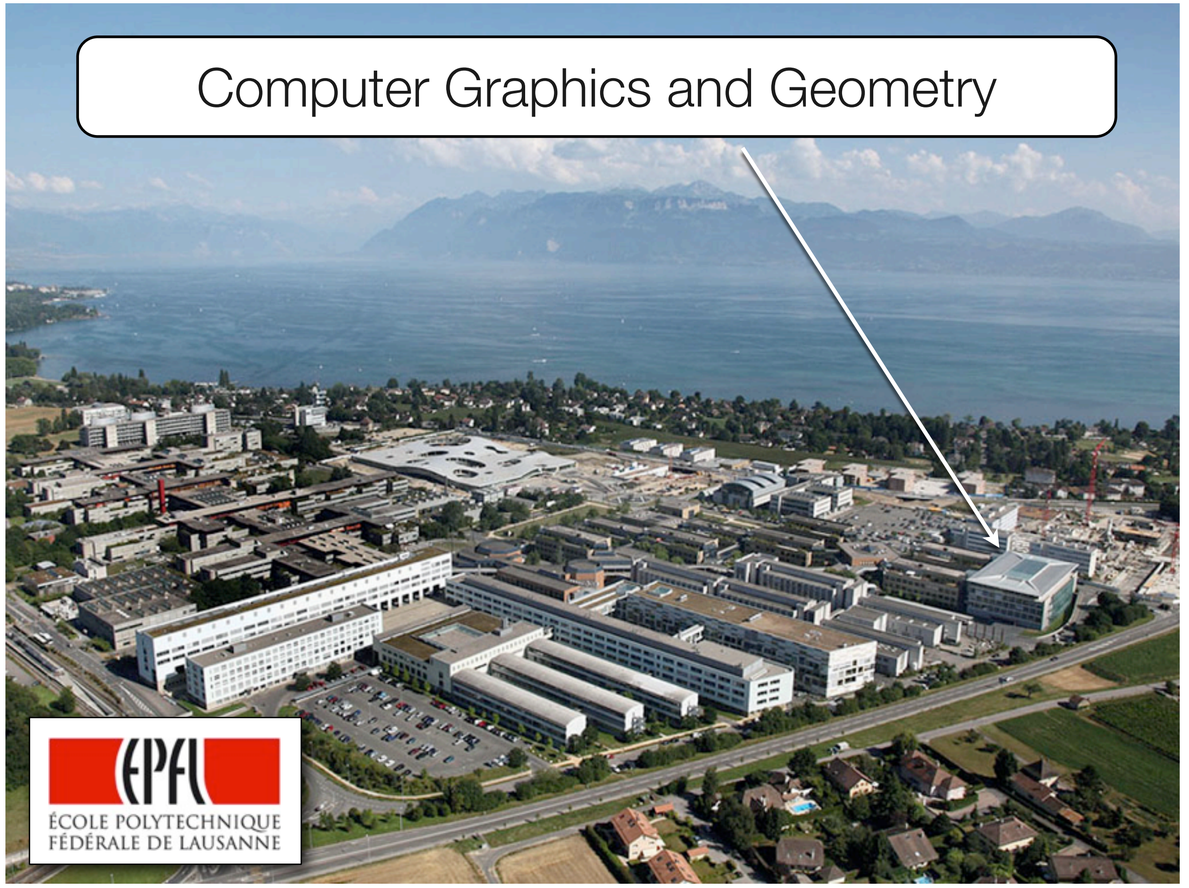
Sofien Bouaziz Andrea Tagliasacchi Mark Pauly

Presenters

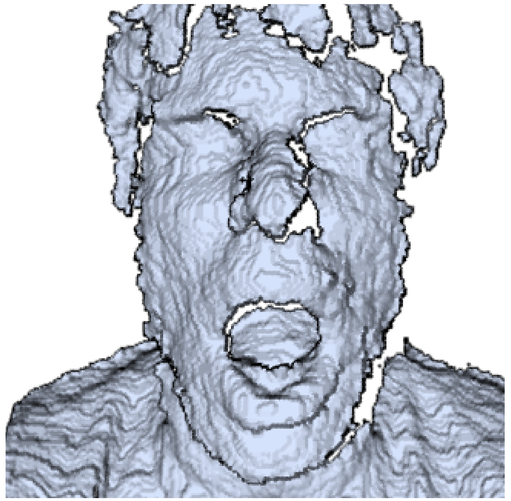
Sofien Bouaziz

Andrea Tagliasacchi

Mark Pauly

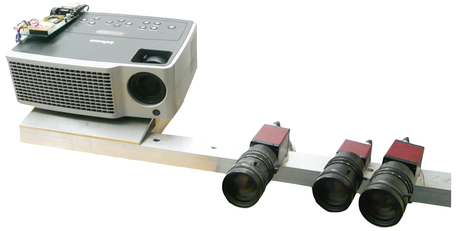


RGB-D Sensors



RGB-D Sensors

2008



RGB-D Sensors

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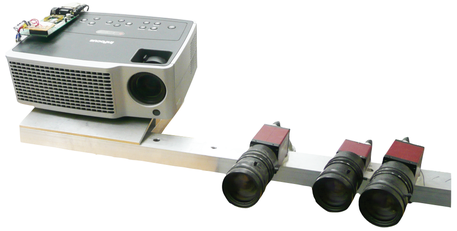

RGB-D Sensors

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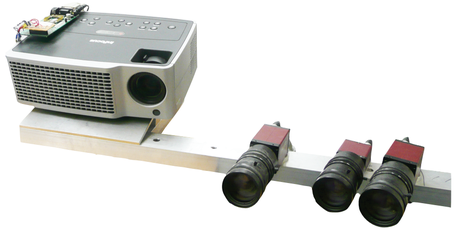
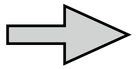


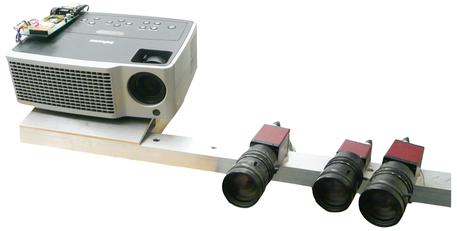


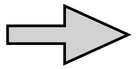
2010

RGB-D Sensors

2008

2010



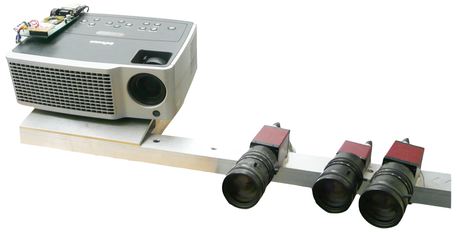


RGB-D Sensors

2008

2010

2013

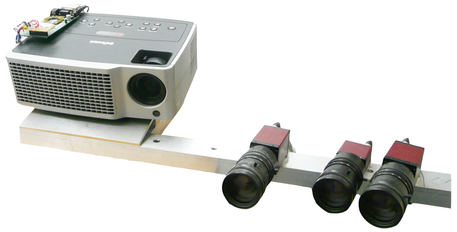


RGB-D Sensors

2008

2010

2013

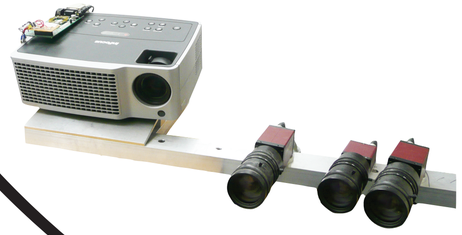


RGB-D Sensors

2008

2010

2013



size/cost


Faceshift
Motion Capture
Aisle
800

Overview

Introduction

- Registration
  - 3D Geometry
  - 2D Images
  - Combined 2D / 3D
- Applications
  - Rigid Scanning
  - Non-rigid Modeling
  - Realtime Face Tracking

Conclusions

RGB-D Sensors

http://www.openni.org

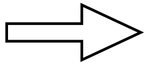
http://www.openni.org/openni-programmers-guide

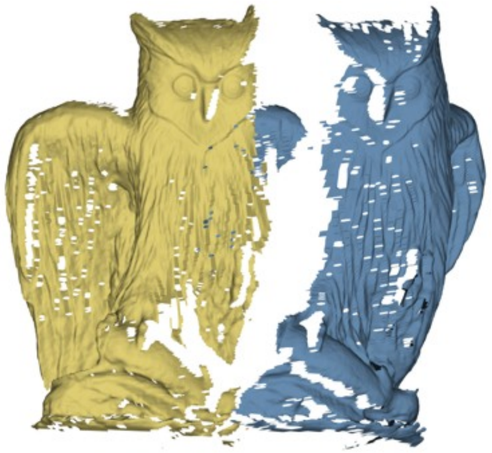
Registration - Examples

- Scan to scan

Registration - Examples

- Scan to scan





Registration - Examples

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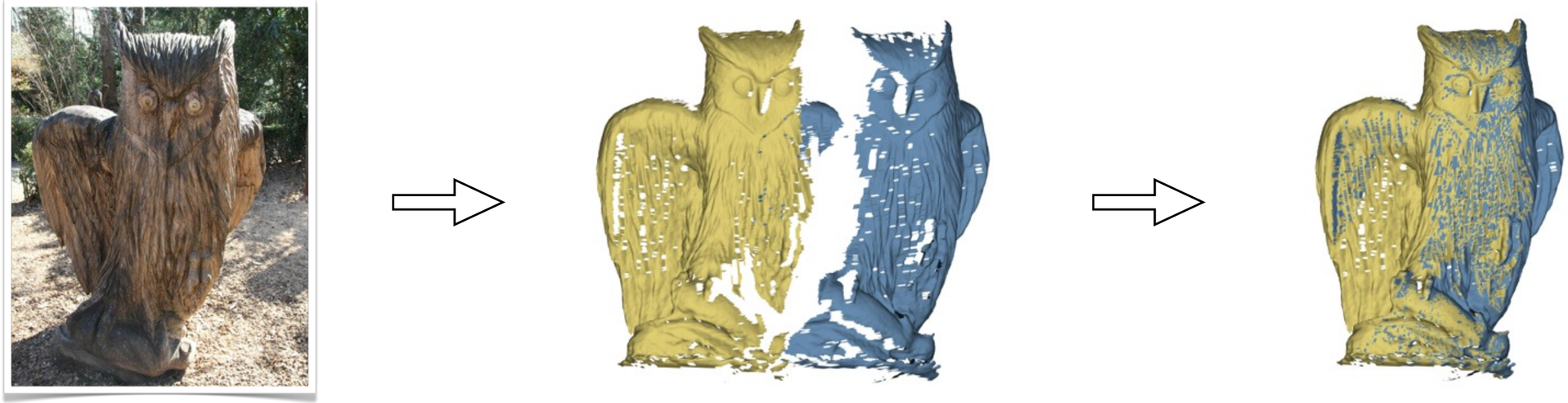

Registration - Examples

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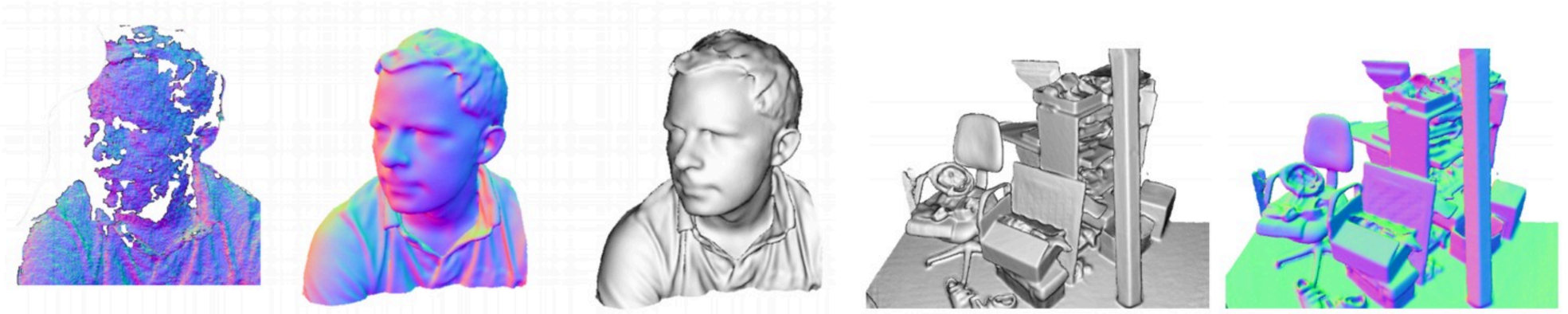
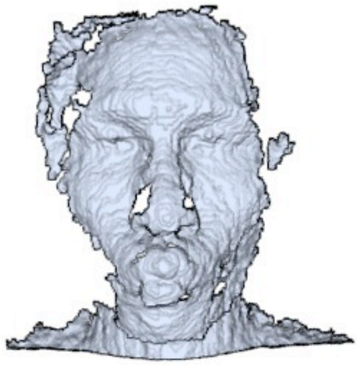


Newcombe, Izadi, Hilliges, Molyneaux, Kim, Davison, Kohli, Shotton, Hodges, Fitzgibbon:
KinectFusion: Real-Time Dense Surface Mapping and Tracking, *ISMAR 2011*

Registration - Examples

- Parameterized template to scan



Registration - Examples

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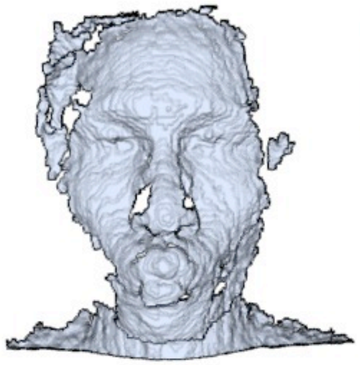

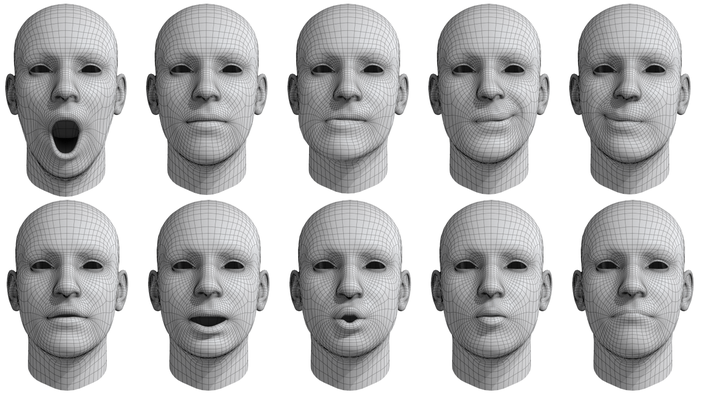

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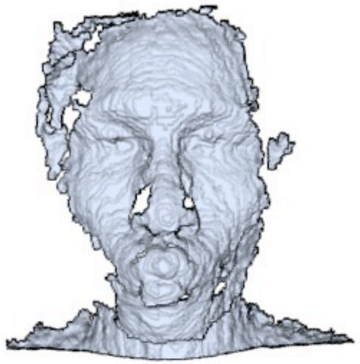
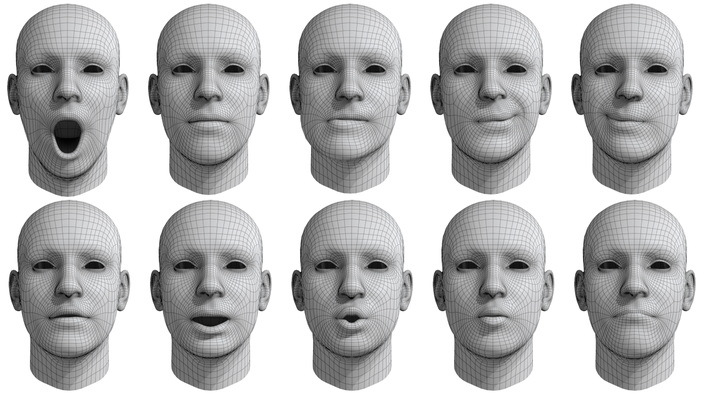
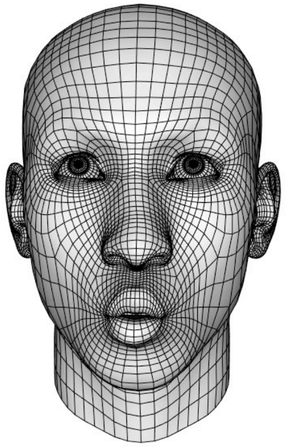
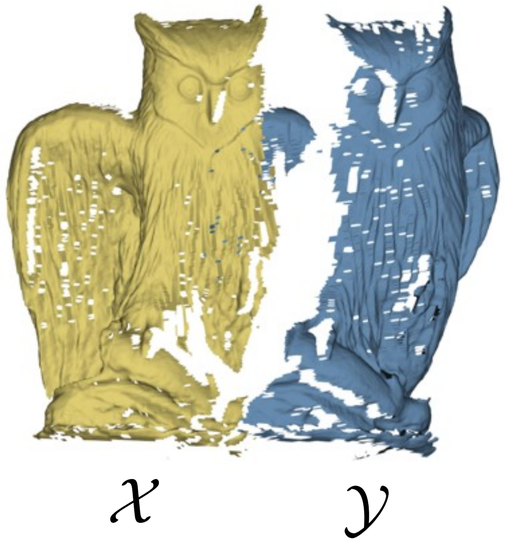






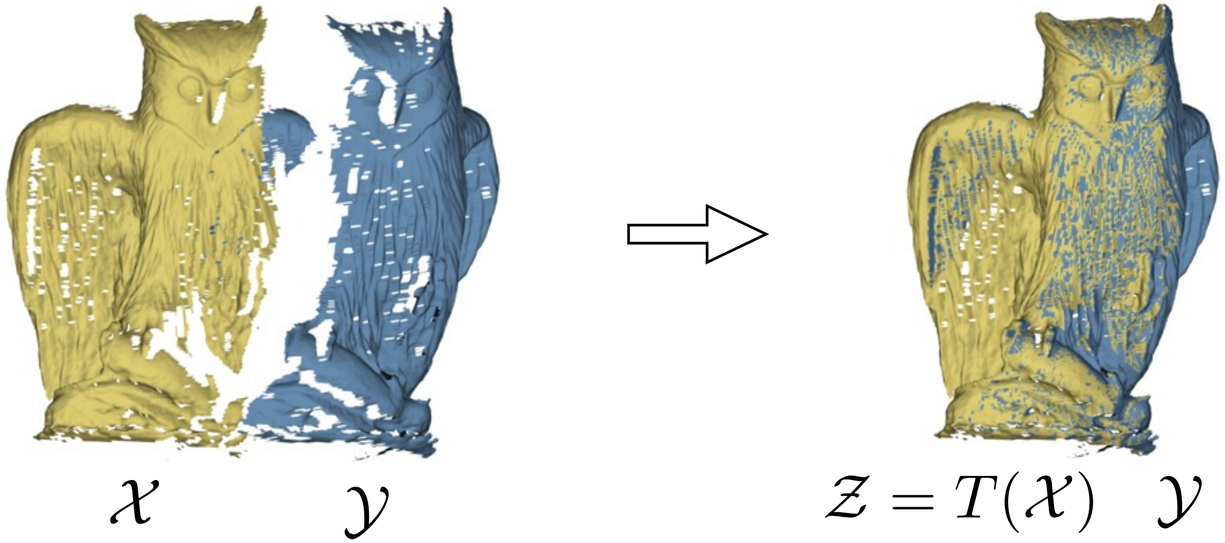
Pairwise Registration

- Align a *source model* $\mathcal{X}$ onto a *target model* $\mathcal{Y}$



Pairwise Registration

- Align a *source model* $\mathcal{X}$ onto a *target model* $\mathcal{Y}$
  - find a *transformation* $T(\mathcal{X})$ that brings $\mathcal{X}$ into alignment with $\mathcal{Y}$



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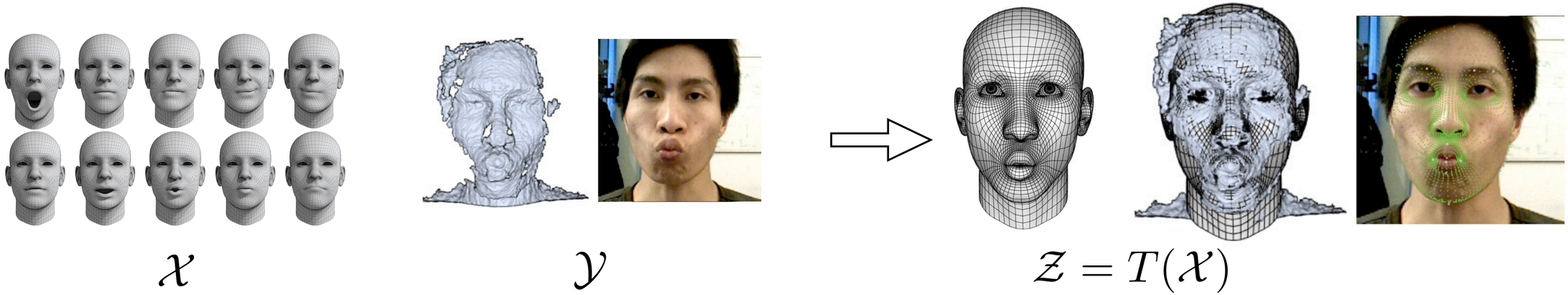

$\mathcal{X}$ $\mathcal{Y}$ $\mathcal{Z} = T(\mathcal{X})$

Pairwise Registration

- Align a *source model* $\mathcal{X}$ onto a *target model* $\mathcal{Y}$
  - find a *transformation* $T(\mathcal{X})$ that brings $\mathcal{X}$ into alignment with $\mathcal{Y}$
- Two main questions:

Pairwise Registration

- Align a *source model* $\mathcal{X}$ onto a *target model* $\mathcal{Y}$
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- Two main questions:
  - How do we measure the quality of the alignment?

Pairwise Registration

- Align a *source model* $\mathcal{X}$ onto a *target model* $\mathcal{Y}$
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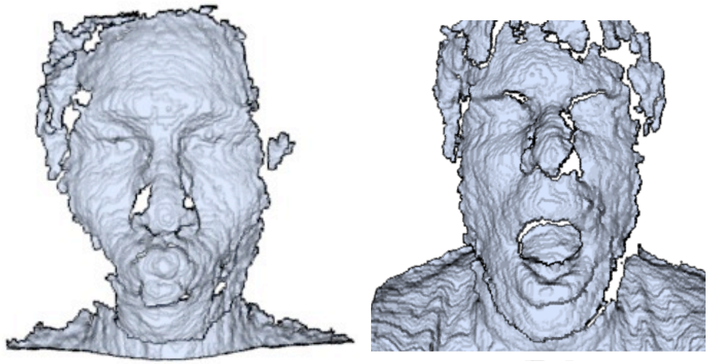
- Two main questions:
  - How do we measure the quality of the alignment?
  - What transformations are allowed / good?

Pairwise Registration

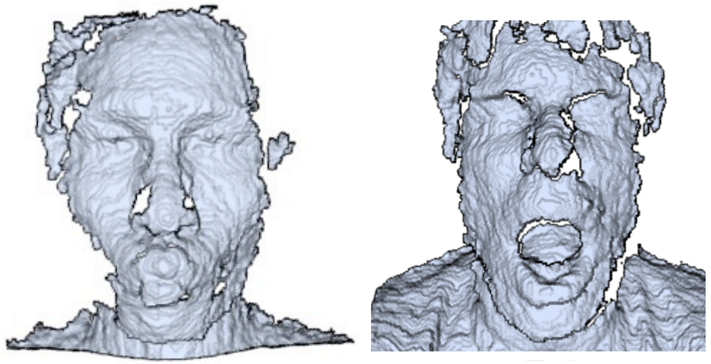
- Issues



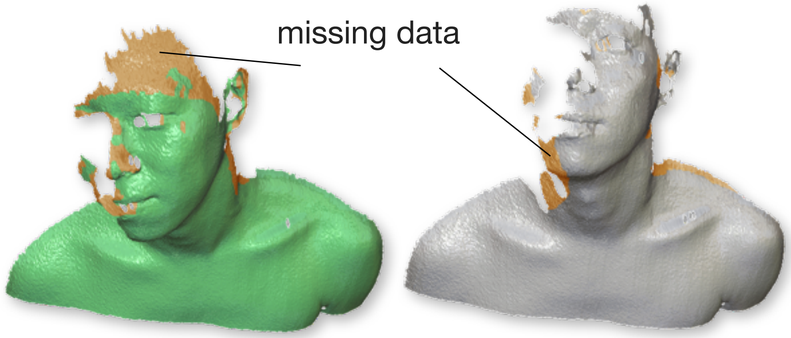
Noise

Pairwise Registration

- Issues



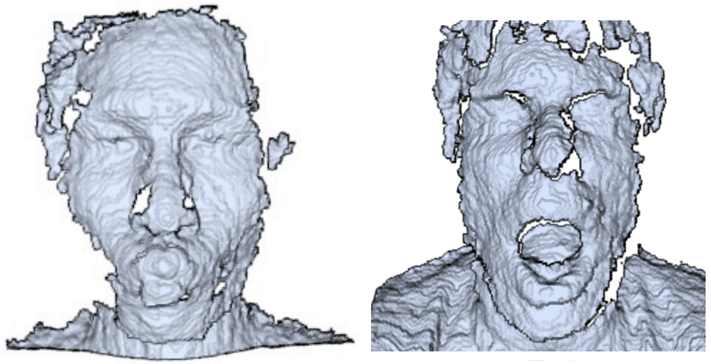
Noise



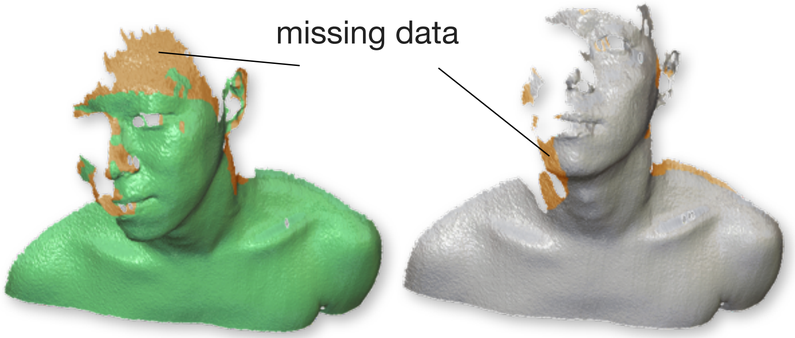
Partial matching

Pairwise Registration

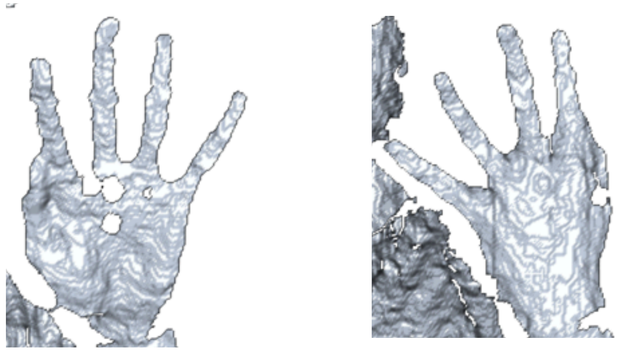
- Issues



Noise



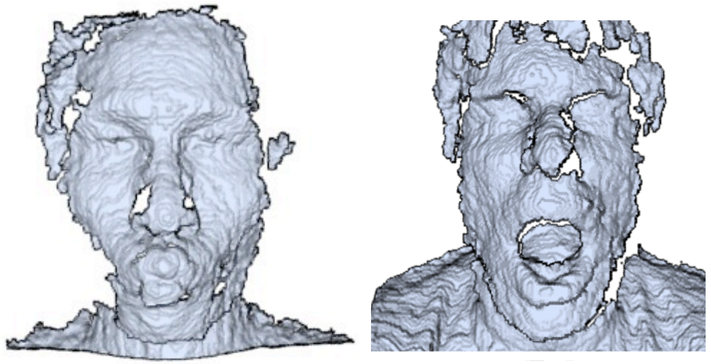
Partial matching



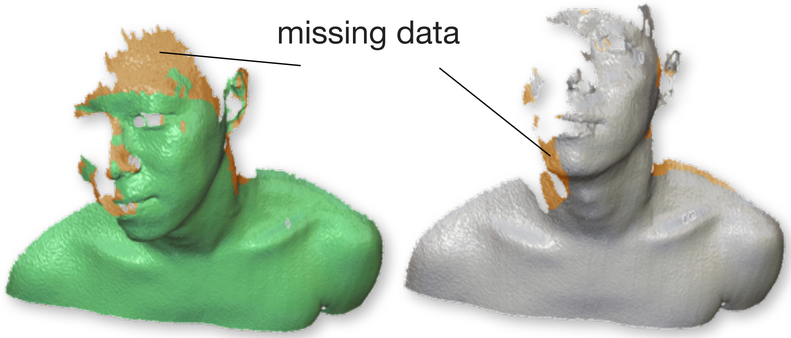
Ambiguity

Pairwise Registration

- Issues



Noise



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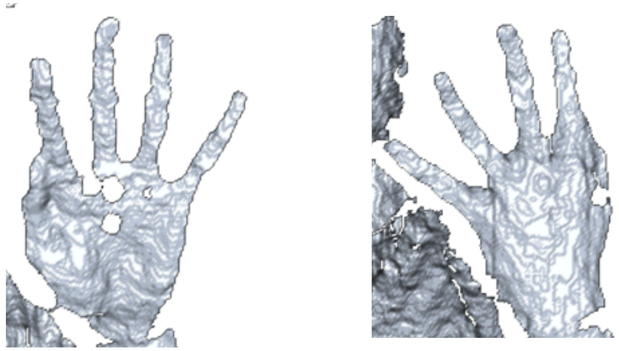

Ambiguity

Illumination changes

Overview

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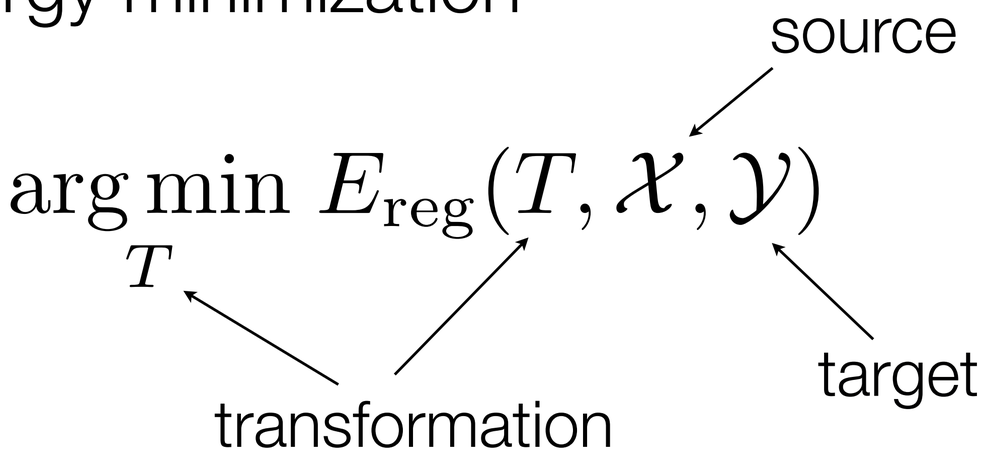
Conclusions

Registration

- Registration as energy minimization



Registration

- Registration as energy minimization

$$\arg\min_{T} E_{\text{reg}}(T, \mathcal{X}, \mathcal{Y})$$

$$E_{\text{reg}}(T, \mathcal{X}, \mathcal{Y}) = E_{\text{match}}(T, \mathcal{X}, \mathcal{Y}) + E_{\text{prior}}(T)$$

Alignment Error

How do we measure the quality of the alignment?

Registration

- Registration as energy minimization

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Alignment Error

How do we measure the quality of the alignment?

Transformation Error

What transformations are allowed / good?

Registration

- Alignment Error

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(T, \mathcal{X}, \mathcal{Y})$$

Registration

- Alignment Error

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(T, \mathcal{X}, \mathcal{Y}) = \int_{\mathcal{X}} \varphi(T(\mathbf{x}), \mathcal{Y}) d\mathbf{x}$$

distance function

Registration

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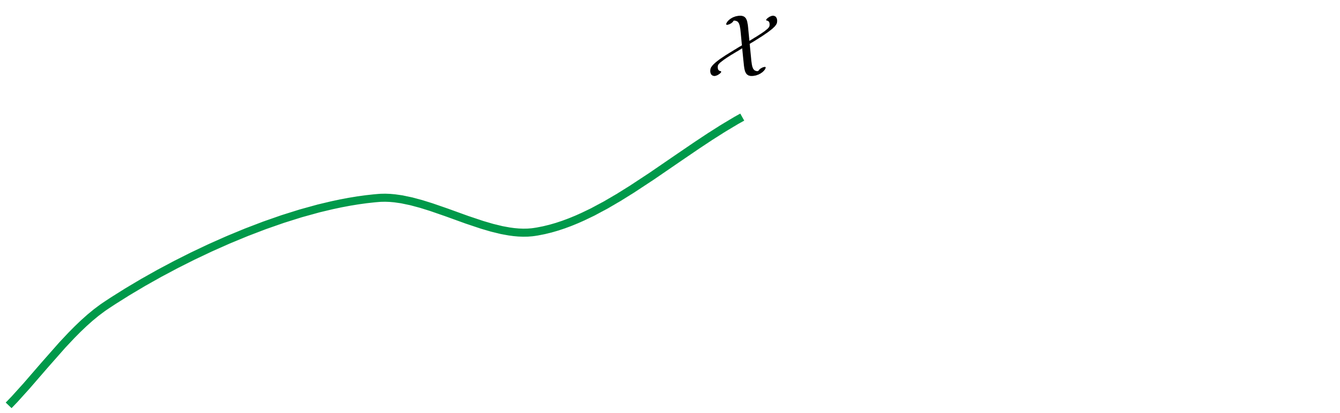

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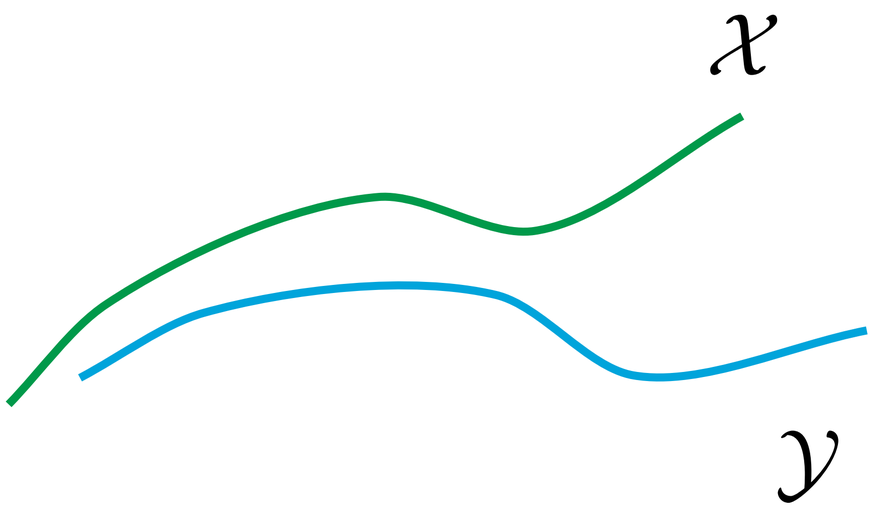

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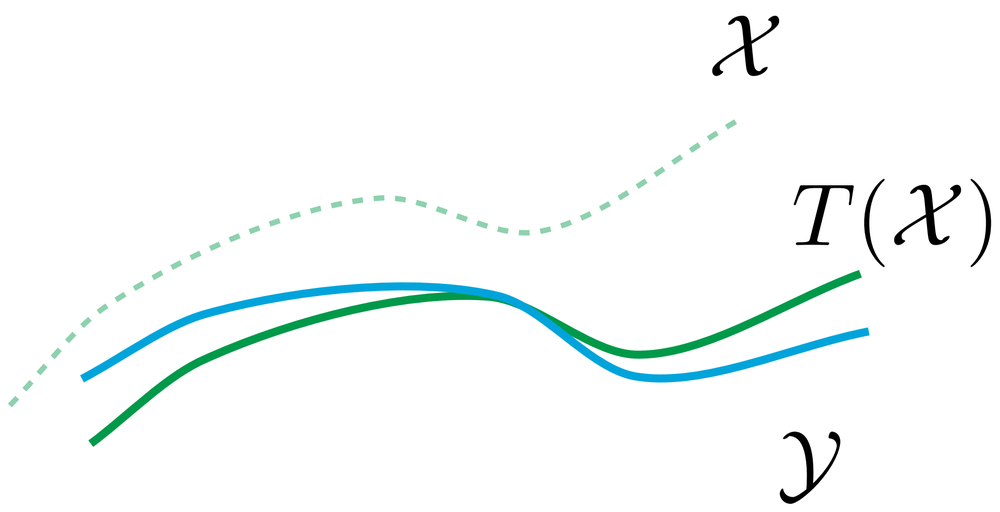

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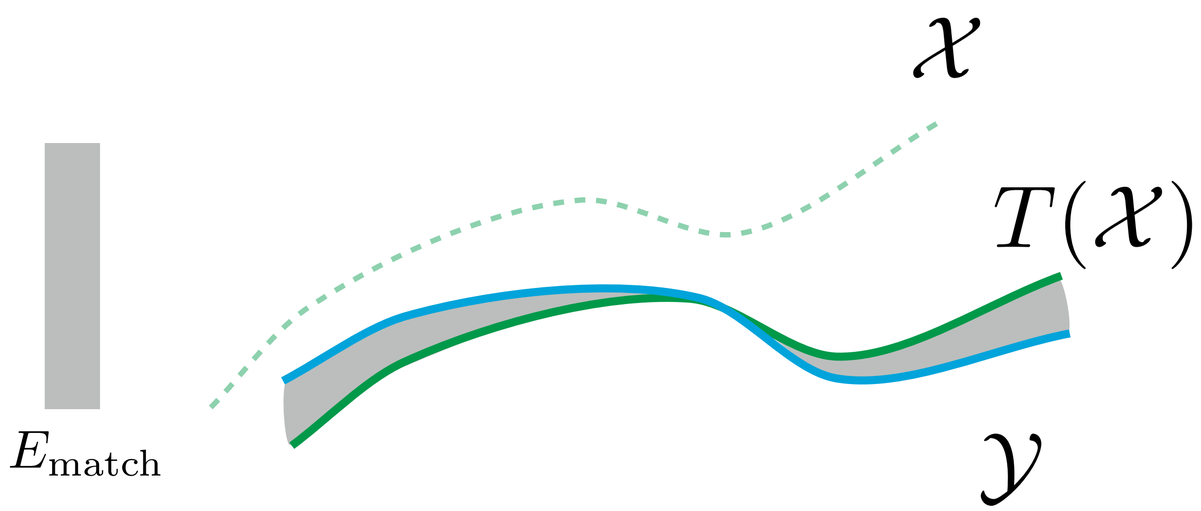

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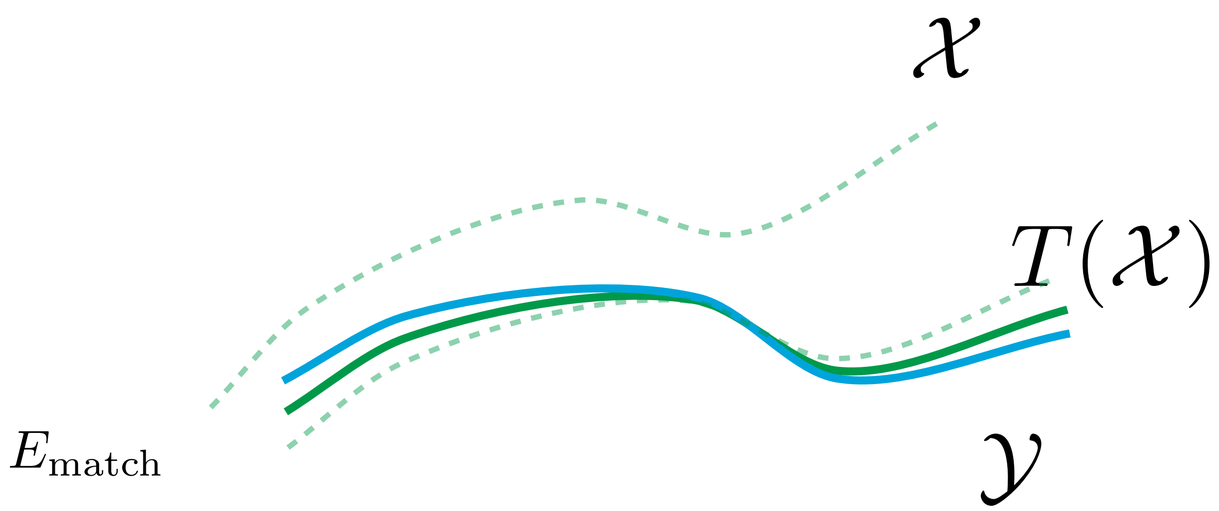

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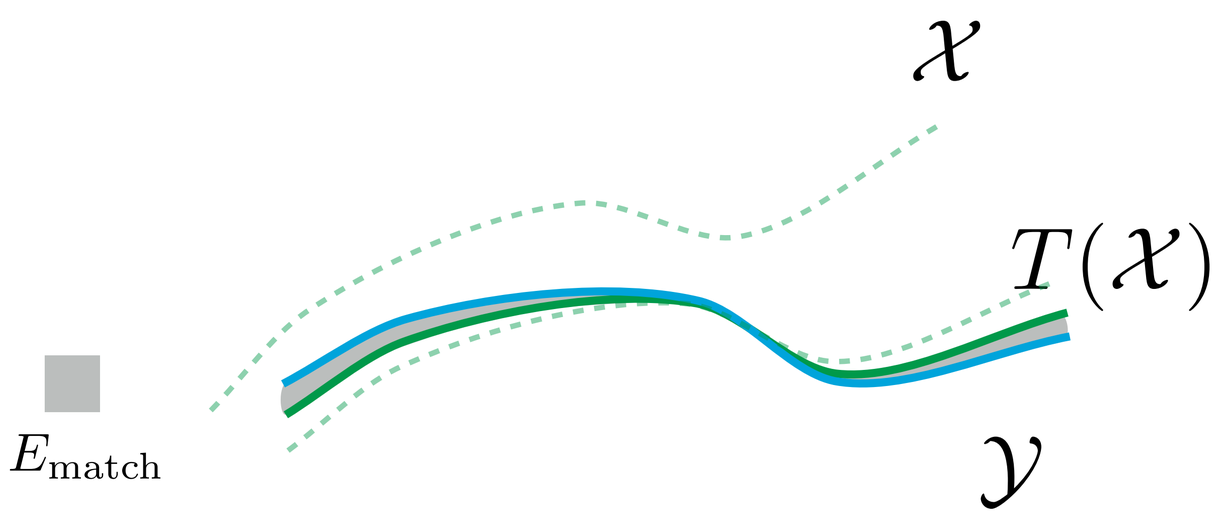


Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

elastic

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

elastic

articulated

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

elastic

articulated

composite

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

elastic

articulated

composite

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid motion prior

rigid

elastic

articulated

composite

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

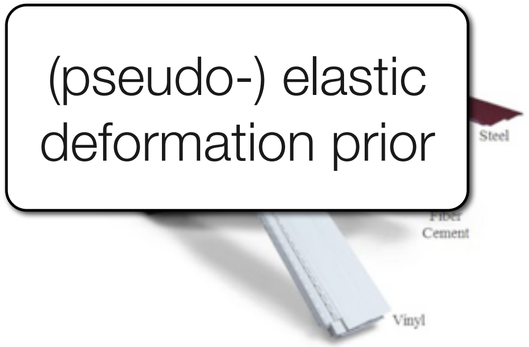
rigid motion prior

rigid

articulated

composite

(pseudo-) elastic deformation prior



elastic

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

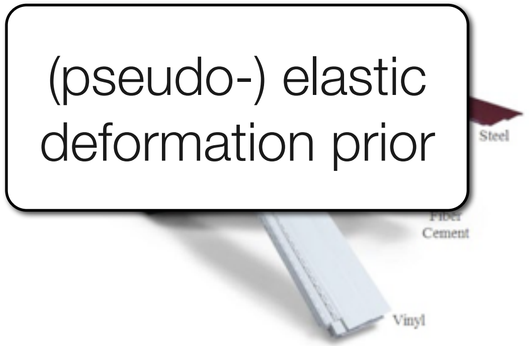
rigid motion prior

rigid

composite

skeletal model prior

articulated



(pseudo-) elastic deformation prior

elastic

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid motion prior

rigid

(pseudo-) elastic deformation prior

elastic

skeletal model prior

articulated

data-driven prior

composite

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

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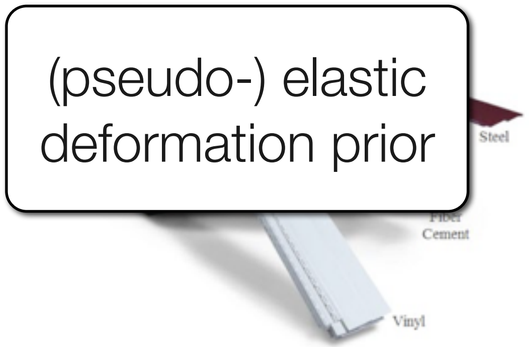
rigid

skeletal model prior

articulated

data-driven prior

composite



(pseudo-) elastic deformation prior

elastic

?

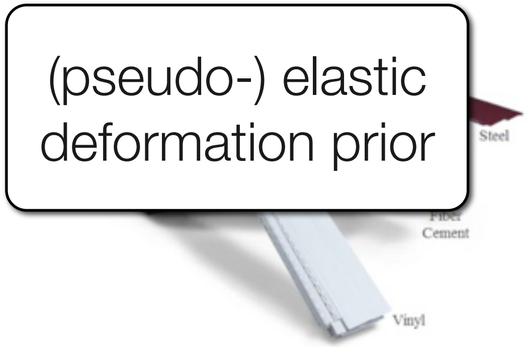
fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid motion prior

rigid



(pseudo-) elastic deformation prior

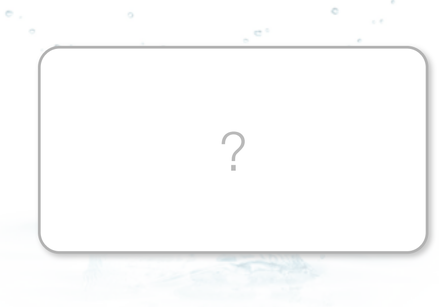
elastic

skeletal model prior

articulated

data-driven prior

composite



?

fluid

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

- Registration as energy minimization

$$\arg\min_{T} E_{\text{reg}}(T, \mathcal{X}, \mathcal{Y})$$

source

transformation

target

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E_{reg}

$\mathcal{Z}_1 = T_1(\mathcal{X})$

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source

target

transformation

Input

$(\mathcal{X}, \mathcal{Y})$

$\Rightarrow$

E_{reg}

$\mathcal{Z}_1 = T_1(\mathcal{X})$

$\mathcal{Z}_2 = T_2(\mathcal{X})$

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

- Registration as energy minimization
  - typically non-linear
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$$\arg\min_{T} E_{\text{reg}}(T, \mathcal{X}, \mathcal{Y})$$

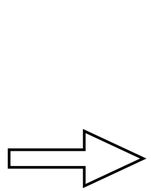
source

target

transformation

Input

$(\mathcal{X}, \mathcal{Y})$



E_{reg}

$\mathcal{Z}_1 = T_1(\mathcal{X})$

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$\dots$

$\mathcal{Z}_n = T_n(\mathcal{X})$

Registration

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

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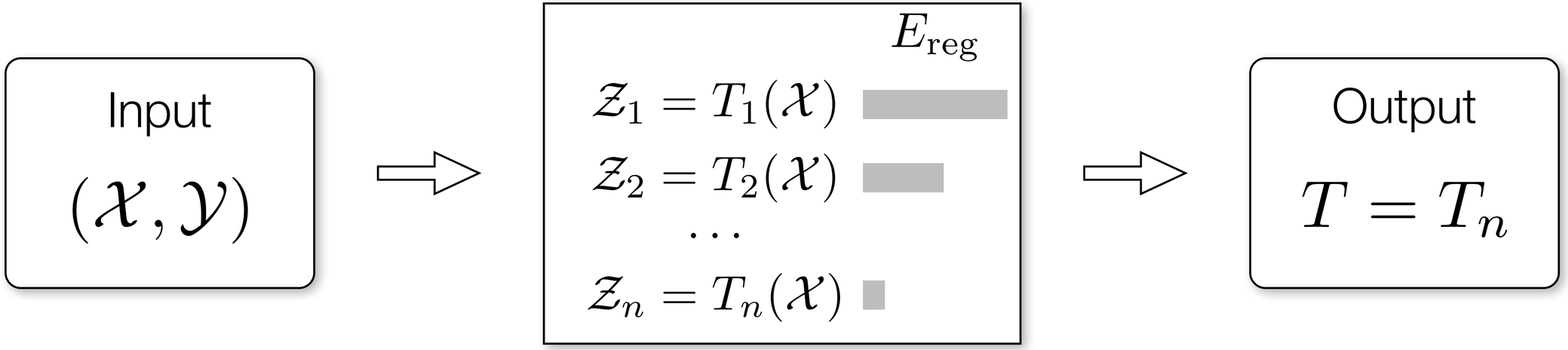


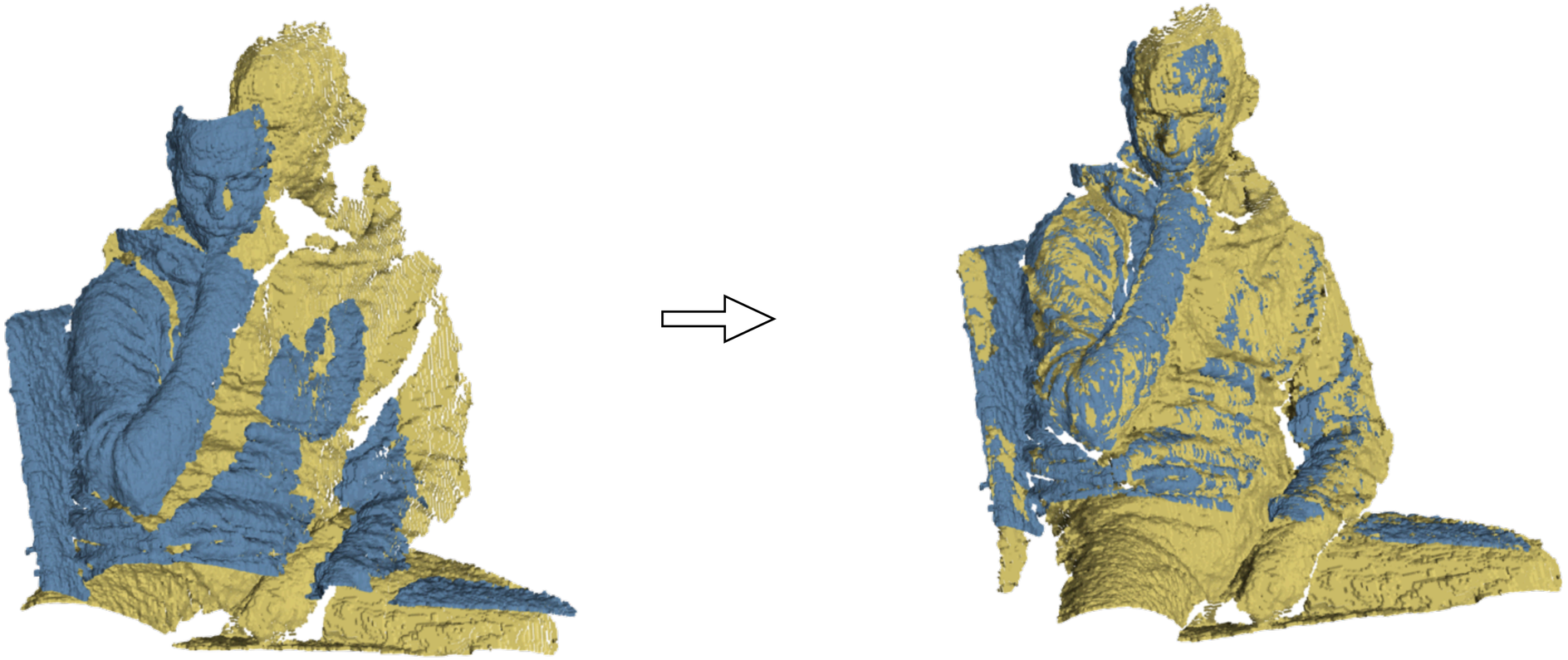
Overview

Introduction

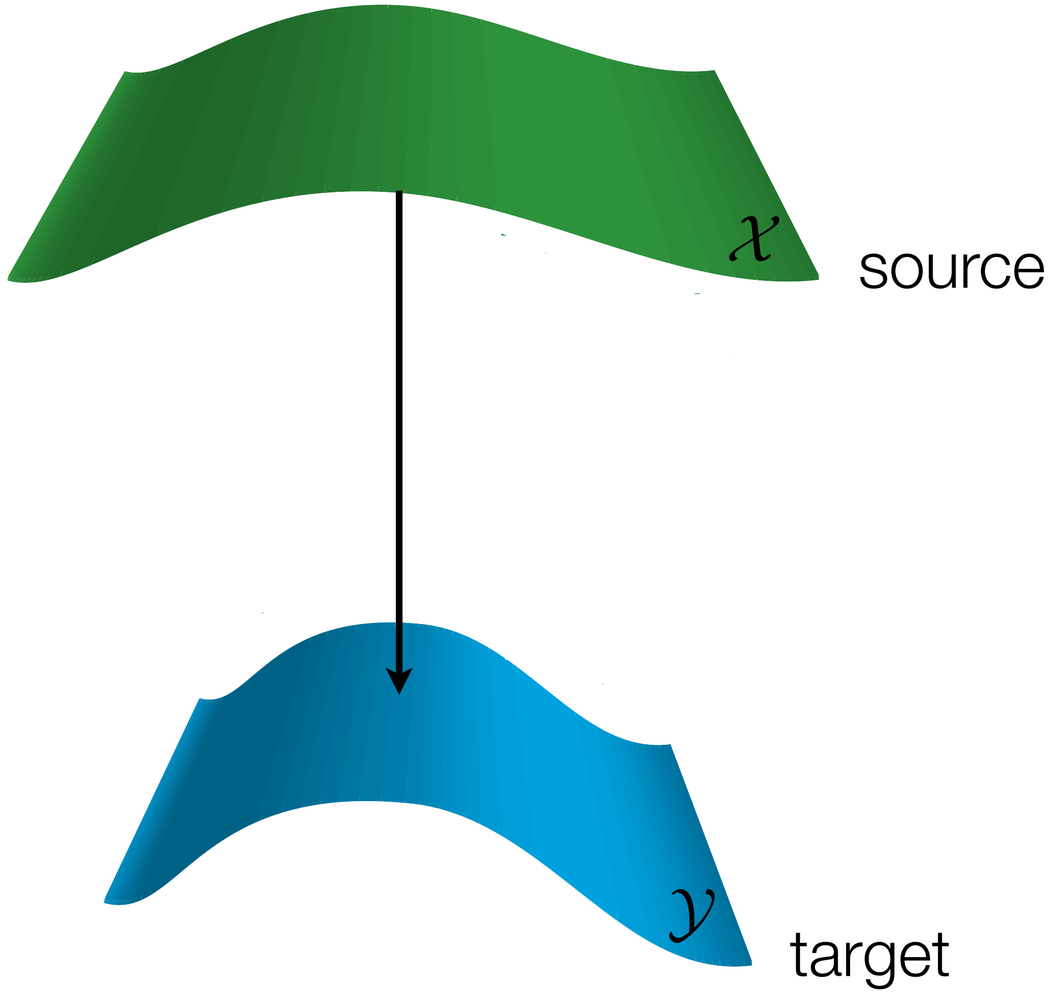
- Registration
  - **3D Geometry**
  - 2D Images
  - Combined 2D / 3D
- Applications
  - Rigid Scanning
  - Non-rigid Modeling
  - Realtime Face Tracking

Conclusions

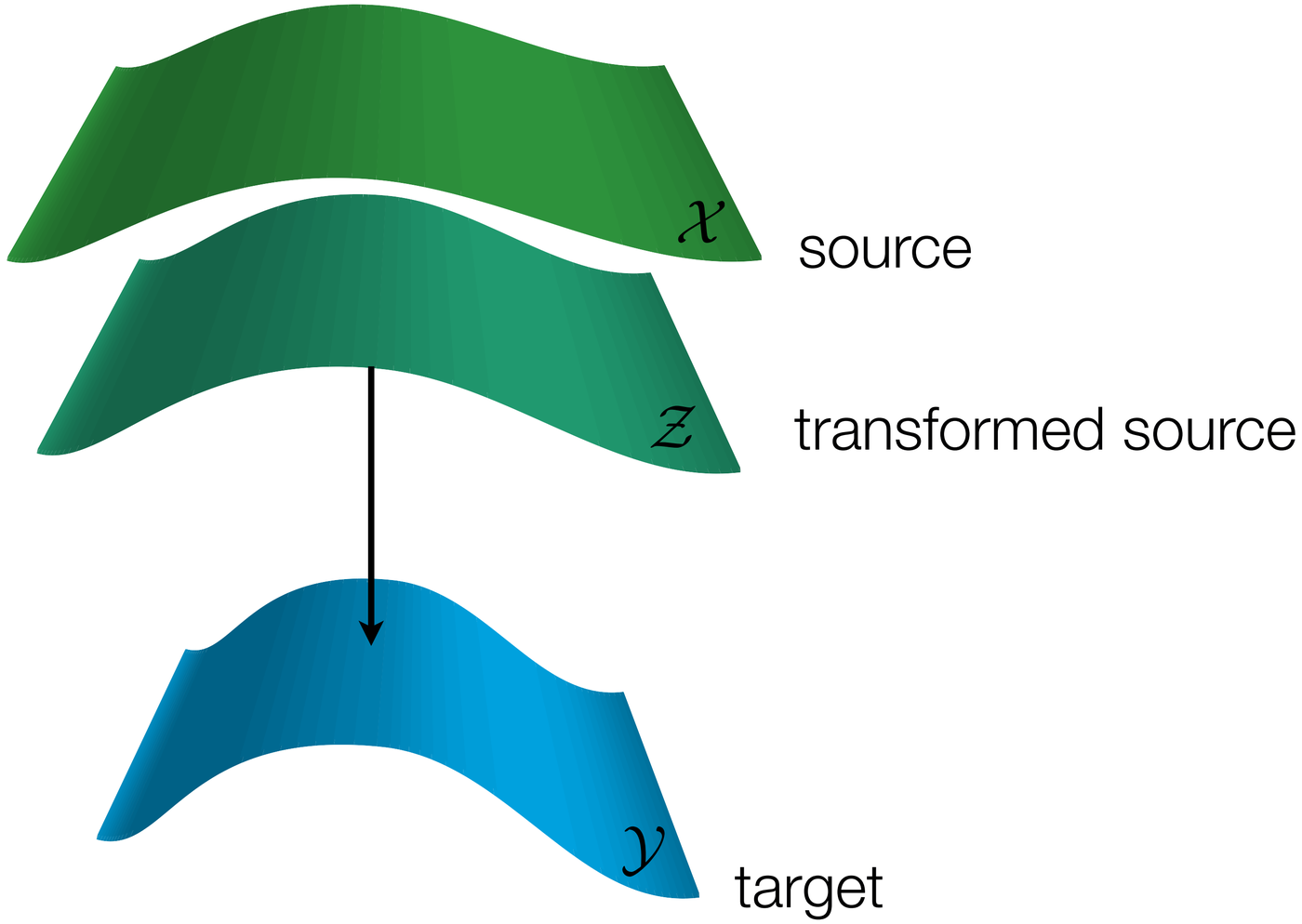
3D Registration



3D Registration

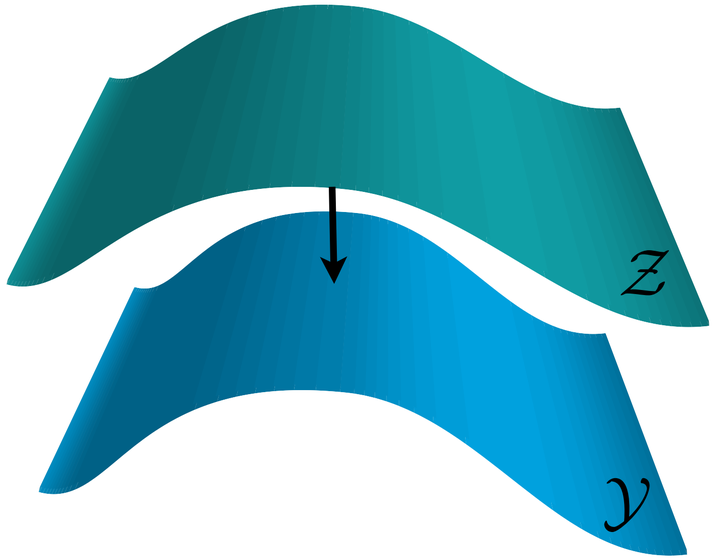


3D Registration



3D Registration

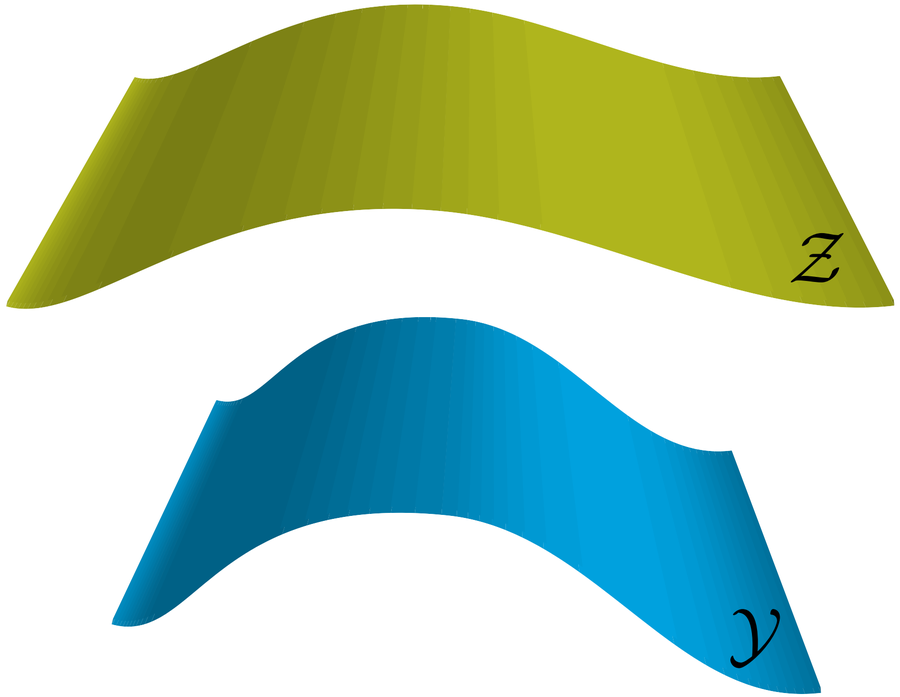
source



transformed source

target

3D Registration - Matching



$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(\mathcal{Z}) = \int_{\mathcal{Z}} \varphi(\mathbf{z}, \mathcal{Y}) d\mathbf{z}$$

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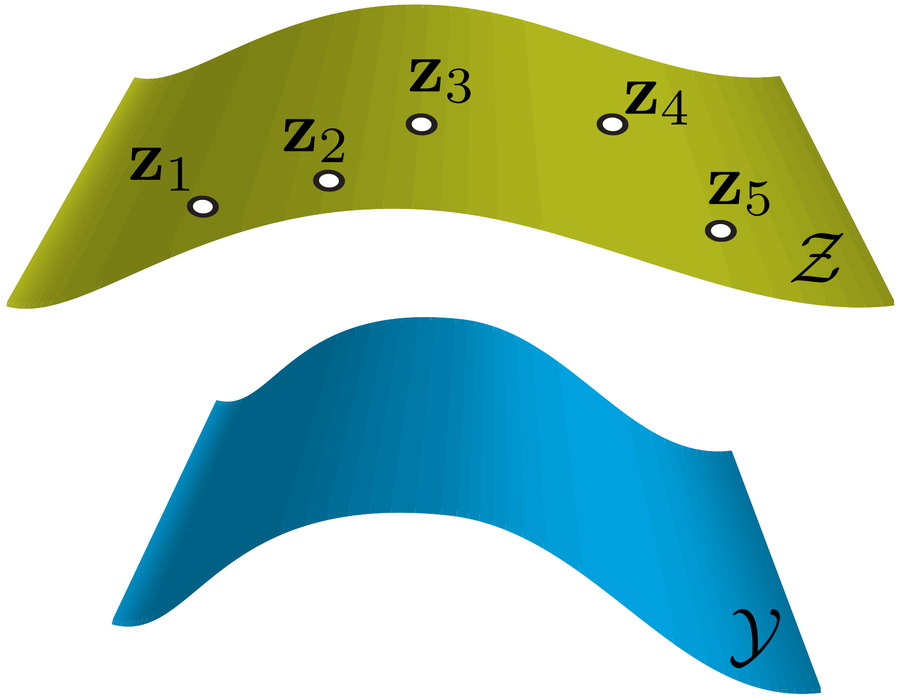

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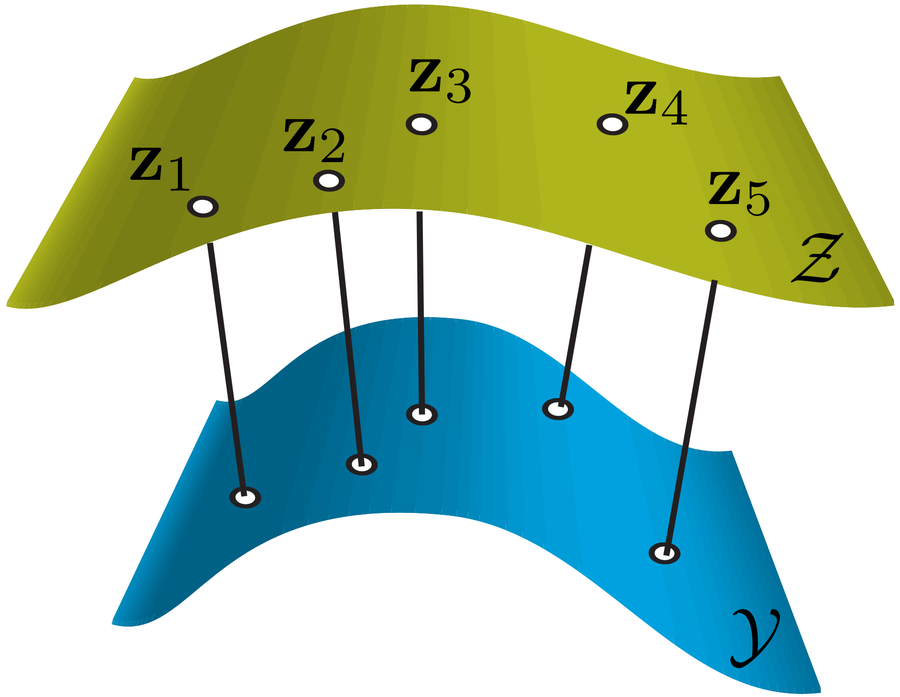

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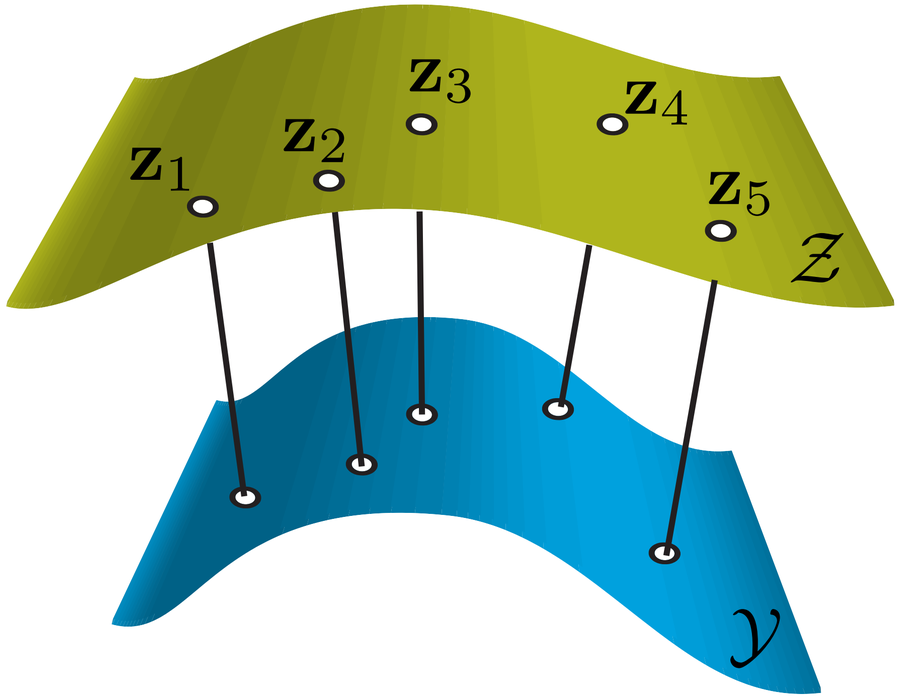

discretized matching cost based on point correspondences

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(\mathcal{Z}) = \int_{\mathcal{Z}} \varphi(\mathbf{z}, \mathcal{Y}) d\mathbf{z}$$

$$\Downarrow$$

$$E_{\text{match}}(\mathcal{Z}) = \sum_{i=1}^{n} w_i \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2$$

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transformed
point on source

3D Registration - Matching

corresponding point on target

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transformed point on source

3D Registration - Matching

correspondence weight

corresponding point on target

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transformed point on source

3D Registration - Example

- Iterative Closest Point (ICP) Algorithm

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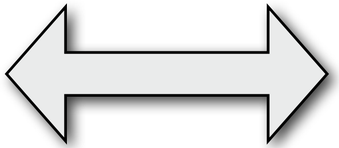

Iterate until convergence

DEMO

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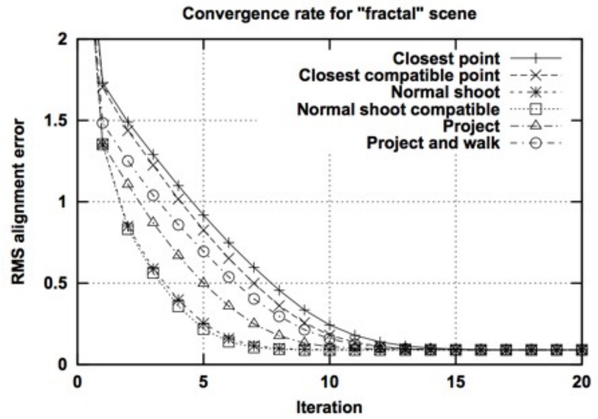

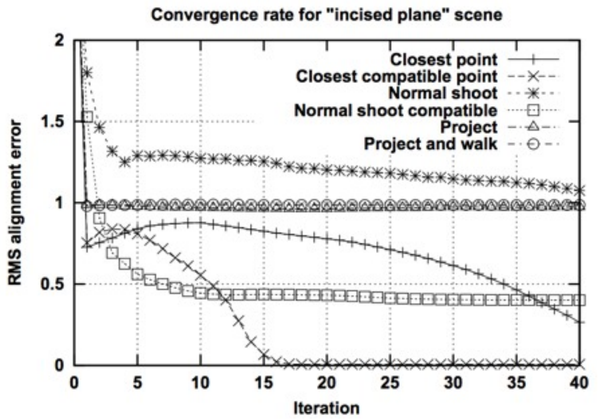

Rusinkiewicz, Levoy: **Efficient Variants of the ICP Algorithm**, *3D Digital Imaging and Modeling, 2001*

3D Registration - Example

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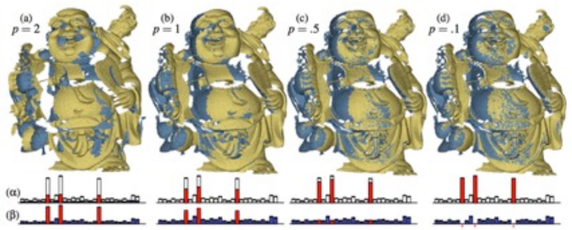


Bouaziz, Tagliasacchi, Pauly: **Sparse Iterative Closest Point**, *SGP 2013*

3D Registration - Prior

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

rigid

elastic

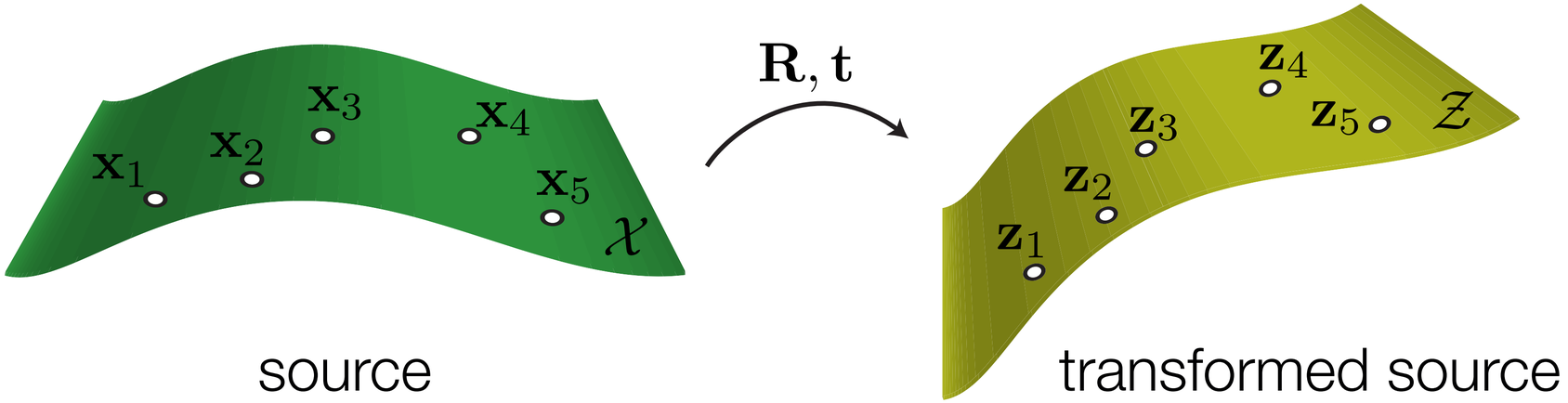
articulated

composite

fluid

3D Registration - Prior

- Global Rigidity $E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$



3D Registration - Prior

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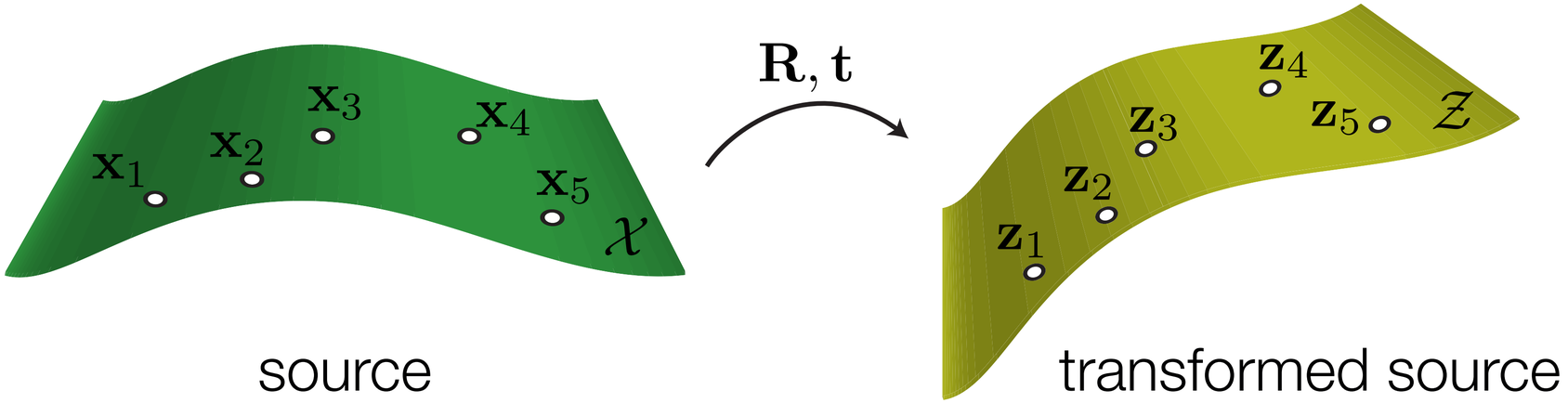

$$E_{\text{prior}}(Z, \mathbf{R}, \mathbf{t}) = \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

3D Registration - Prior

- Local Rigidity $E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$

3D Registration - Prior

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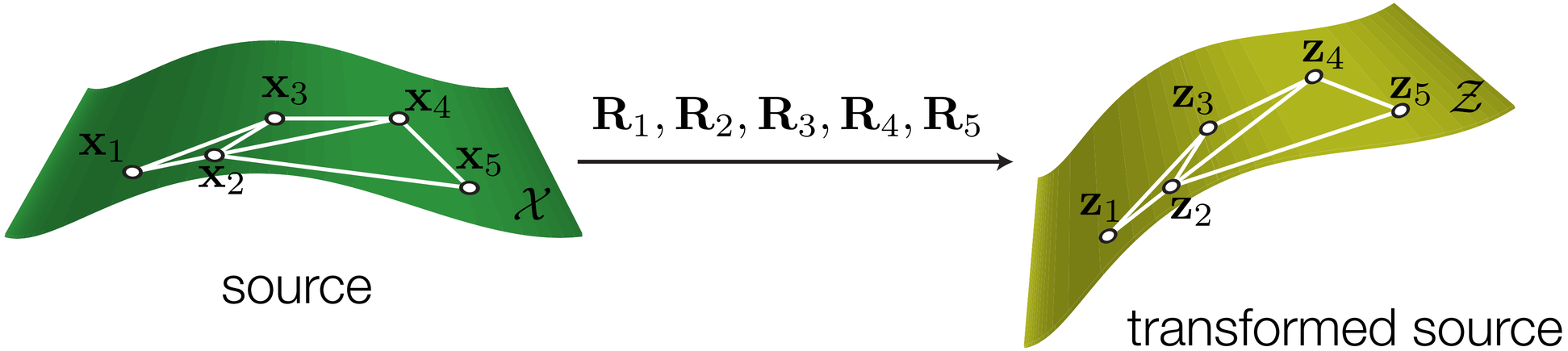

3D Registration - Prior

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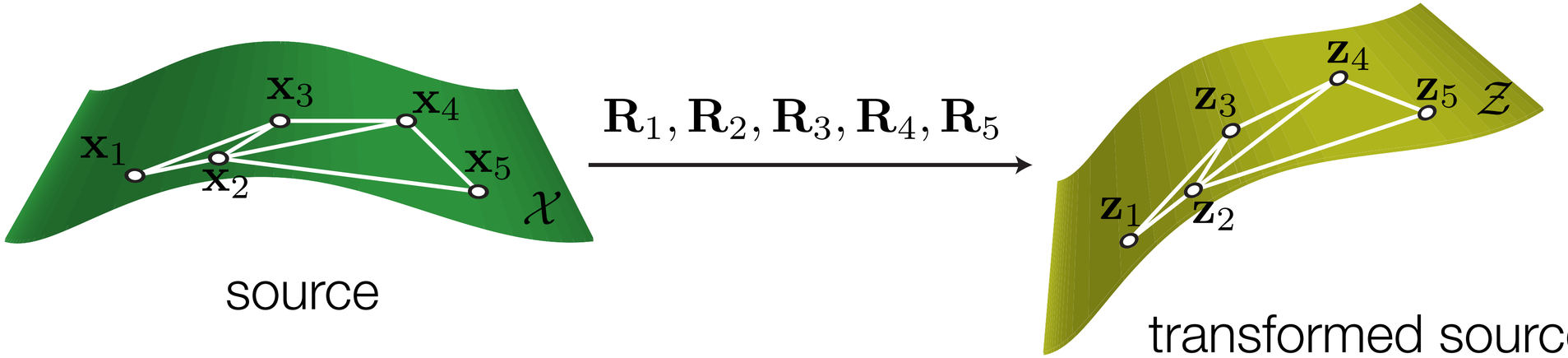

source

transformed source

$$E_{\text{prior}}(Z, \mathbf{R}_i|_{i=1}^{n}) = \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2$$

3D Registration - Prior

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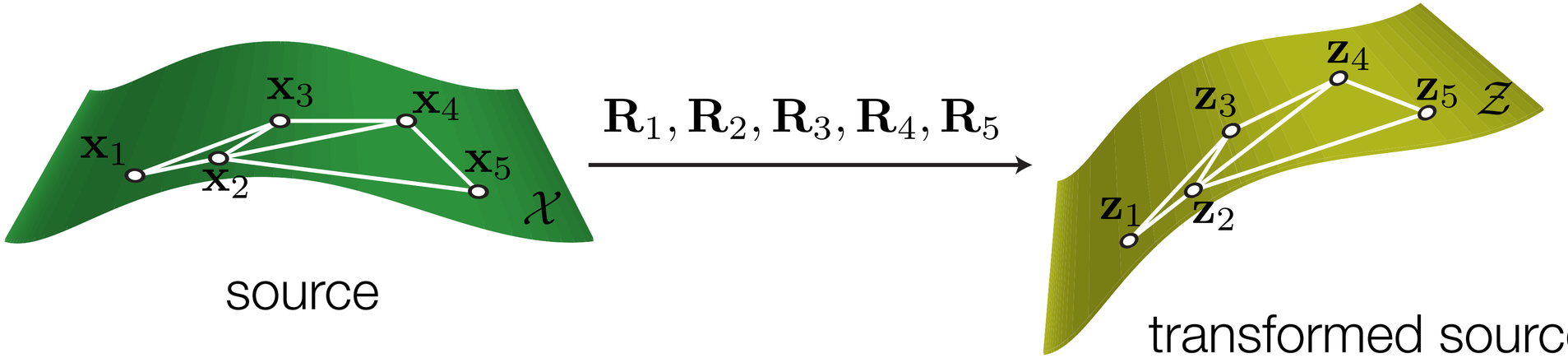

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Sorkine, Alexa: **As-Rigid-As-Possible Surface Modeling**, *SGP 2007*

3D Registration - Prior

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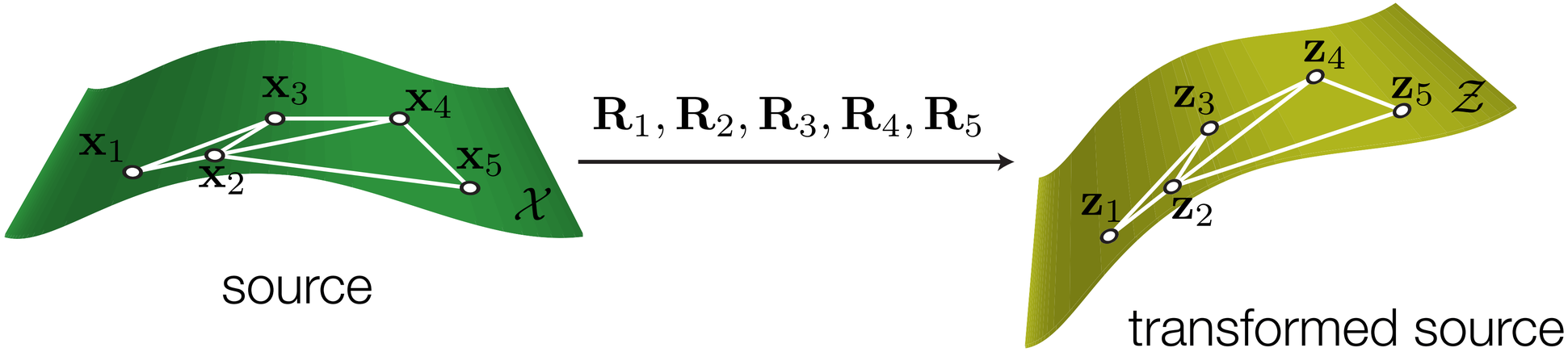

DEMO

3D Registration - Prior

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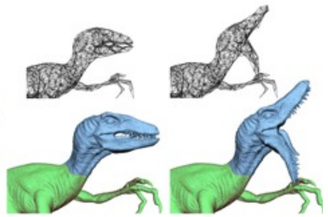
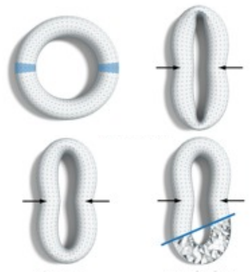


Sumner, Schmid, Pauly:
Embedded Deformation for Shape Manipulation
ACM SIGGRAPH 2007



Bouaziz, Deuss, Schwartzburg, Weise, Pauly:
Shape-Up: Shaping Discrete Geometry With Projection
SGP 2012

3D Registration - Prior

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3D Registration - Prior

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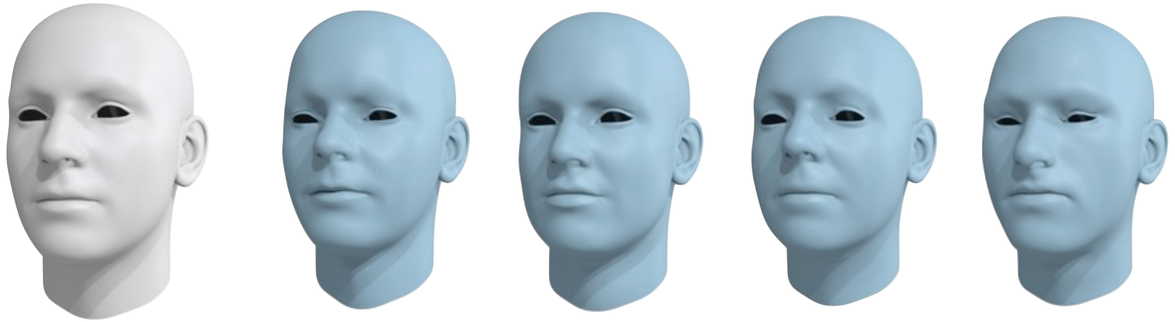

3D Registration - Prior

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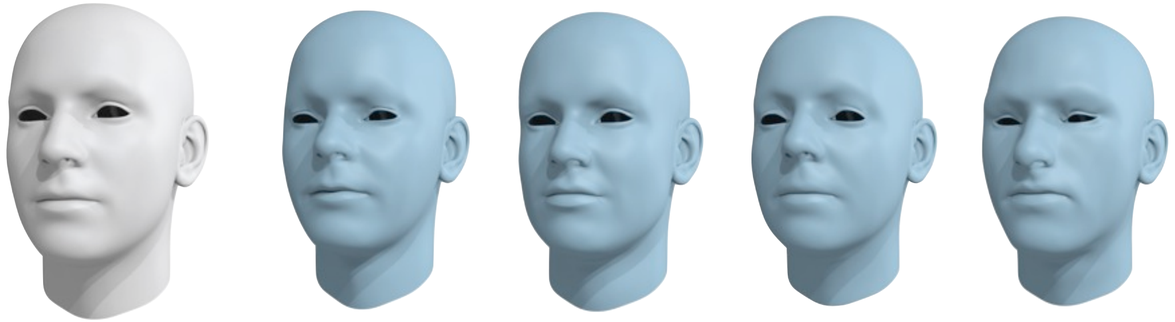

$\mathbf{m}$ $\mathbf{p}_1$ $\mathbf{p}_2$ $\mathbf{p}_3$ $\mathbf{p}_4$

$$\mathbf{s} = \mathbf{P}\mathbf{d} + \mathbf{m}$$

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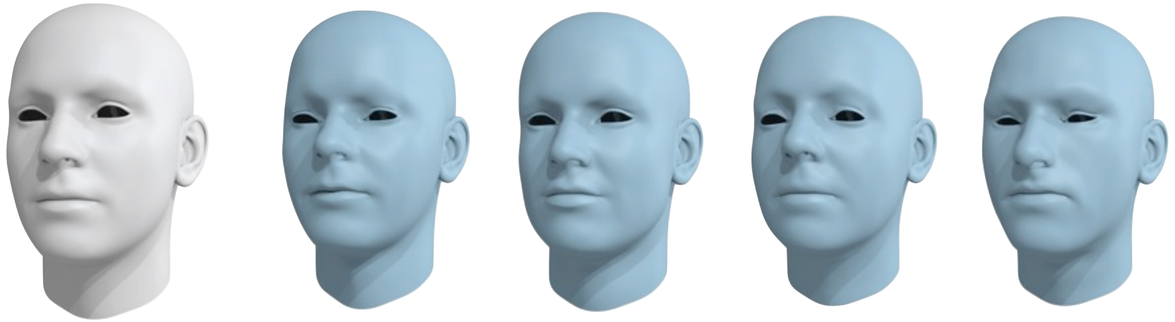

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mean shape

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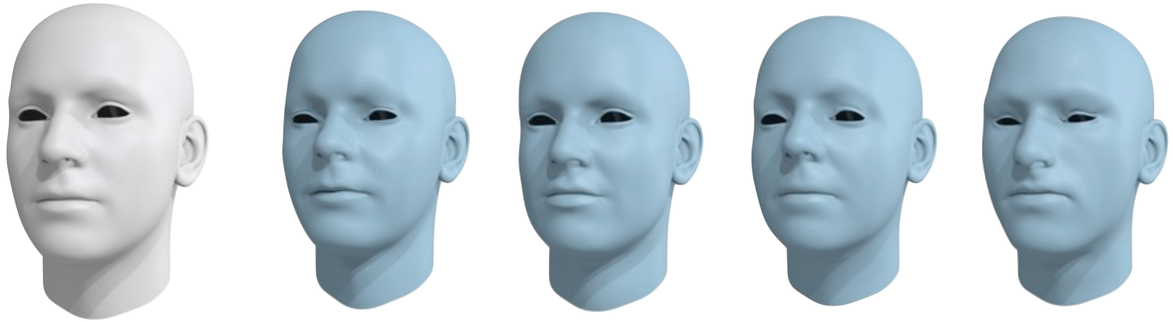

$$\mathbf{s} = \mathbf{P}\mathbf{d} + \mathbf{m}$$

basis

mean shape

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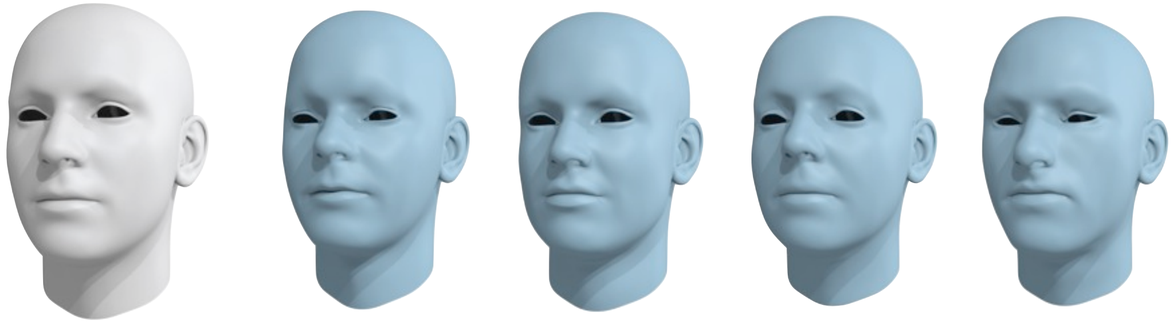

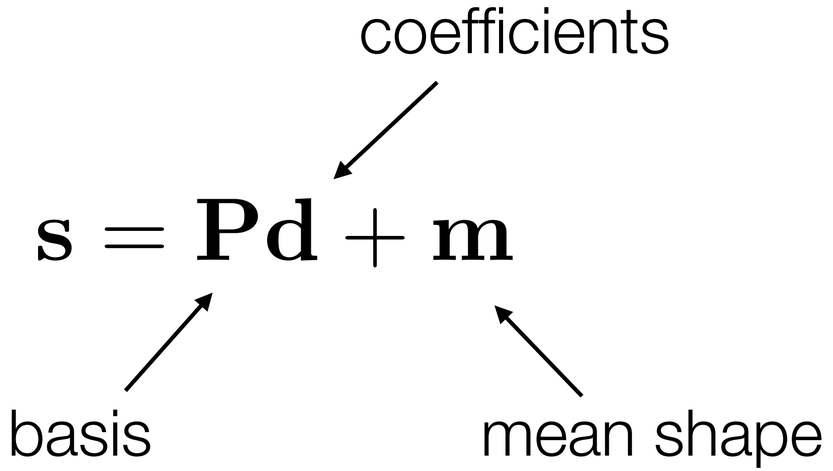

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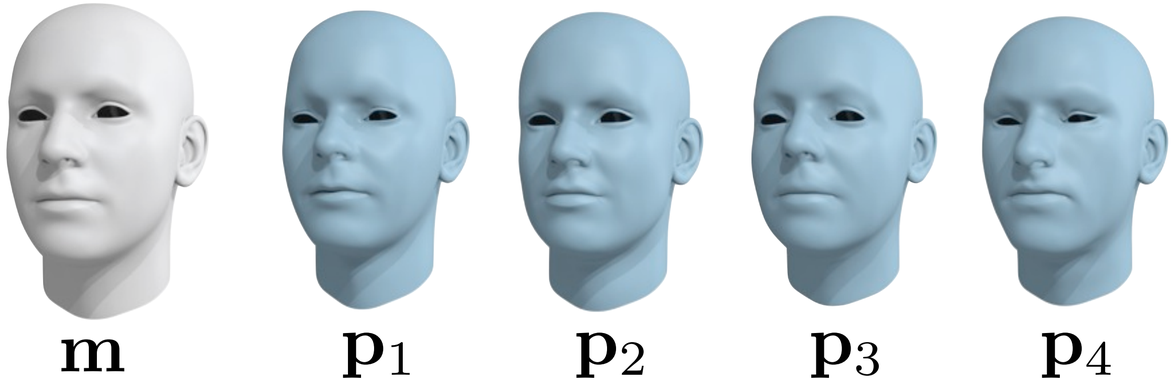
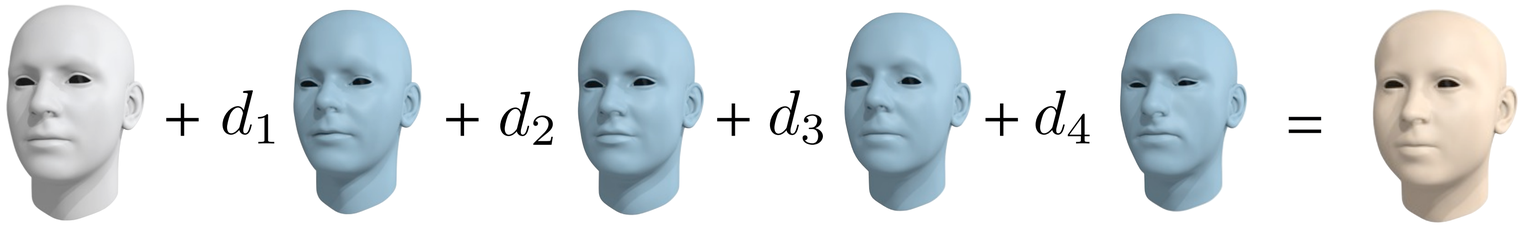


coefficients

$$\mathbf{s} = \mathbf{P}\mathbf{d} + \mathbf{m}$$

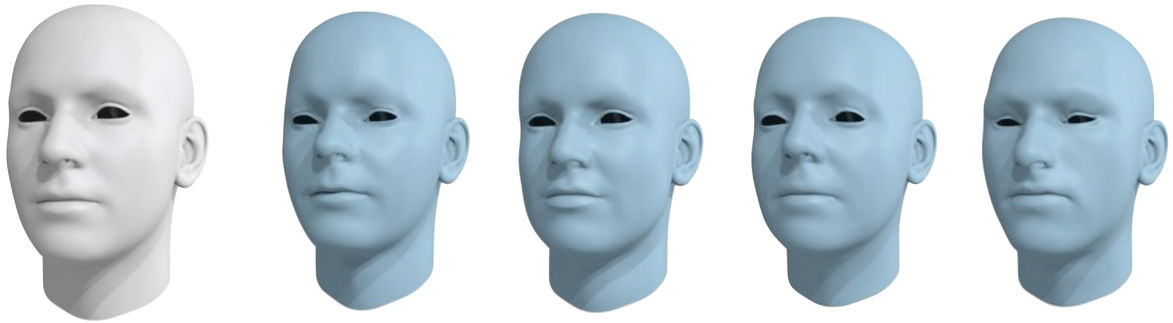
basis

mean shape



3D Registration - Prior

- Linear Model $E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$



$$\mathbf{s} = \mathbf{P}\mathbf{d} + \mathbf{m}$$

$$E_{\text{prior}}(Z, \mathbf{d}) = \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{P}_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

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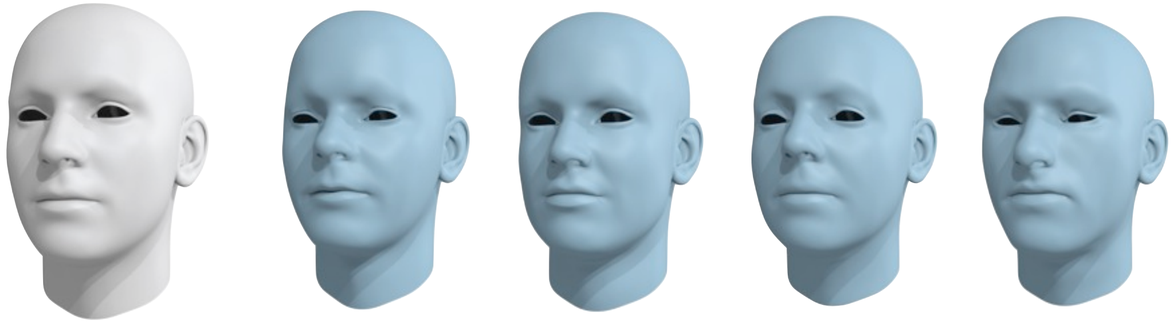

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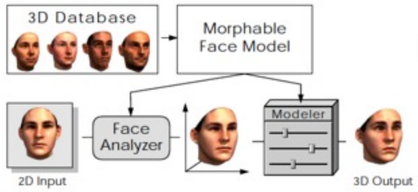

Blanz, Vetter: **A Morphable Model for the Synthesis of 3D Faces**
ACM SIGGRAPH 1999

3D Registration - Prior

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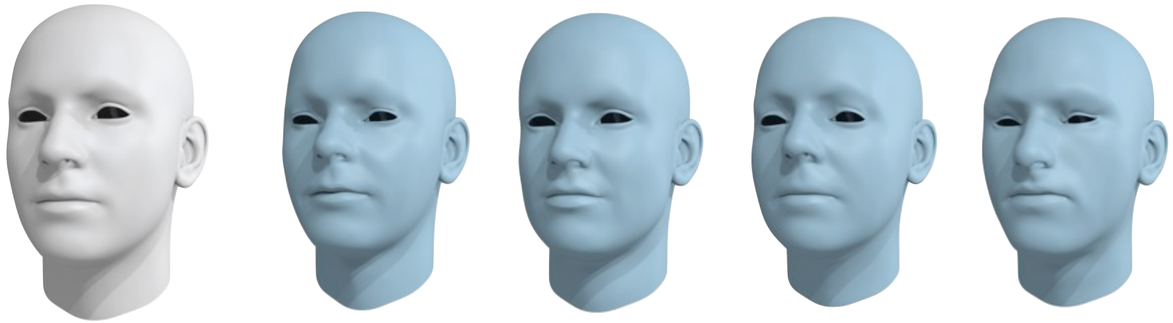

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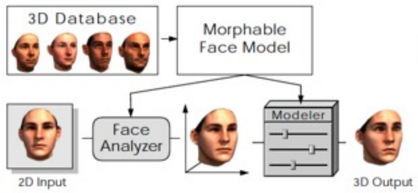

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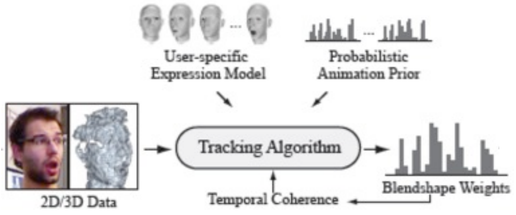

Overview

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  - Non-rigid Modeling
  - Realtime Face Tracking

Conclusions

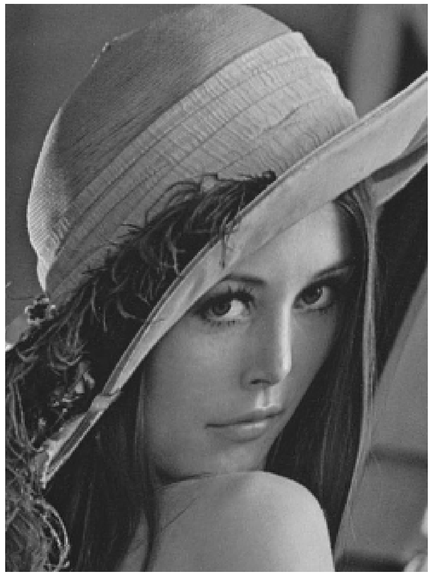
2D Registration

Source

I

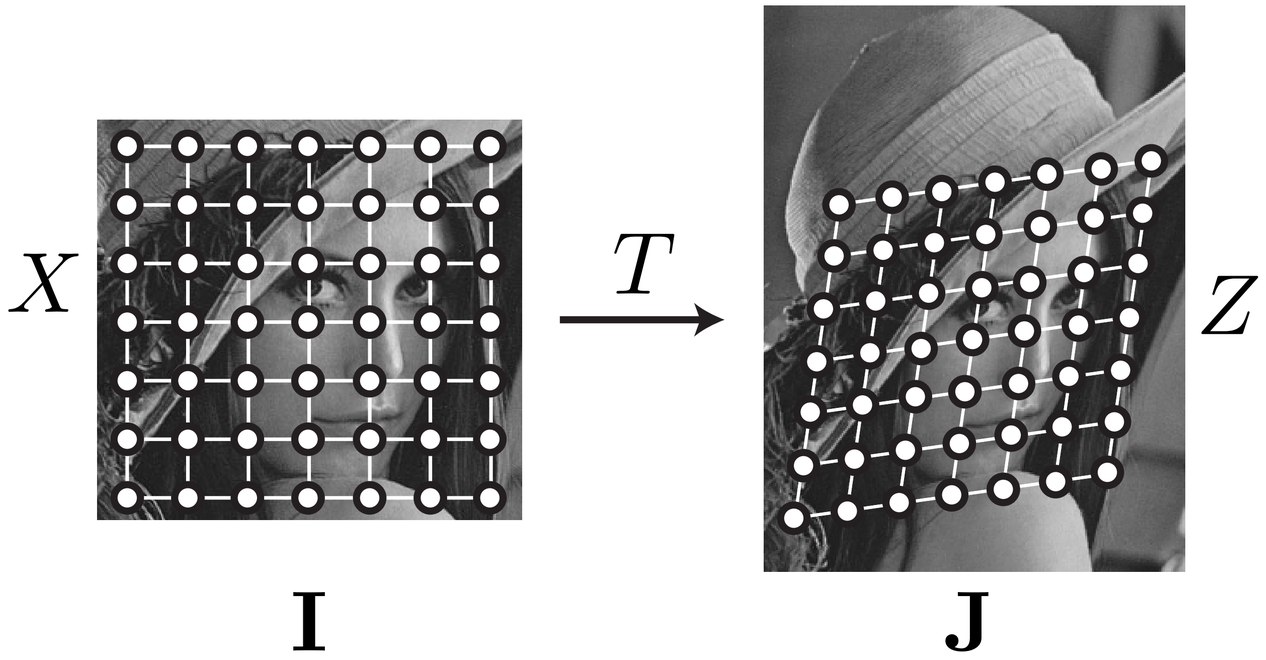
?

Target

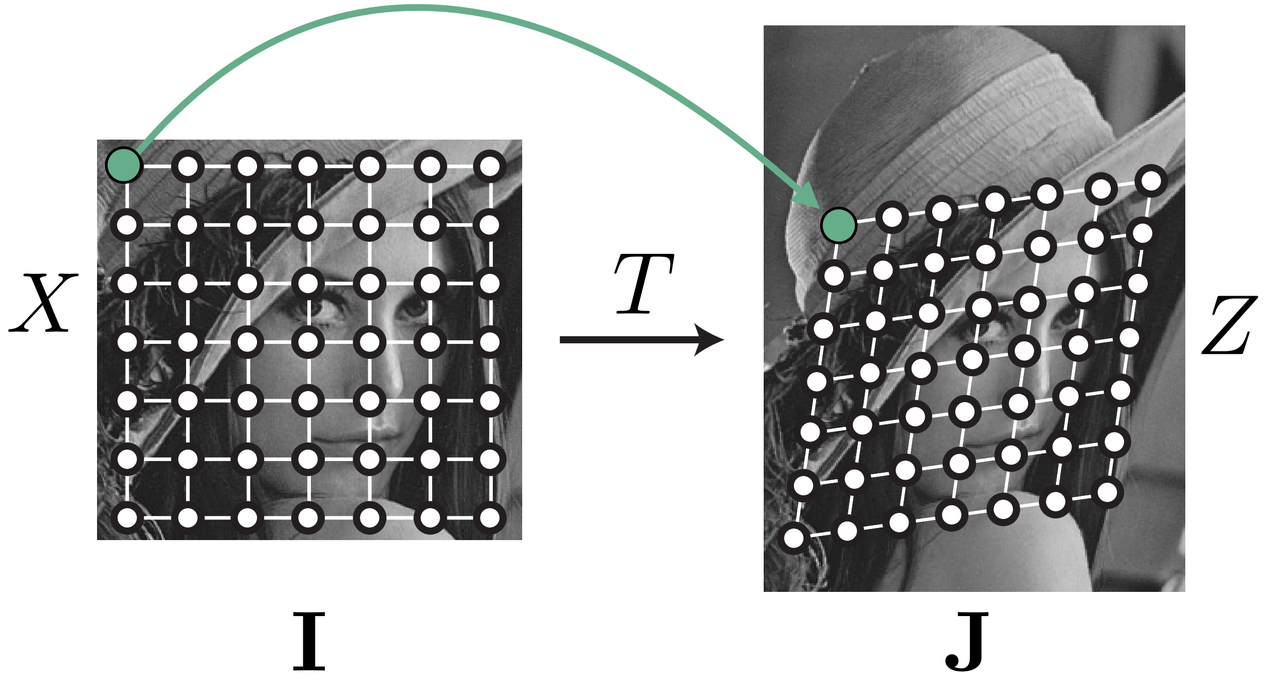


J

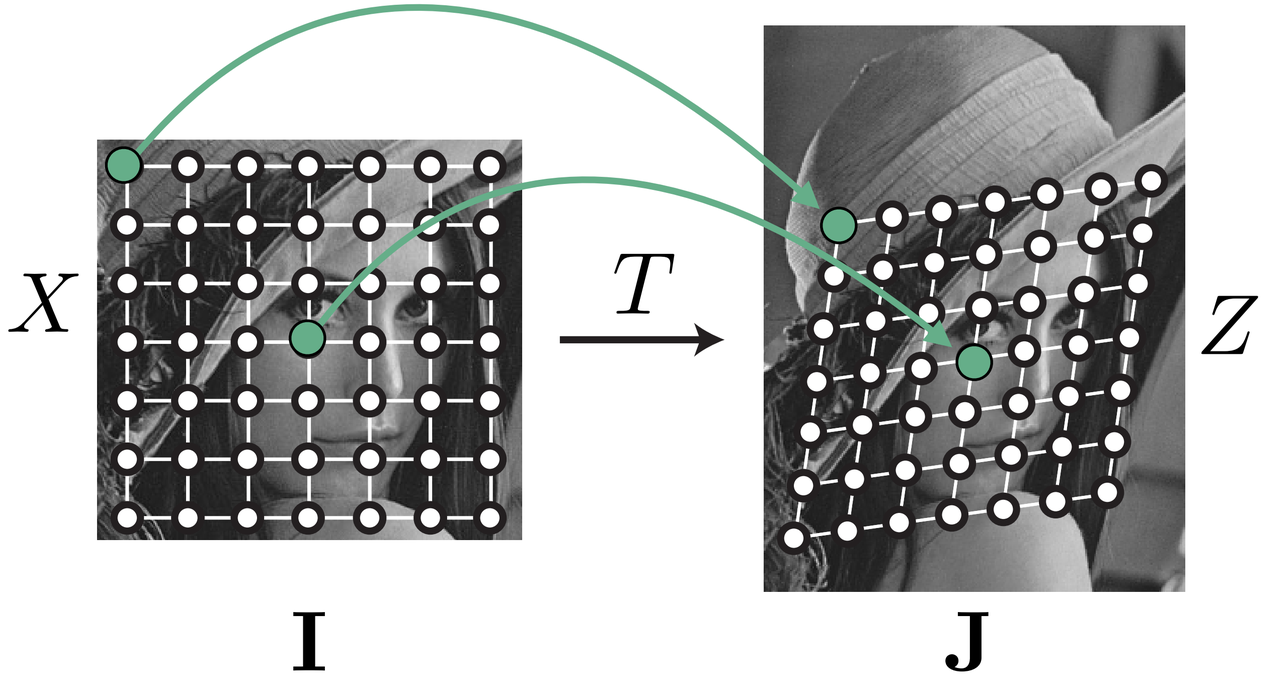
2D Registration



2D Registration



2D Registration



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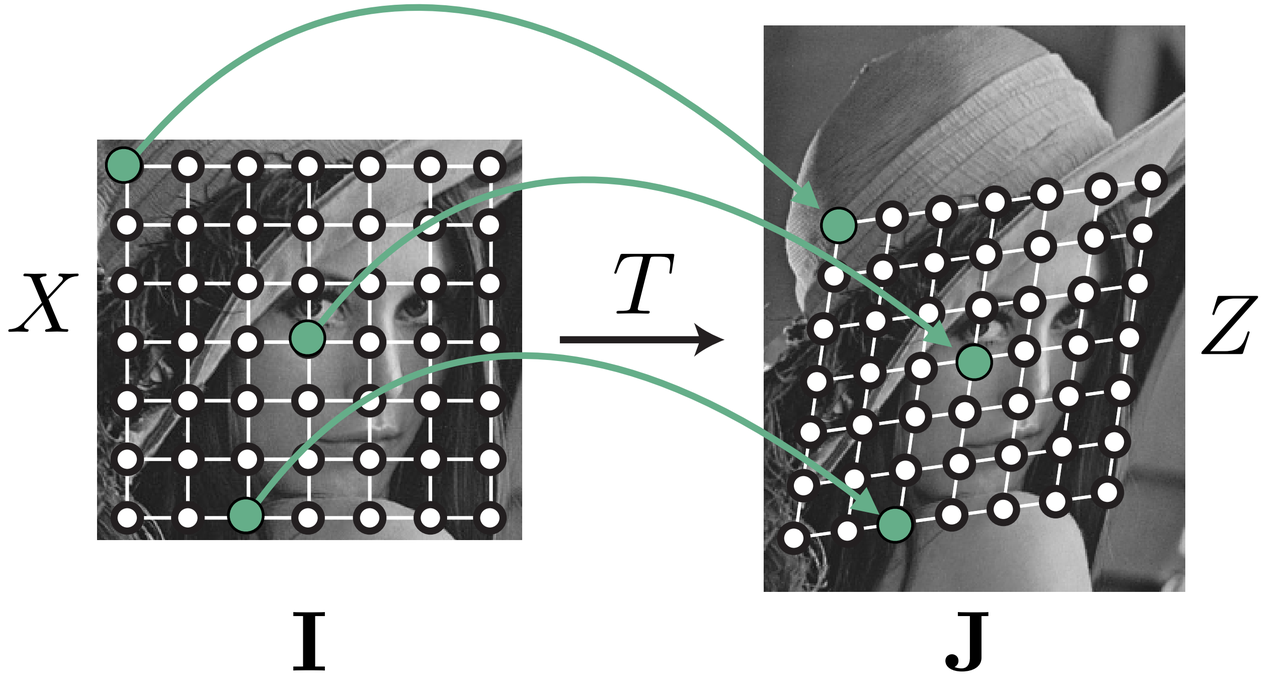

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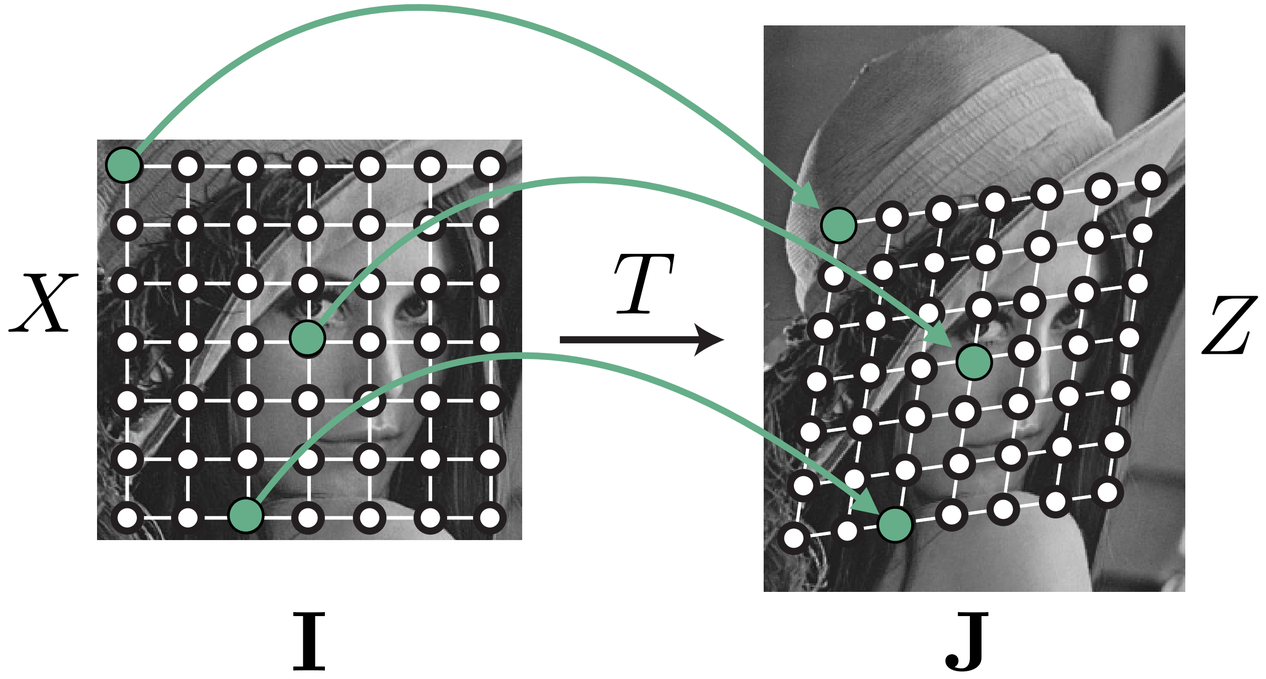
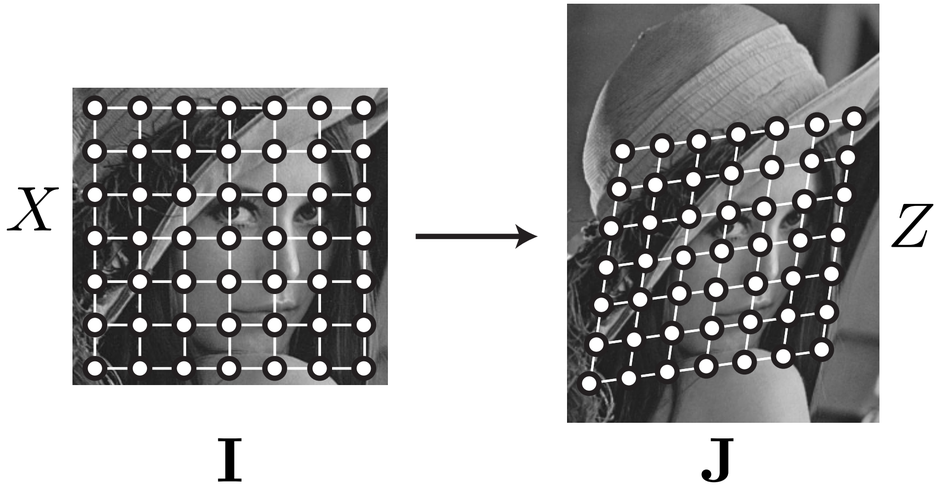


DEMO

2D Registration - Matching



$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(Z) = \sum_{i=1}^{n} \|\mathbf{I}(\mathbf{x}_i) - \mathbf{J}(\mathbf{z}_i)\|_2^2$$

color value at $\mathbf{x}_i$ of image $\mathbf{I}$

color value at $\mathbf{z}_i$ of image $\mathbf{J}$

2D Registration - Prior

- Lucas-Kanade
  - Constant displacement field

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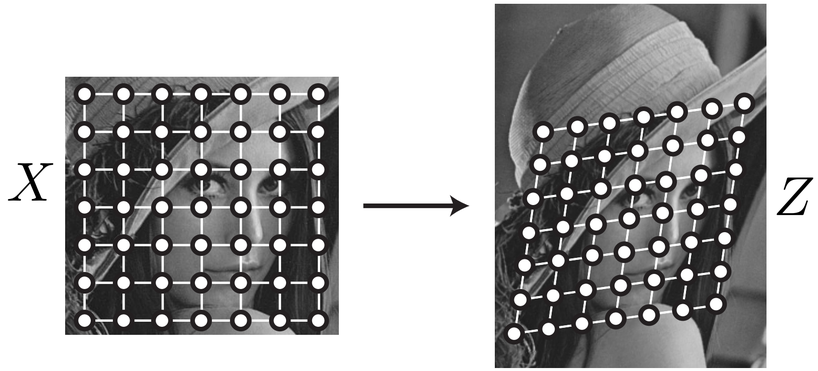

$$E_{\text{prior}}(Z) = \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{x}_j) - (\mathbf{z}_i - \mathbf{x}_i)\|_2^2$$

Lucas, Kanade: **An Iterative Image Registration Technique with an Application to Stereo Vision**, *IJCAI 1981*

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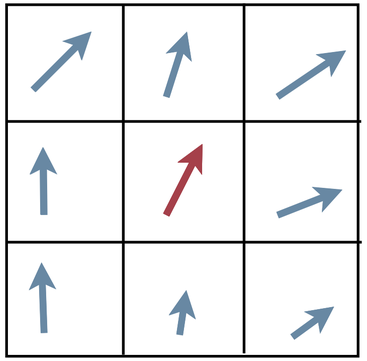

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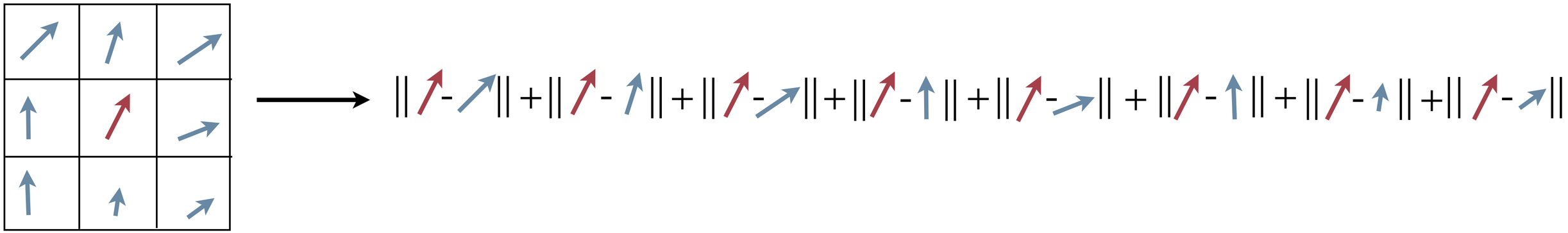
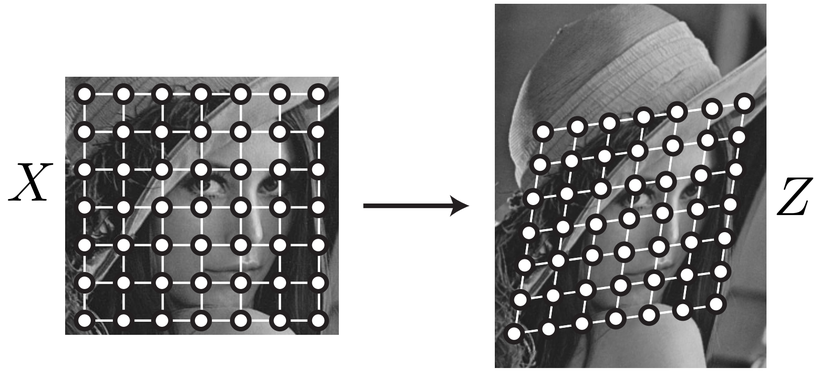


Lucas, Kanade: **An Iterative Image Registration Technique with an Application to Stereo Vision**, *IJCAI 1981*

2D Registration - Prior

- Horn-Schunck
  - Smooth displacement field

$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$



$$E_{\text{prior}}(Z) = \sum_{i=1}^{n} \left\| (\mathbf{z}_i - \mathbf{x}_i) - \frac{1}{|\mathcal{N}_i|} \sum_{j \in \mathcal{N}_i} (\mathbf{z}_j - \mathbf{x}_j) \right\|_2^2$$

Horn, Schunk: “**Determining Optical Flow”**, *Artificial Intelligence Journal 1981*

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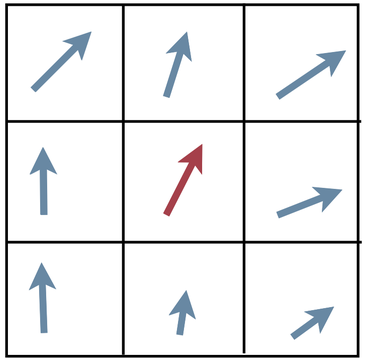

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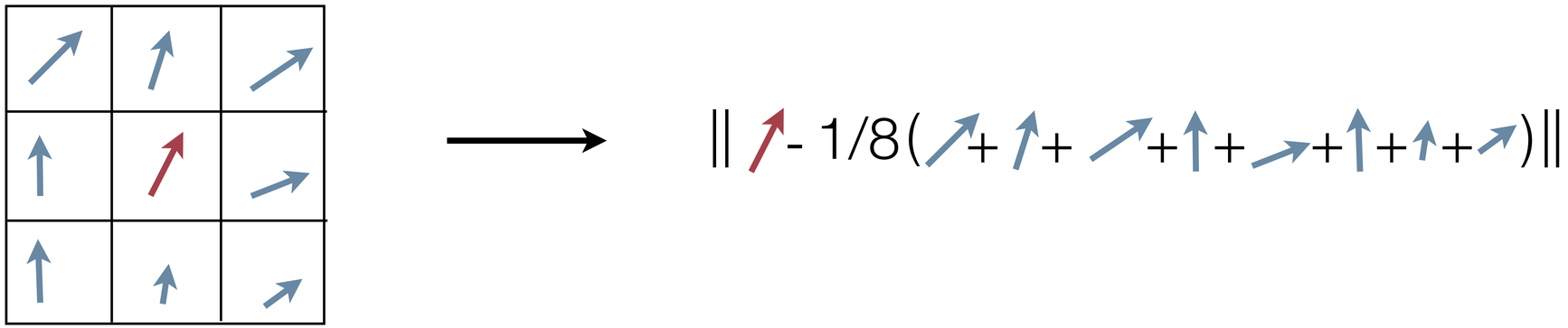

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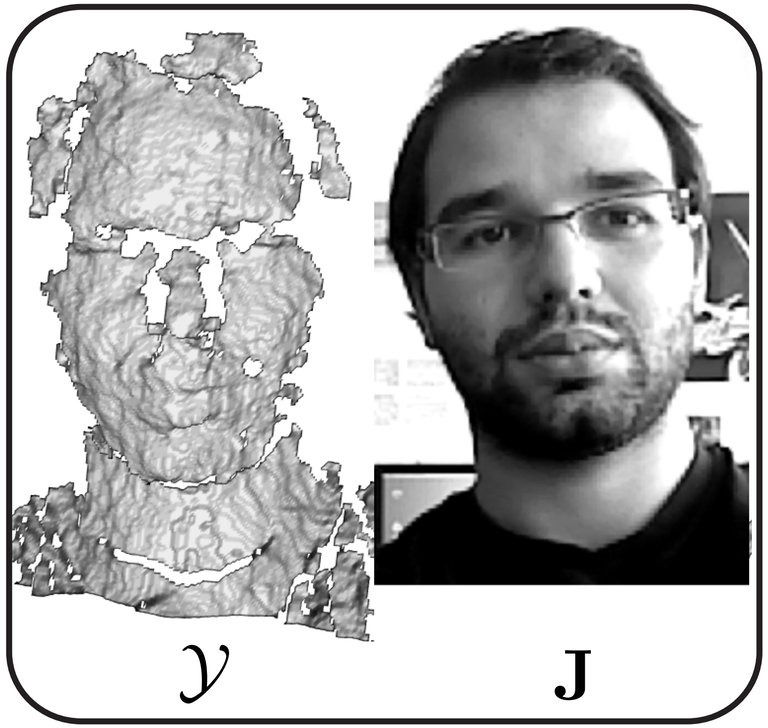
2D/3D Registration

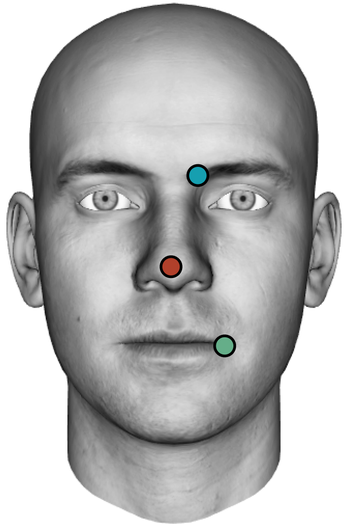
$\mathcal{X}$ $\mathbf{I}$

?



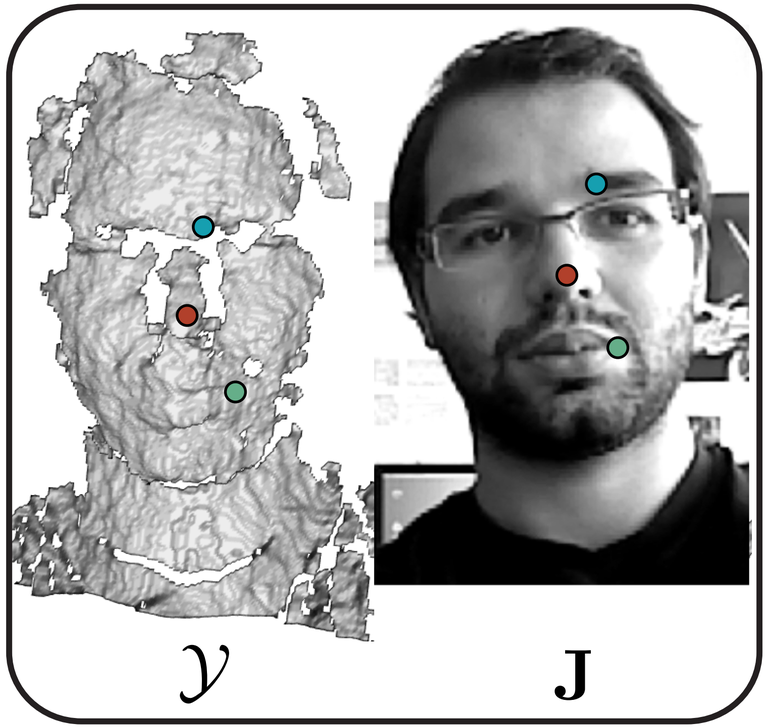
$\mathcal{Y}$ $\mathbf{J}$

2D/3D Registration



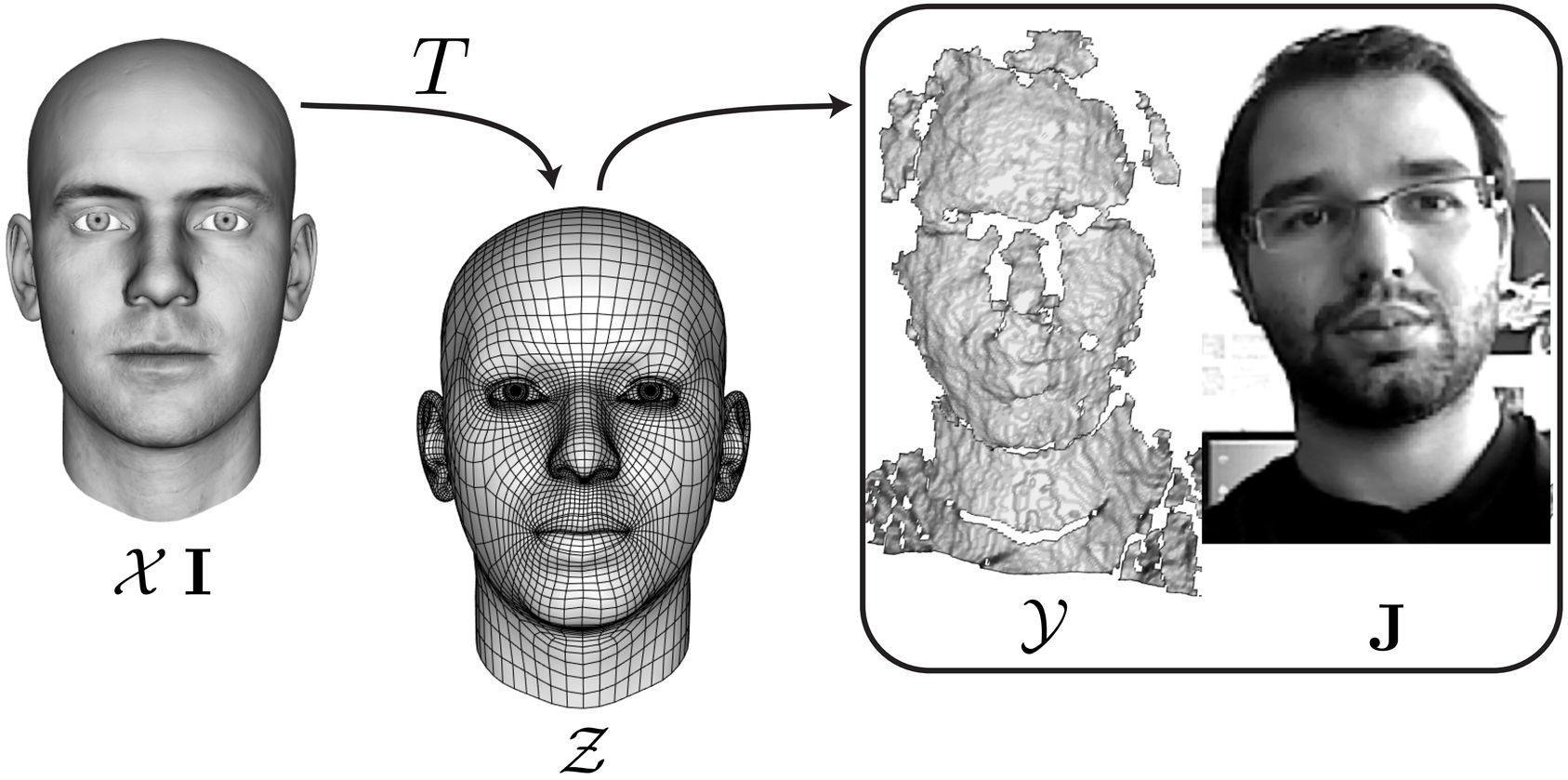
$\mathcal{X}$ $\mathbf{I}$

?



$\mathcal{Y}$ $\mathbf{J}$

2D/3D Registration



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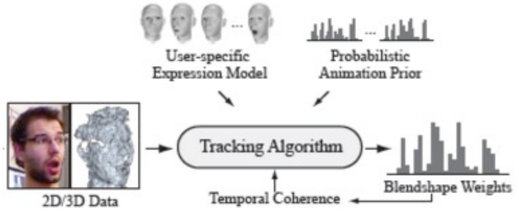
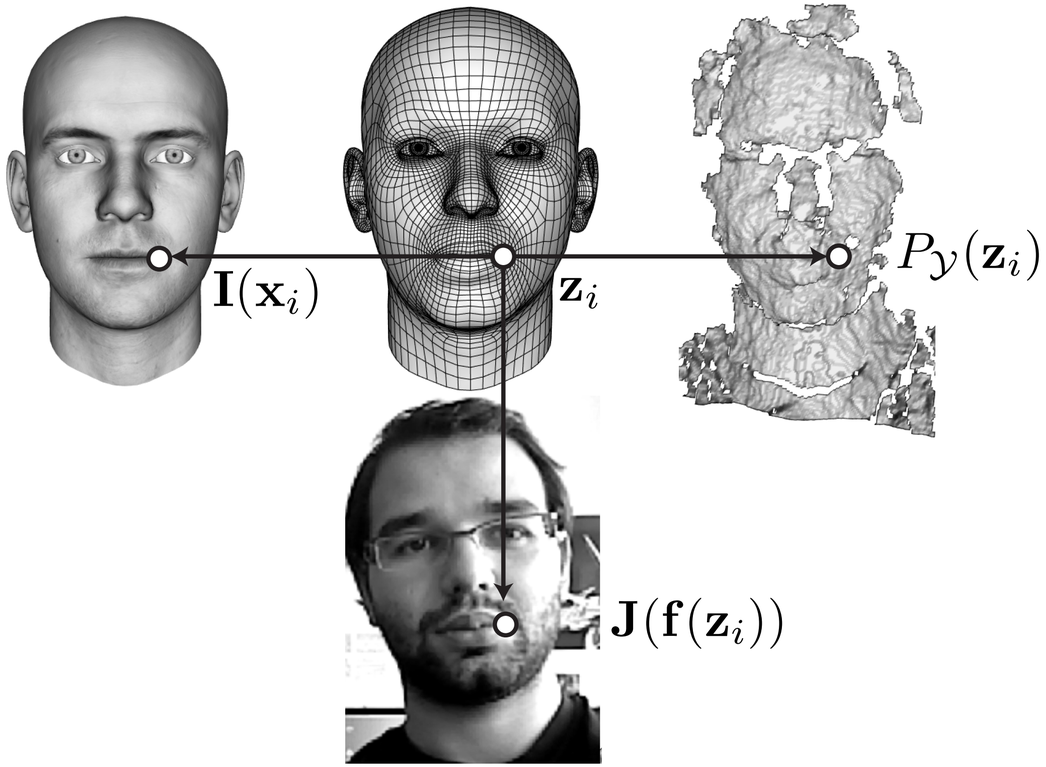


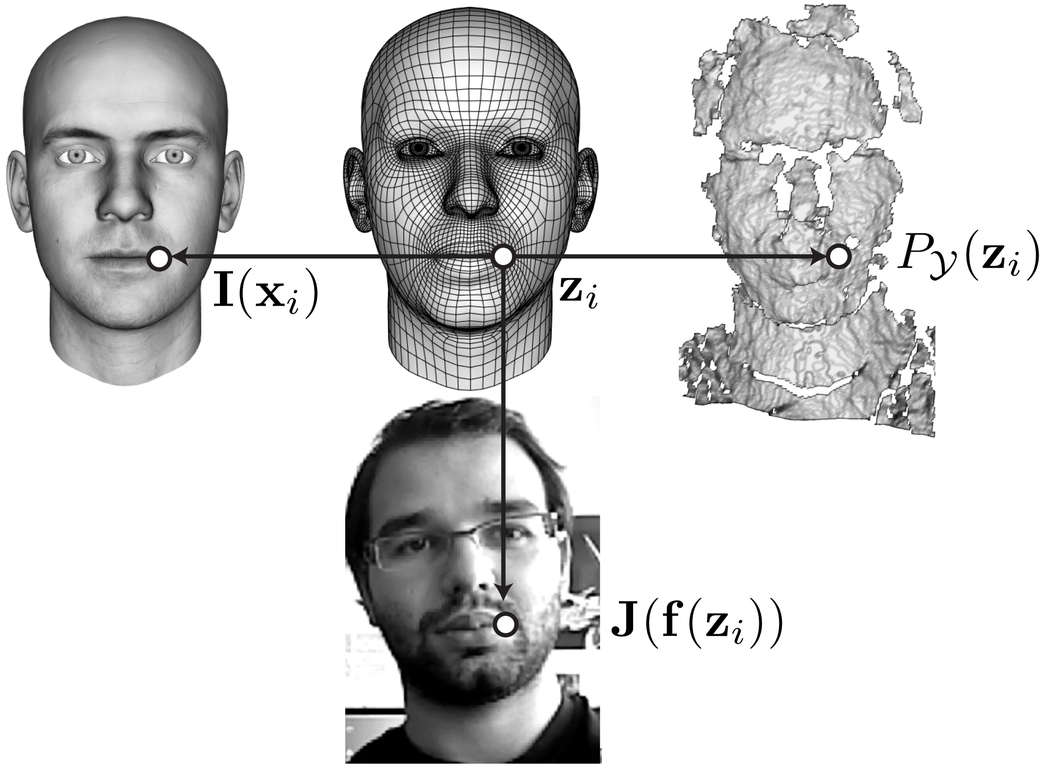
2D/3D - Matching



$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

$$E_{\text{match}}(Z) = w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{I}(\mathbf{x}_i) - \mathbf{J}(\mathbf{f}(\mathbf{z}_i))\|_2^2$$

2D/3D - Matching



$$E_{\text{reg}} = E_{\text{match}} + E_{\text{prior}}$$

projection of the 3D vertex in the 2D image

$$E_{\text{match}}(Z) = w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{I}(\mathbf{x}_i) - \mathbf{J}(\mathbf{f}(\mathbf{z}_i))\|_2^2$$

2D/3D - Matching

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Orthographic projection $\mathbf{f}(\mathbf{z}_i) = \begin{bmatrix} \mathbf{z}_{i,x} & \mathbf{z}_{i,y} \end{bmatrix}^T$

Perspective projection $\mathbf{f}(\mathbf{z}_i) = \begin{bmatrix} \frac{f\mathbf{z}_{i,x}}{\mathbf{z}_{i,z}} & \frac{f\mathbf{z}_{i,y}}{\mathbf{z}_{i,z}} \end{bmatrix}^T$

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Conclusions

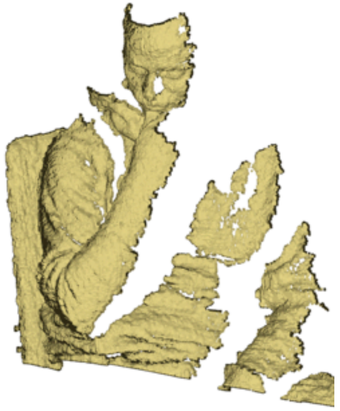
Rigid Scanning

- Popular Kinect application

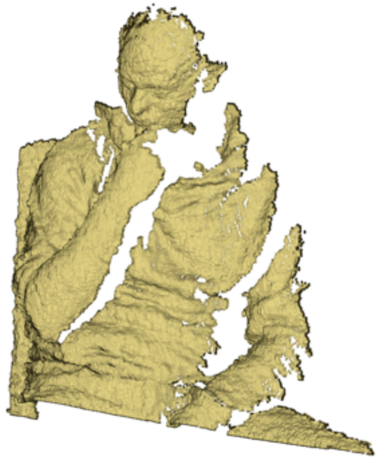
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

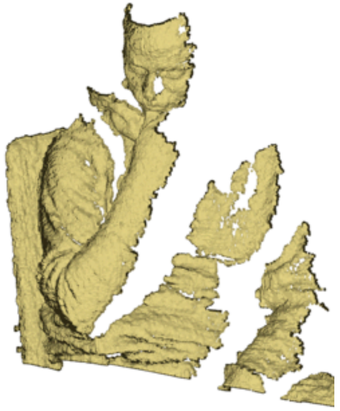
Rigid Scanning

Rigid Scanning

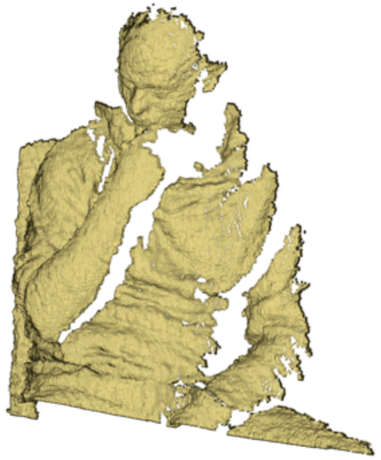


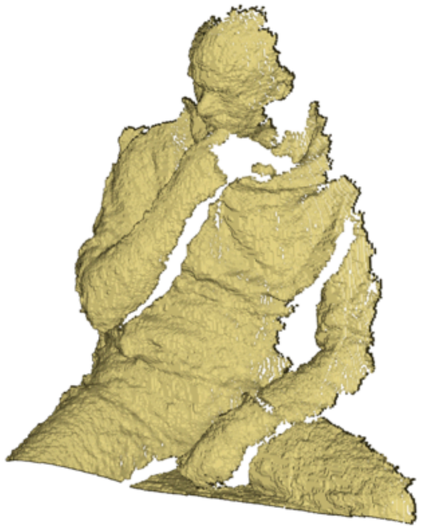
Rigid Scanning

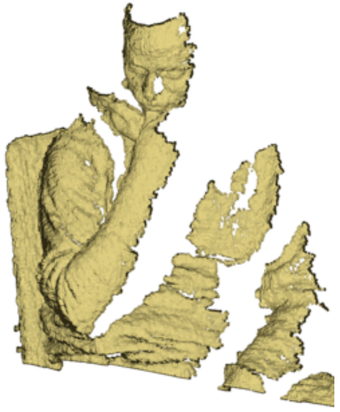




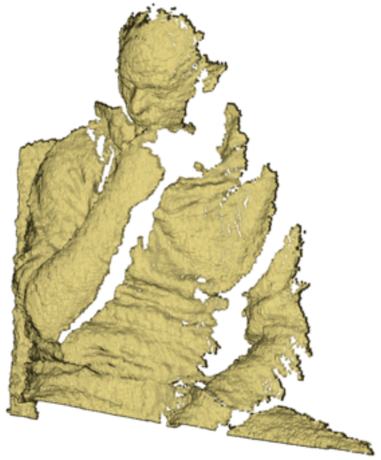
Rigid Scanning

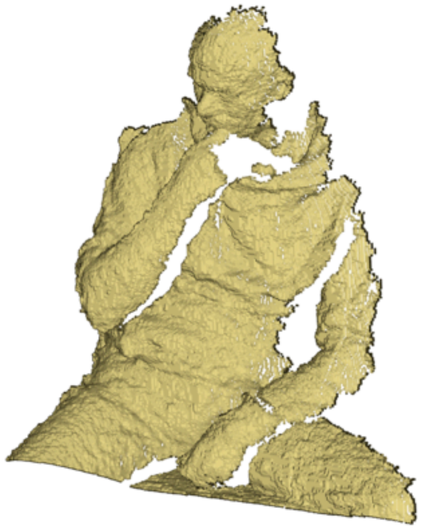


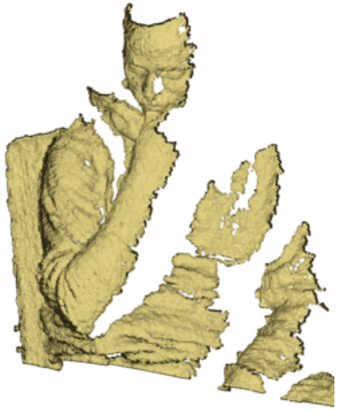


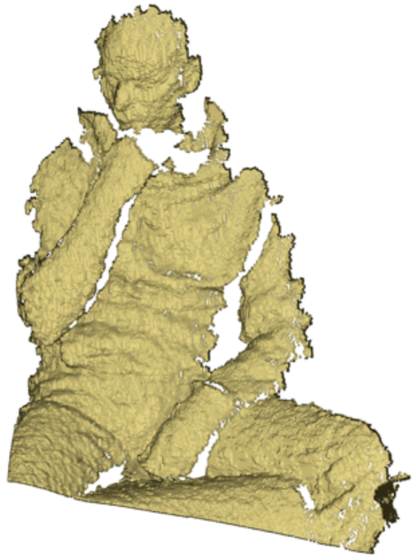


Rigid Scanning

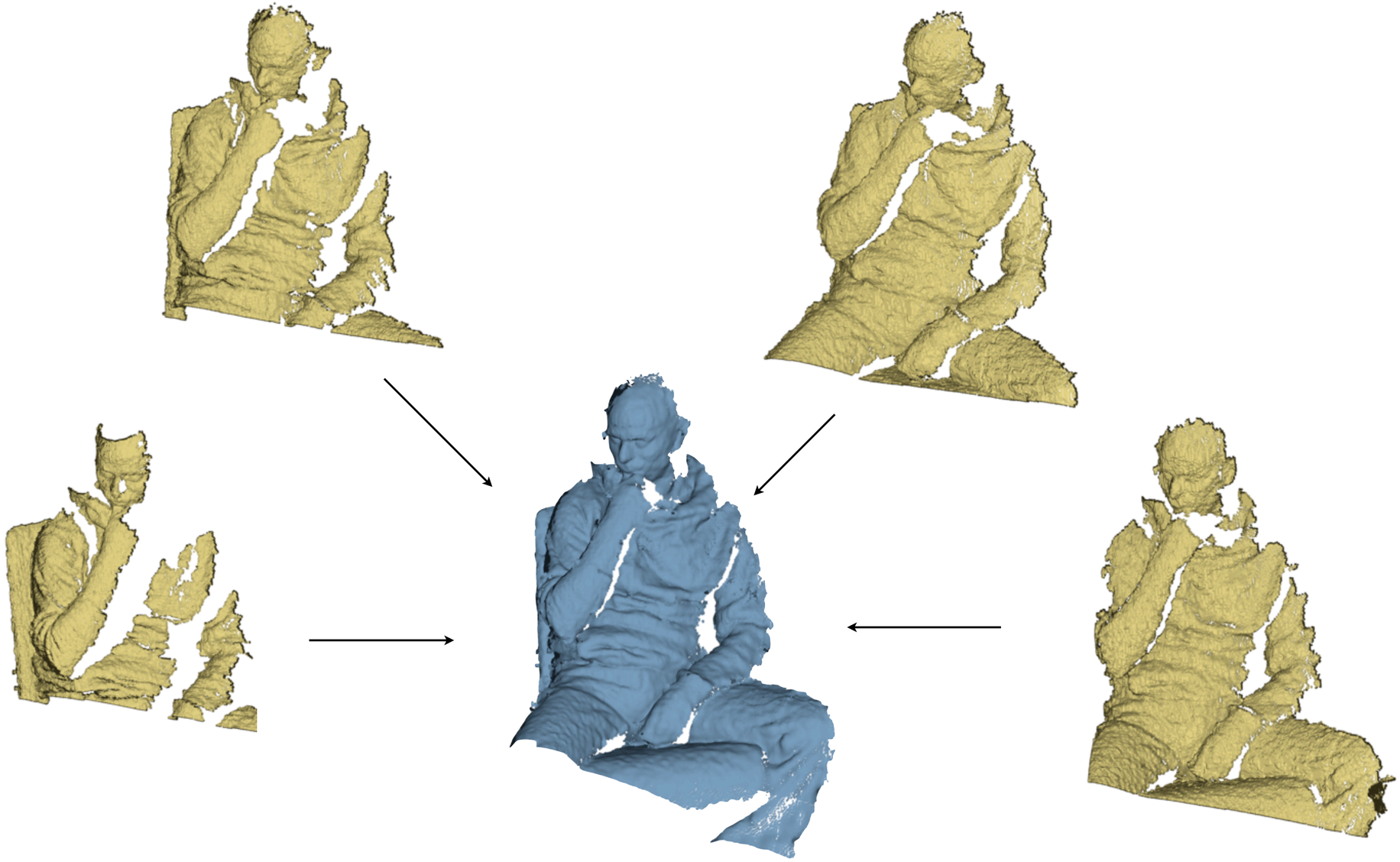








Rigid Scanning



Rigid Scanning - Pipeline

Rigid Scanning - Pipeline

Calibration matrix

K

Depth map

Rigid Scanning - Pipeline

Calibration matrix → **K**

Depth map

Smoothing

Rigid Scanning - Pipeline

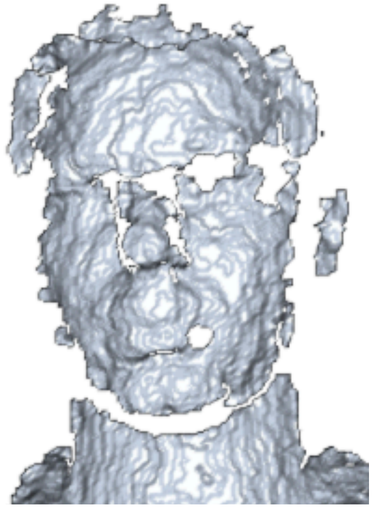
Calibration matrix

K

Depth map

Smoothing

Mesh & Normals



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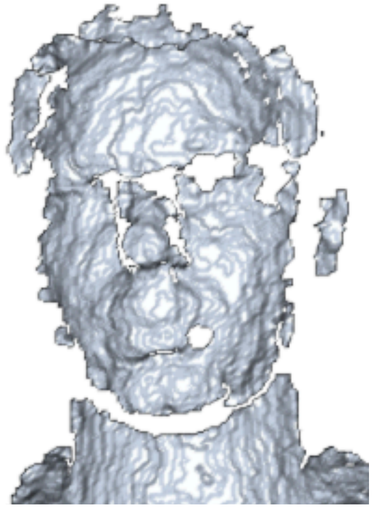
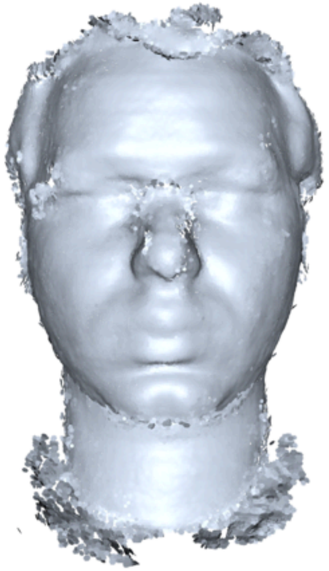


Alignment &
Accumulation



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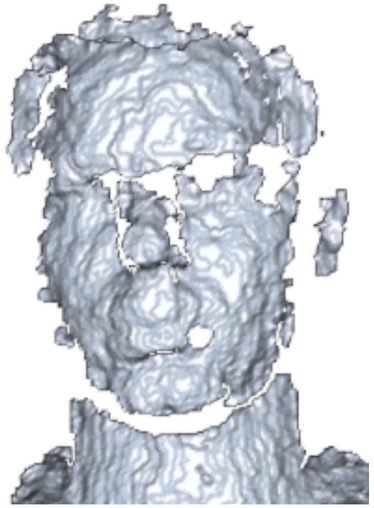

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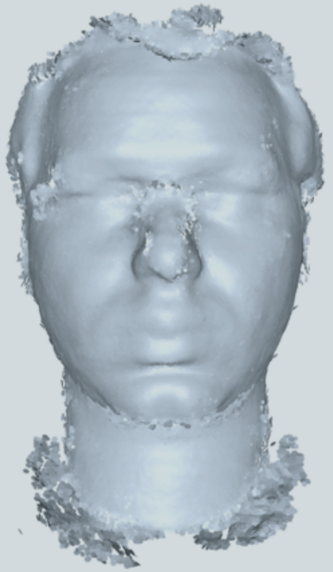


Rigid Scanning - Optimization

$$\underset{Z,\mathbf{R},\mathbf{t}}{\arg\min}\, w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

Rigid Scanning - Optimization

$$\underset{Z,\mathbf{R},\mathbf{t}}{\arg\min}\, w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

matching term

Rigid Scanning - Optimization

$$\underset{Z,\mathbf{R},\mathbf{t}}{\arg\min}\, w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

matching term

rigid prior

Rigid Scanning - Optimization

$$\arg\min_{Z,\mathbf{R},\mathbf{t}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

matching term

rigid prior

Rigid Scanning - Optimization

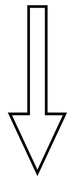
$$\arg\min_{Z,\mathbf{R},\mathbf{t}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

$$\Downarrow$$

$$\arg\min_{Z^{t+1},\tilde{\mathbf{R}},\tilde{\mathbf{t}}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^{t})\|_2^2 + w_2 \sum_{i=1}^{n} ||\mathbf{z}_i^{t+1} - (\tilde{\mathbf{R}}(\mathbf{R}^t\mathbf{x}_i + \mathbf{t}^t) + \tilde{\mathbf{t}})||_2^2$$

Rigid Scanning - Optimization

$$\arg\min_{Z,\mathbf{R},\mathbf{t}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$



$$\arg\min_{Z^{t+1},\tilde{\mathbf{R}},\tilde{\mathbf{t}}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)\|_2^2 + w_2 \sum_{i=1}^{n} ||\mathbf{z}_i^{t+1} - (\tilde{\mathbf{R}}(\mathbf{R}^t\mathbf{x}_i + \mathbf{t}^t) + \tilde{\mathbf{t}})||_2^2$$

use previous estimate
= closest point

Rigid Scanning - Optimization

$$\arg\min_{Z,\mathbf{R},\mathbf{t}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

$$\Downarrow$$

$$\arg\min_{Z^{t+1},\tilde{\mathbf{R}},\tilde{\mathbf{t}}} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^{t})\|_2^2 + w_2 \sum_{i=1}^{n} ||\mathbf{z}_i^{t+1} - (\tilde{\mathbf{R}}(\mathbf{R}^t\mathbf{x}_i + \mathbf{t}^t) + \tilde{\mathbf{t}})||_2^2$$

use previous estimate
= closest point

linearize rotation matrix

$$\mathbf{R}^{t+1} = \tilde{\mathbf{R}}\mathbf{R}^t$$

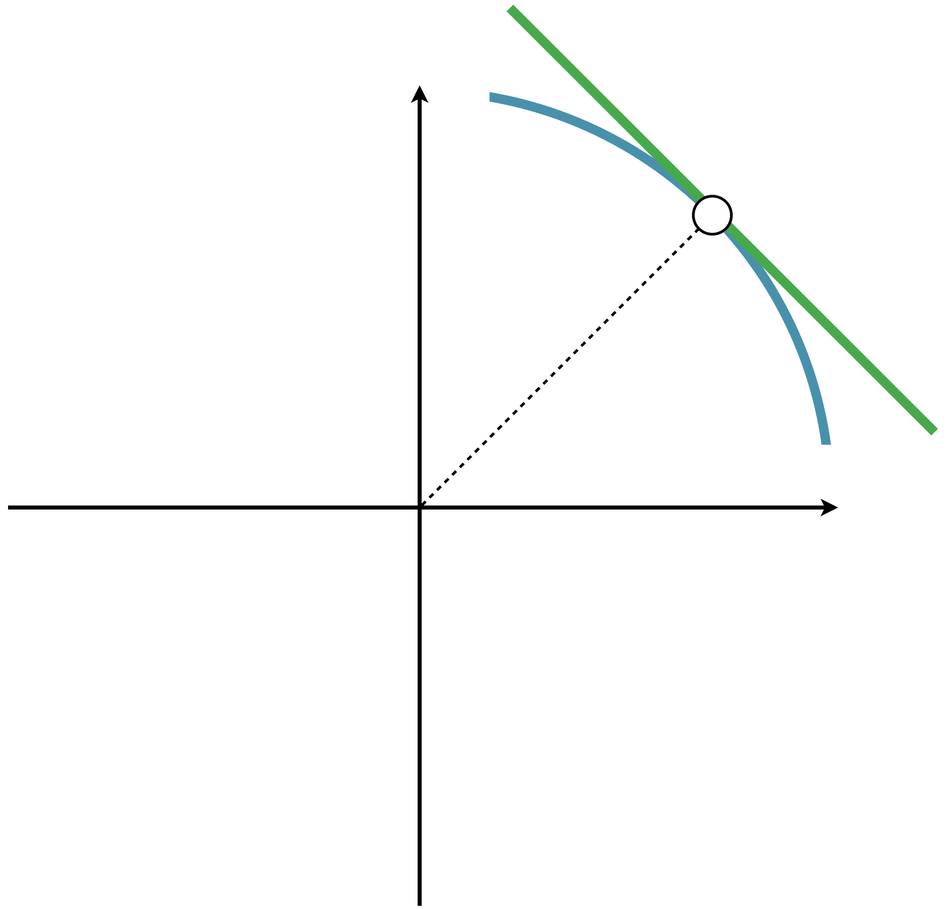
$$\mathbf{t}^{t+1} = \tilde{\mathbf{R}}\mathbf{t}^t + \tilde{\mathbf{t}}$$

Rigid Scanning - Optimization

Rotation matrix linearization

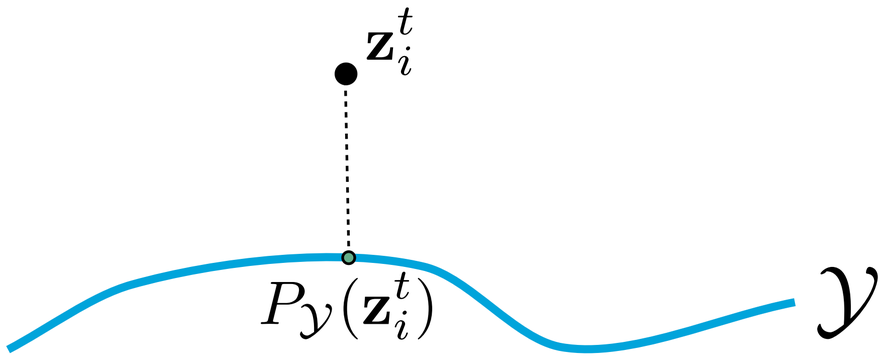
$$\sin(\theta) \approx \theta \quad \cos(\theta) \approx 1$$

$$\mathbf{R} \approx \tilde{\mathbf{R}} = \begin{bmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{bmatrix}$$



Rigid Scanning - Optimization

$$\|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)\|_2^2$$



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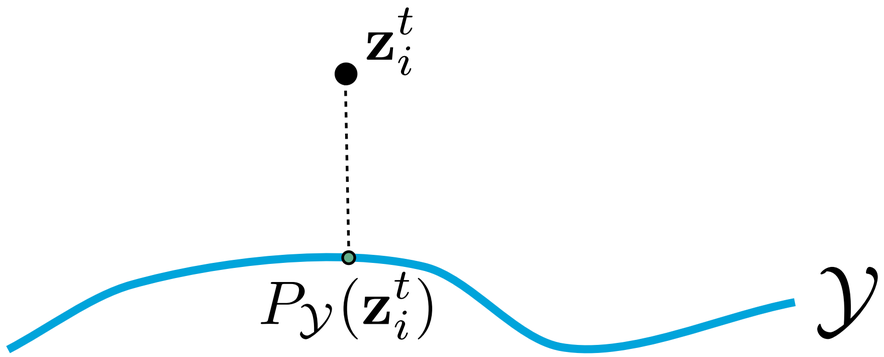
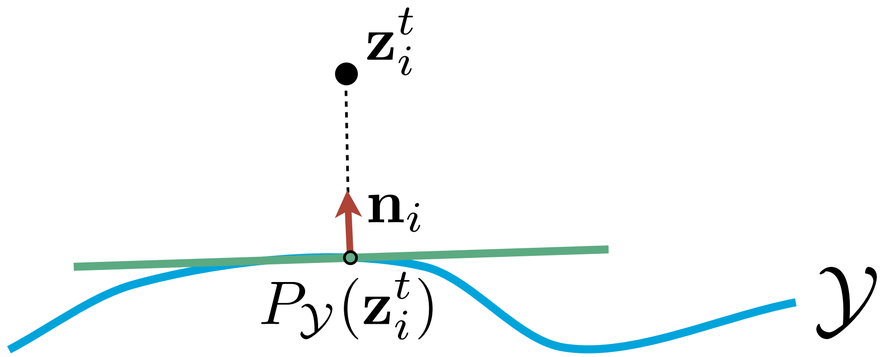
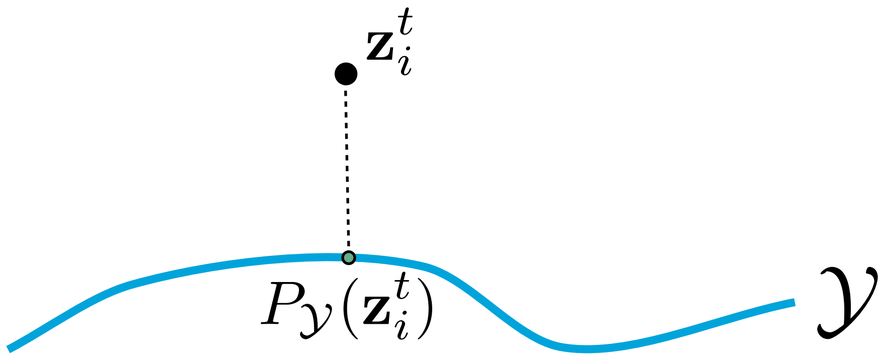
$$\|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)\|_2^2$$



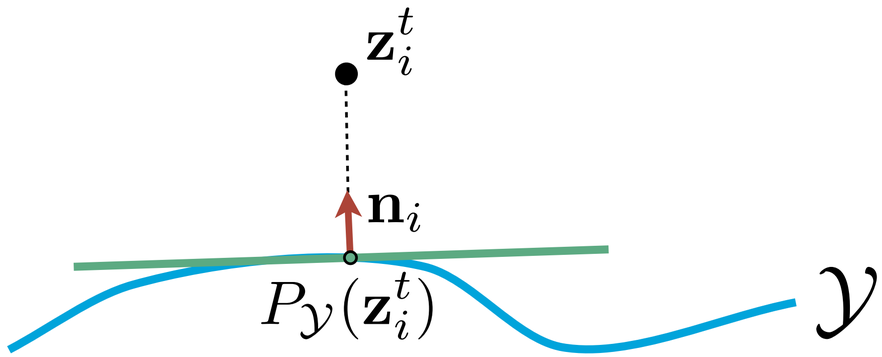


Rigid Scanning - Optimization

$$\|\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)\|_2^2$$



$$(\mathbf{n}_i^T(\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)))^2$$



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Rigid Scanning - Optimization

$$\underset{Z,\mathbf{R},\mathbf{t}}{\arg\min}\, w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2$$

$$\Downarrow$$

$$\underset{Z^{t+1},\tilde{\mathbf{R}},\tilde{\mathbf{t}}}{\arg\min}\, w_1 \sum_{i=1}^{n} (\mathbf{n}_i^T(\mathbf{z}_i^{t+1} - P_{\mathcal{Y}}(\mathbf{z}_i^t)))^2 + w_2 \sum_{i=1}^{n} ||\mathbf{z}_i^{t+1} - (\tilde{\mathbf{R}}(\mathbf{R}^t\mathbf{x}_i + \mathbf{t}^t) + \tilde{\mathbf{t}})||_2^2$$

Rigid Scanning - Accumulation

Rigid Scanning - Accumulation

- Reduce the number of points

Rigid Scanning - Accumulation

- Reduce the number of points
- Reduce noise

Rigid Scanning - Accumulation

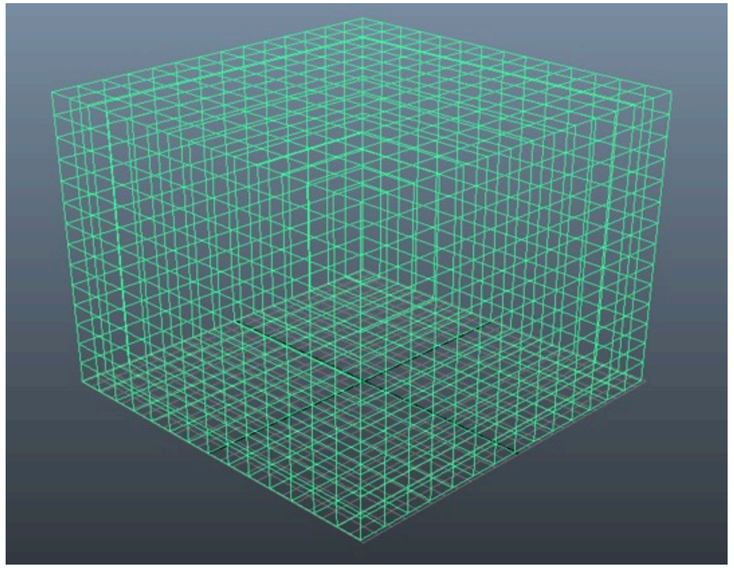
- Reduce the number of points
- Reduce noise

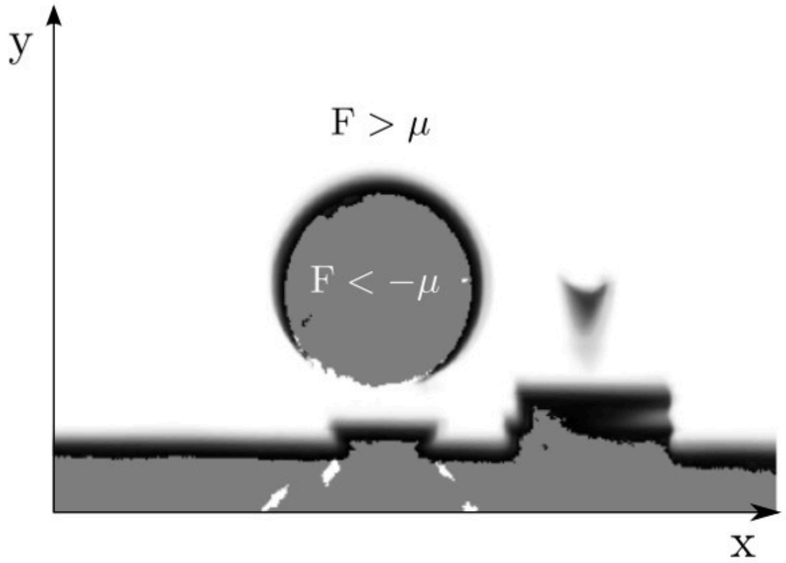
Volume

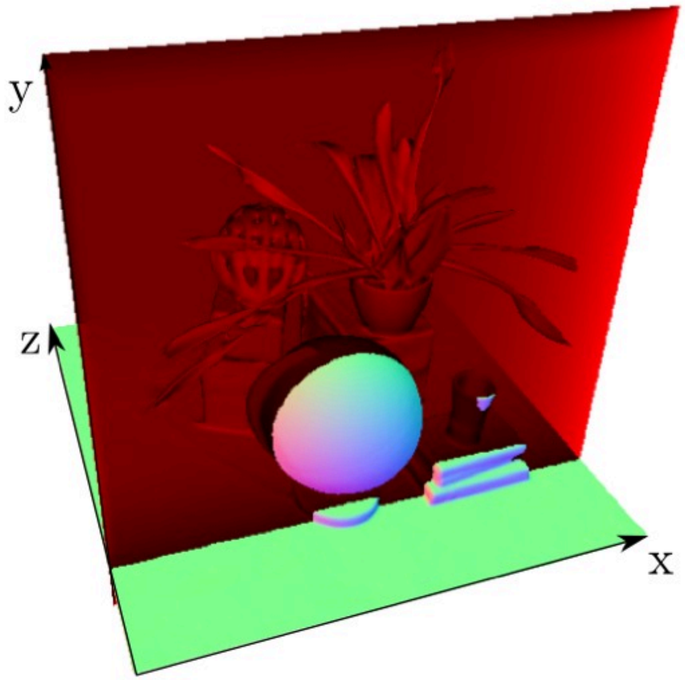
Newcombe, Izadi, Hilliges, Molyneaux, Kim,
Davison, Kohli, Shotton, Hodges, Fitzgibbon:
KinectFusion: Real-Time Dense Surface Mapping and Tracking,
ISMAR 2011

Rigid Scanning - Accumulation

Volumetric accumulation



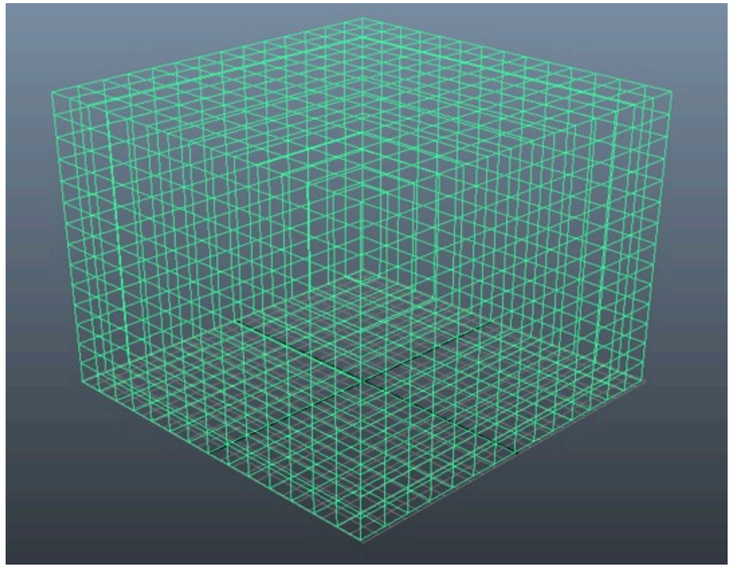


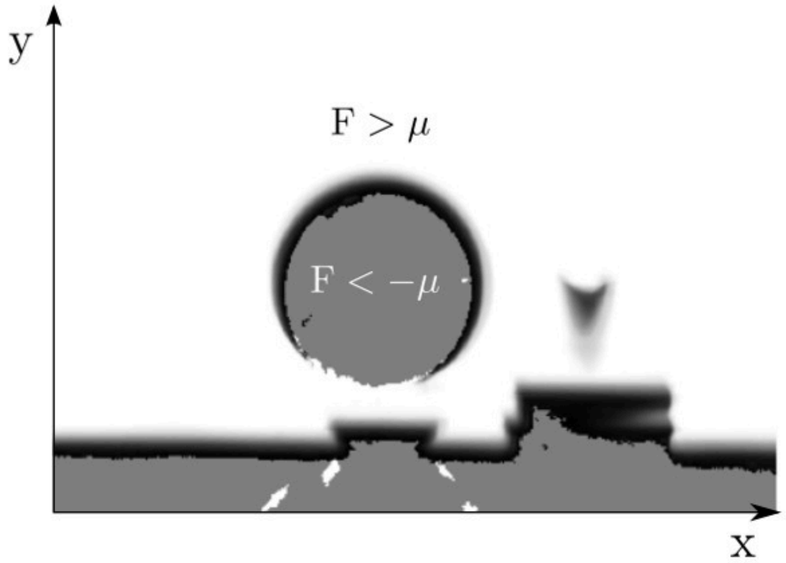


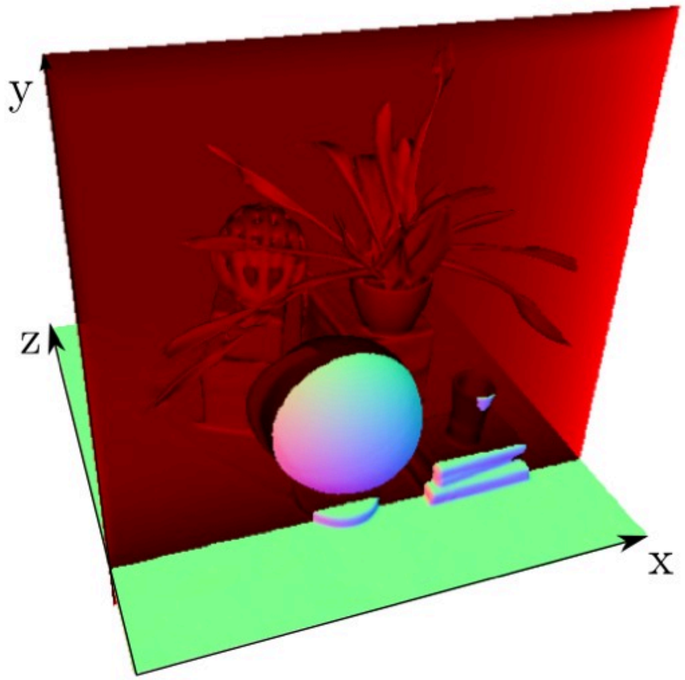
KinectFusion: Real-Time Dense Surface Mapping and Tracking, *ISMAR 2011*

Rigid Scanning - Accumulation

Volumetric accumulation







DEMO

KinectFusion: Real-Time Dense Surface Mapping and Tracking, *ISMAR 2011*

Rigid Scanning - Accumulation

- Reduce the number of points
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ISMAR 2011

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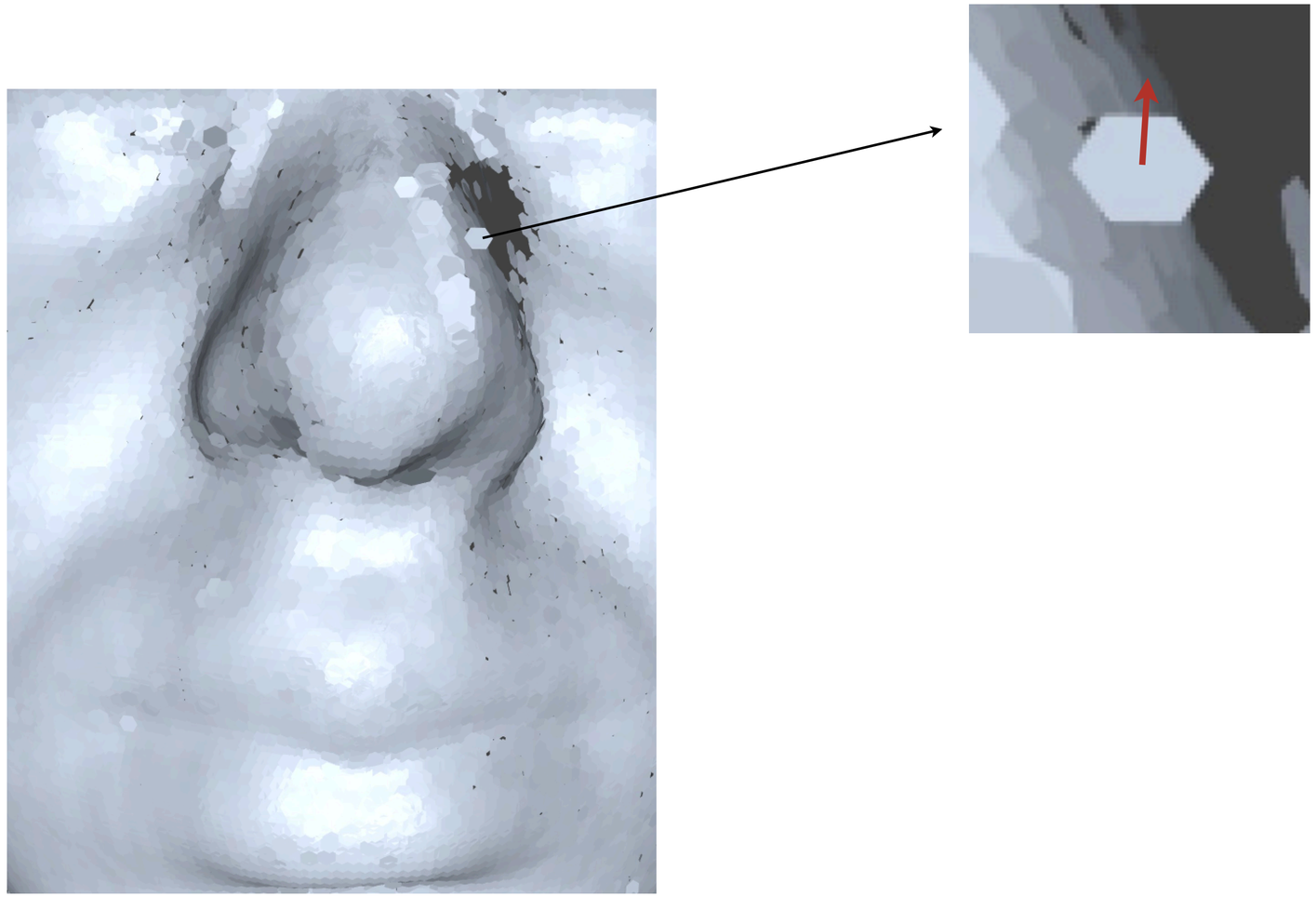
ISMAR 2011

Surface

Weise, Wismer, Leibe, Van Gool:
In-hand Scanning with Online Loop Closure,
3DIM 2009

Rigid Scanning - Accumulation

Surface accumulation

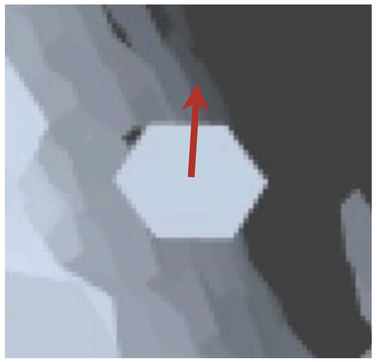


In-hand Scanning with Online Loop Closure, *3DIM 2009*

Rigid Scanning - Accumulation

Surface accumulation

Surfel update



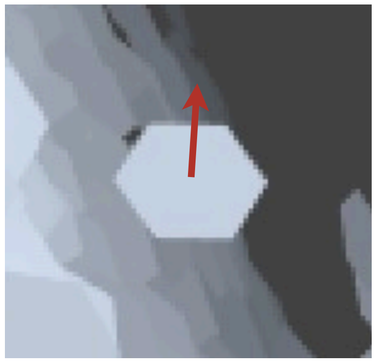
In-hand Scanning with Online Loop Closure, *3DIM 2009*

Rigid Scanning - Accumulation

Surface accumulation

Surfel update

Surfel addition



In-hand Scanning with Online Loop Closure, *3DIM 2009*

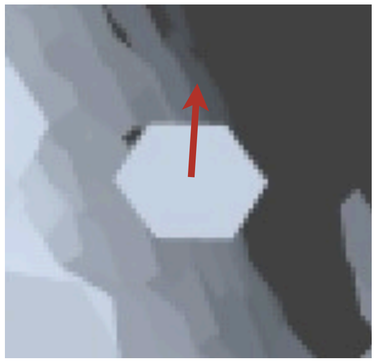
Rigid Scanning - Accumulation

Surface accumulation

Surfel update

Surfel addition

Surfel removal



In-hand Scanning with Online Loop Closure, *3DIM 2009*

Rigid Scanning - Accumulation

Surface accumulation

Surfel update

Surfel addition

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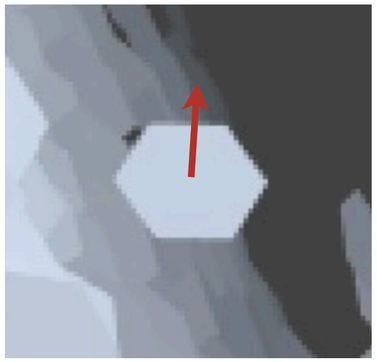


DEMO

In-hand Scanning with Online Loop Closure, *3DIM 2009*

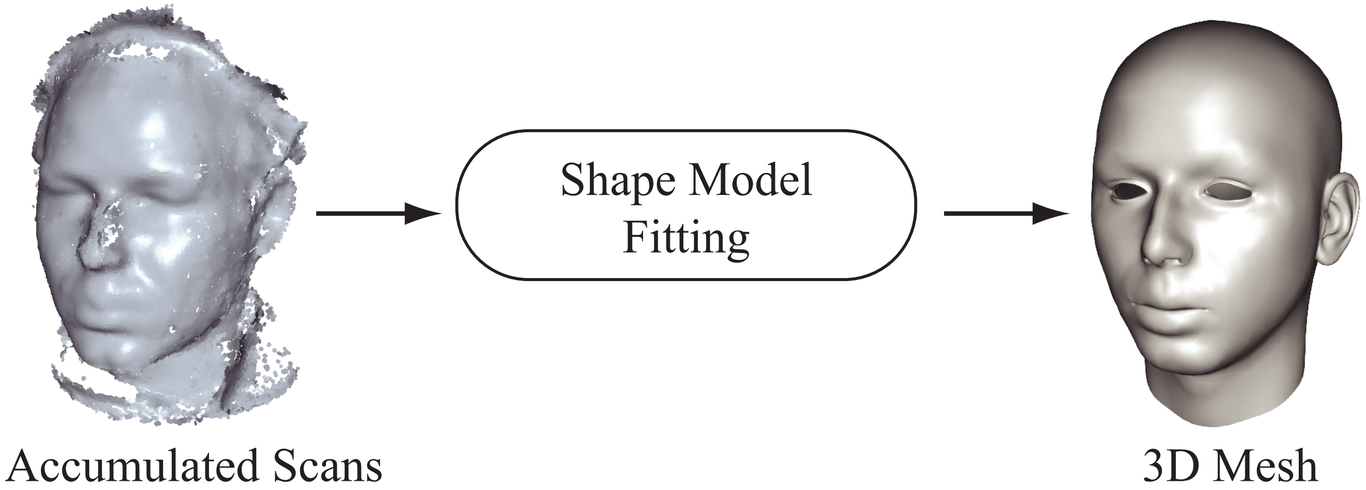
Overview

Introduction

- Registration
  - 3D Geometry
  - 2D Images
  - Combined 2D / 3D
- Applications
  - Rigid Scanning
  - **Non-rigid Modeling**
  - Realtime Face Tracking

Conclusions

Non-Rigid Modeling

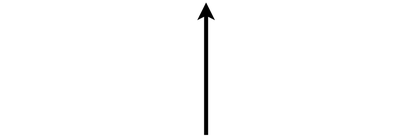


Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} \; w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} \; w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$



matching term

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} \; w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

matching term

rigid prior

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} \; w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

matching term

rigid prior

non-rigid prior

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} \; w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

matching term | rigid prior | non-rigid prior | linear model

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

- How to set the weights for the different energies?

Non-Rigid Modeling

$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

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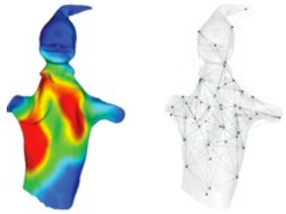

Li, Adams, Guibas, Pauly:
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Global Correspondence Optimization for Non-Rigid Registration of Depth Scans,
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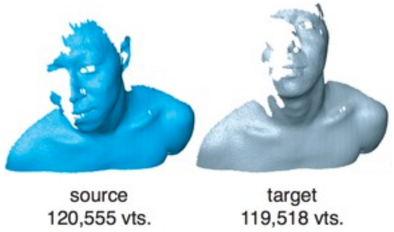

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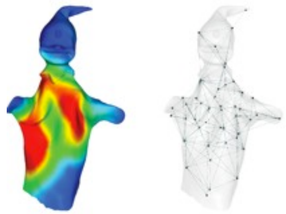
$$\underset{Z,\mathbf{R}_i|_{i=1}^n,\mathbf{R},\mathbf{t},\mathbf{d}}{\arg\min} w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}\mathbf{x}_i + \mathbf{t})\|_2^2 + w_3 \sum_{i=1}^{n} \sum_{j \in \mathcal{N}_i} \|(\mathbf{z}_j - \mathbf{z}_i) - \mathbf{R}_i(\mathbf{x}_j - \mathbf{x}_i)\|_2^2 + w_4 \sum_{i=1}^{n} \|\mathbf{z}_i - (P_i\mathbf{d} + \mathbf{m}_i)\|_2^2$$

- How to set the weights for the different energies?

DEMO



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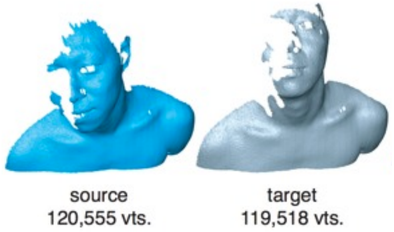

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Face Tracking

- Blendshape model

Face Tracking

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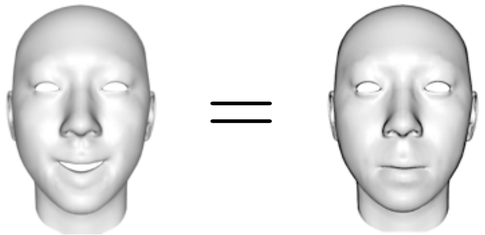
happy smile

Face Tracking

- Blendshape model



happy smile

neutral

Face Tracking

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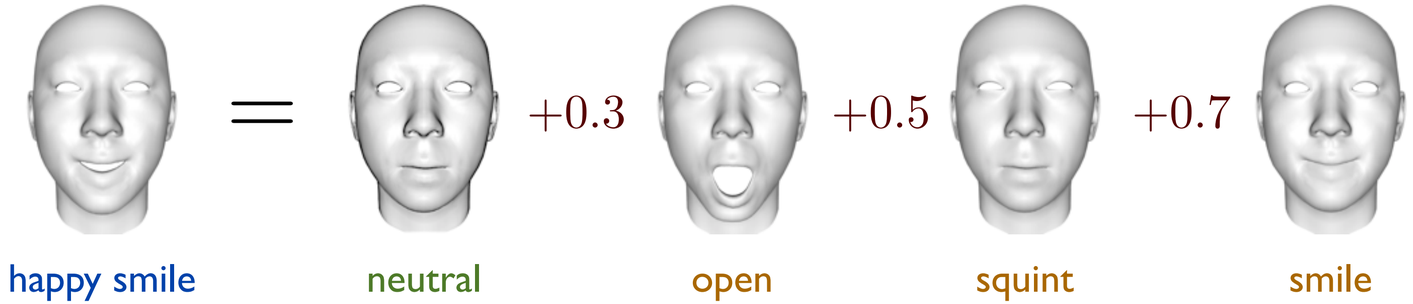

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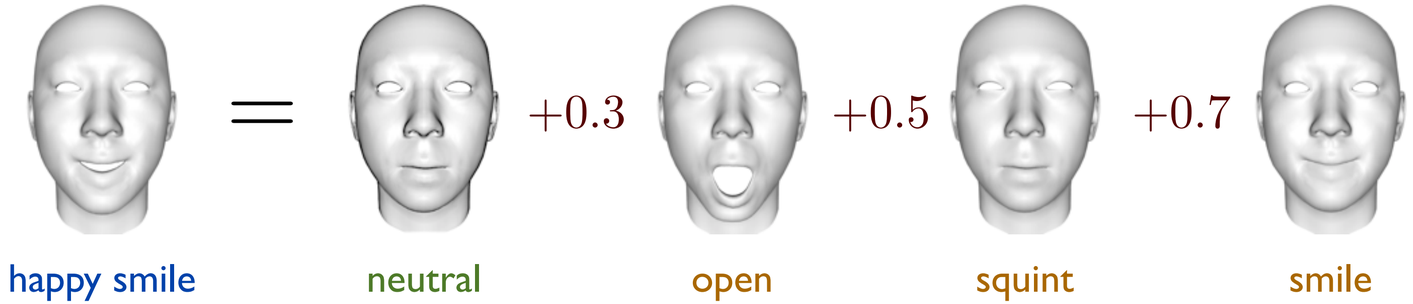

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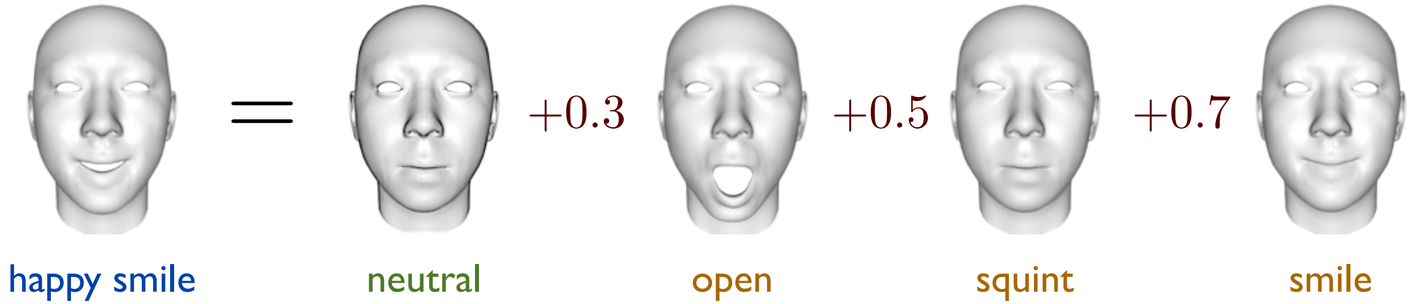

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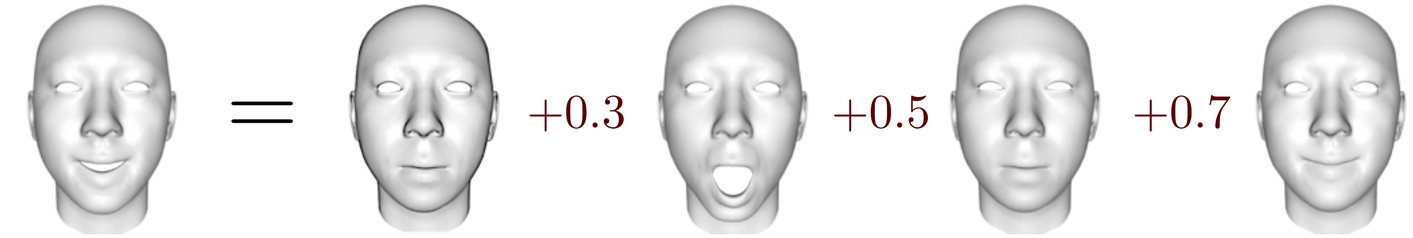

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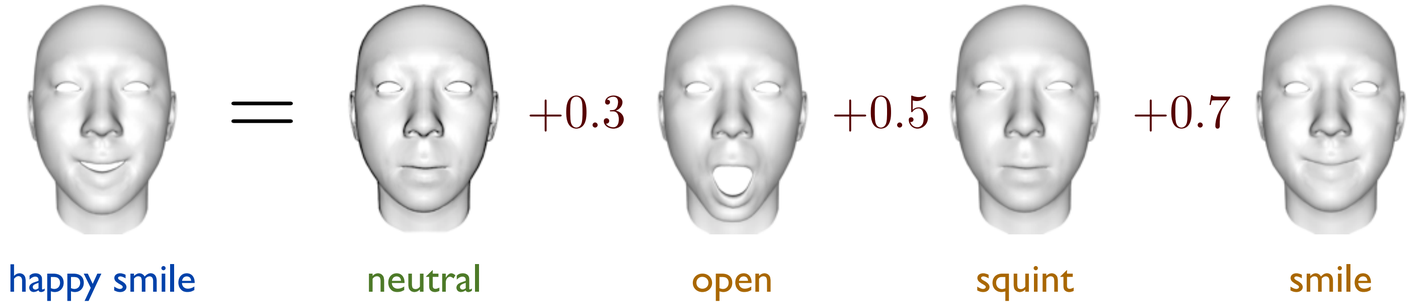

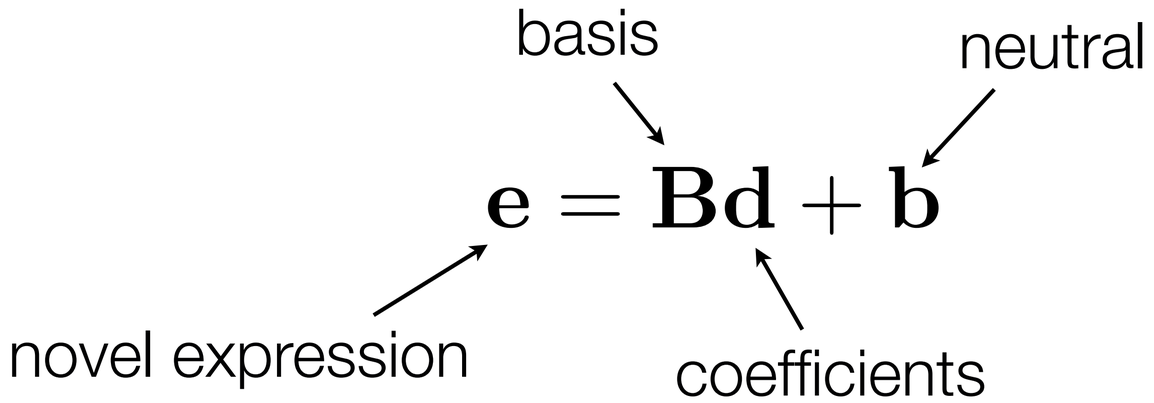

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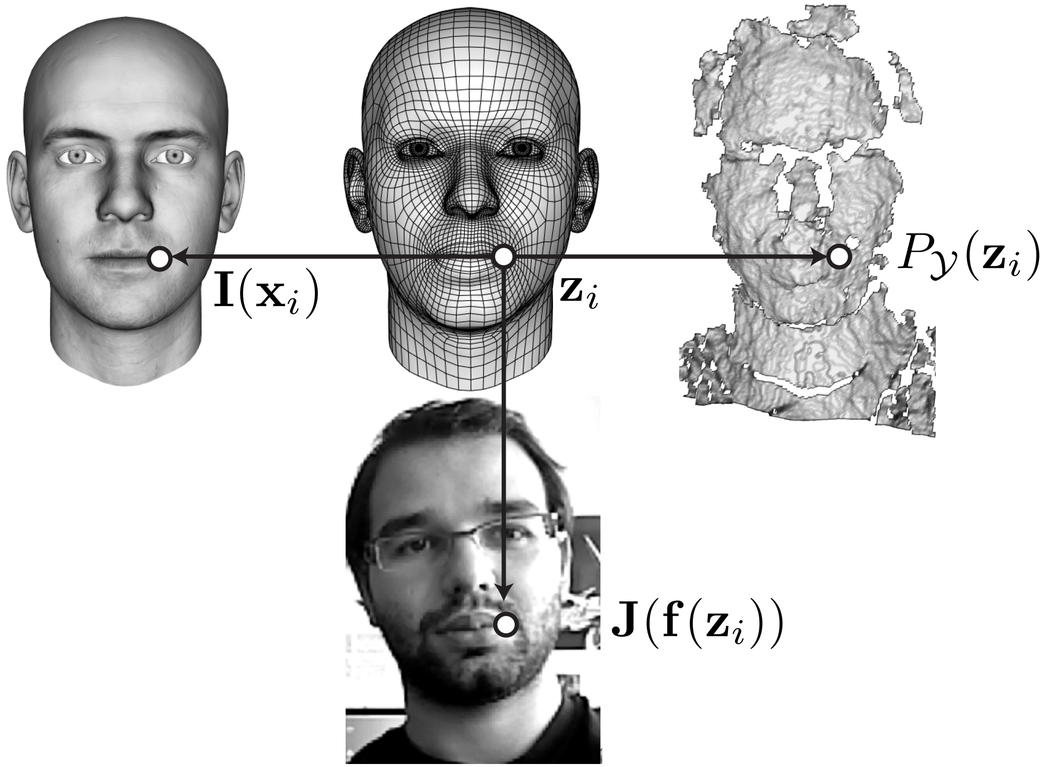
$$\underset{Z,\mathbf{d},\mathbf{R},\mathbf{t}}{\arg\min}\, w_1 \sum_{i=1}^{n} \|\mathbf{z}_i - P_{\mathcal{Y}}(\mathbf{z}_i)\|_2^2 + w_2 \sum_{i=1}^{n} \|\mathbf{I}(\mathbf{x}_i) - \mathbf{J}(\mathbf{f}(\mathbf{z}_i))\|_2^2 + w_3 \sum_{i=1}^{n} \|\mathbf{z}_i - (\mathbf{R}(\mathbf{B}_i\mathbf{d} + \mathbf{b}_i) + \mathbf{t})\|_2^2$$



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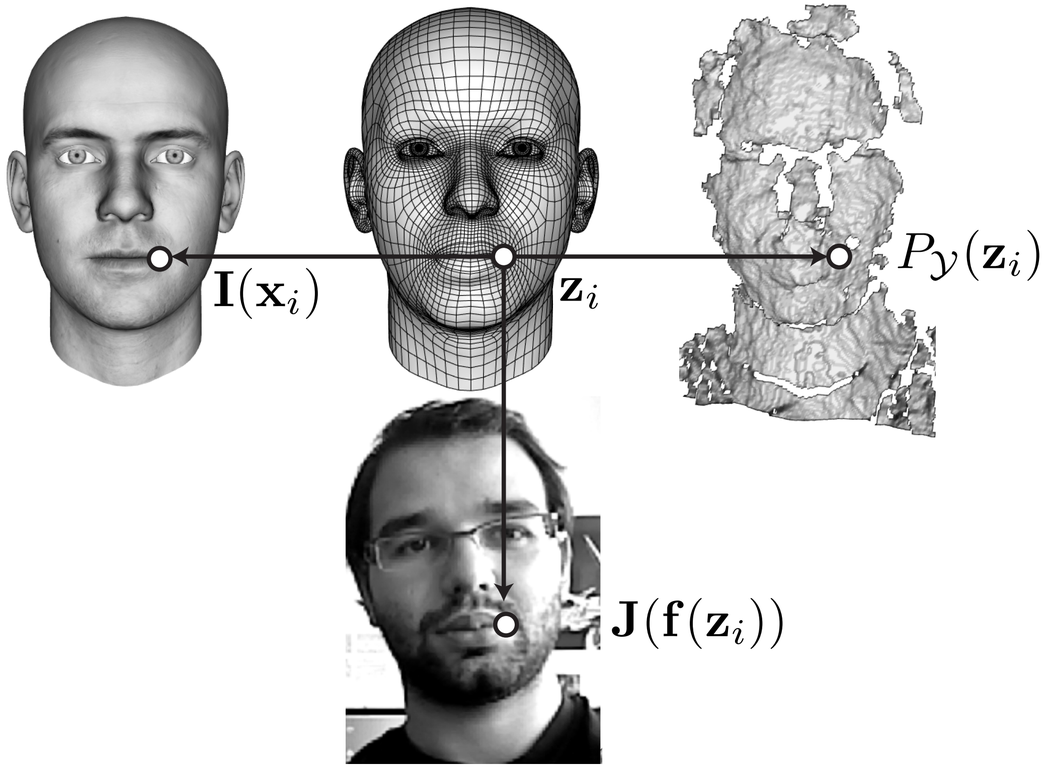

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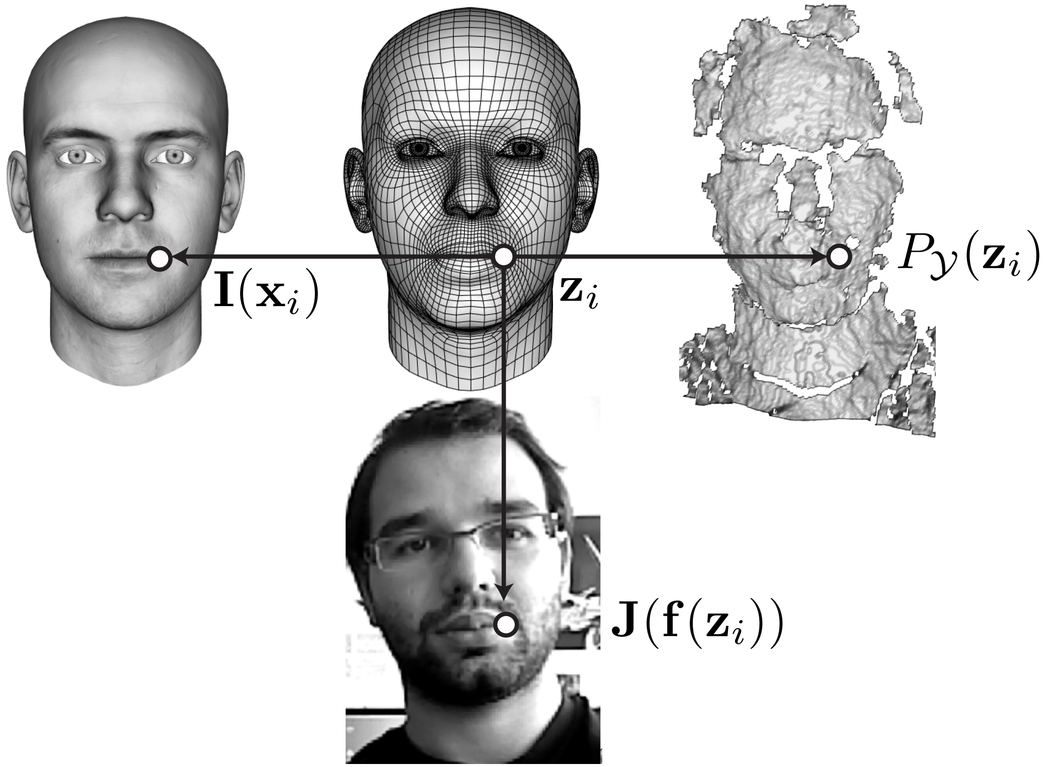

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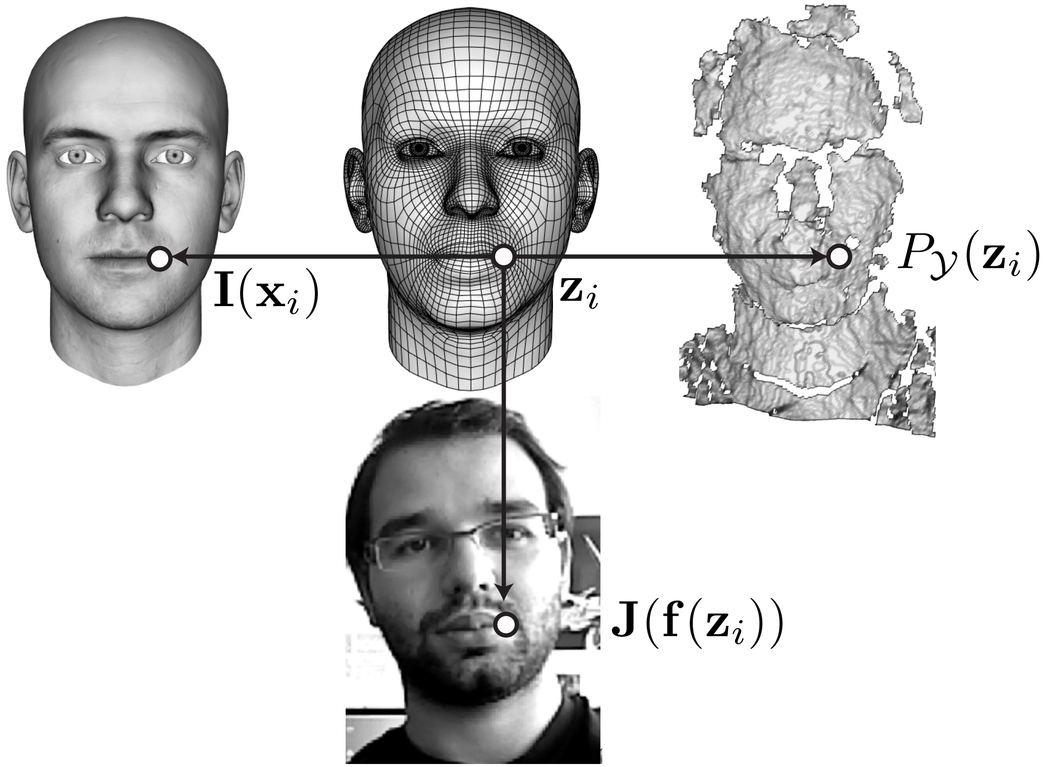

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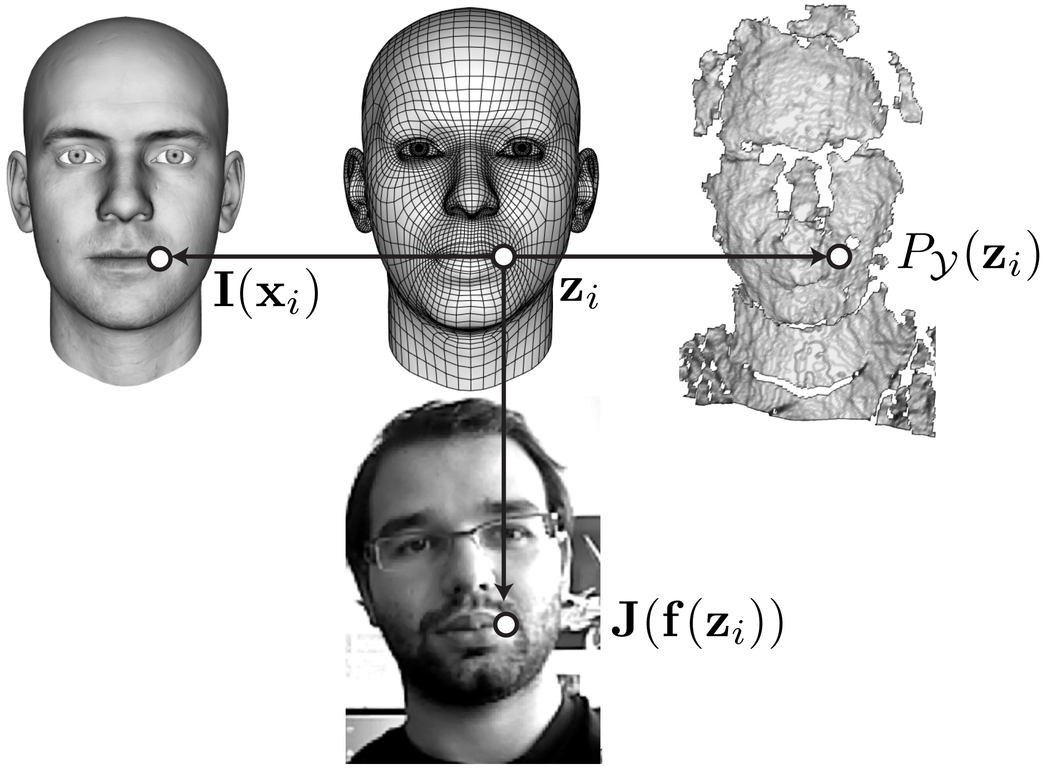

DEMO

Overview

Introduction

- Registration
  - 3D Geometry
  - 2D Images
  - Combined 2D / 3D
- Applications
  - Rigid Scanning
  - Non-rigid Modeling
  - Realtime Face Tracking

Conclusions

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Summary

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  - general framework for integrating image and geometry registration

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Li, Sumner, Pauly: **Global Correspondence Optimization for Non-Rigid Registration of Depth Scans**, *SGP 2008*

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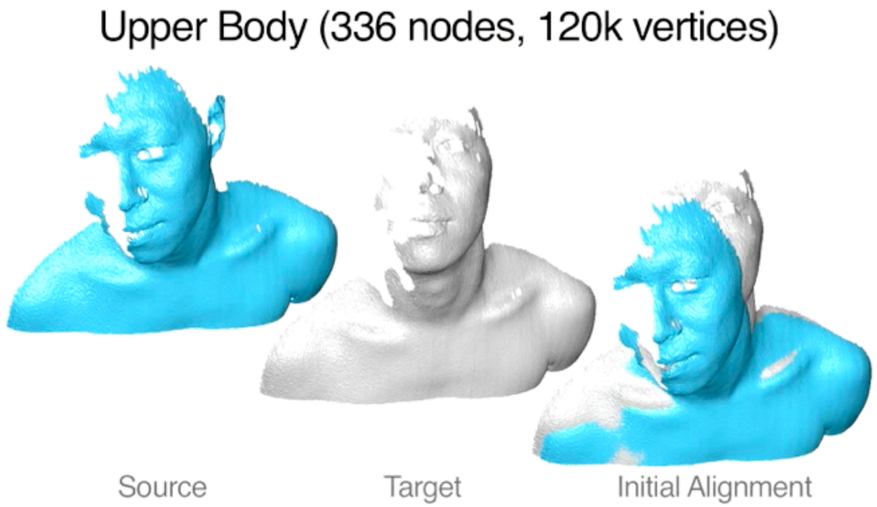

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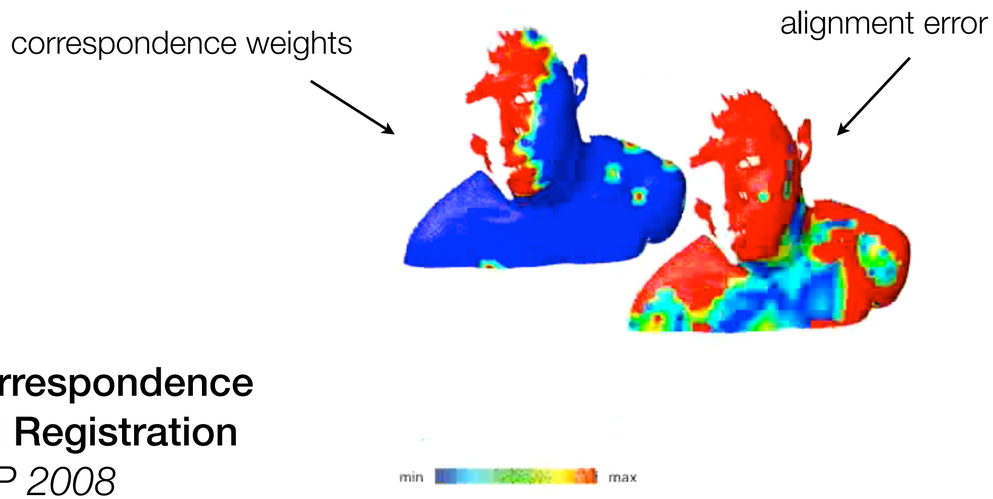

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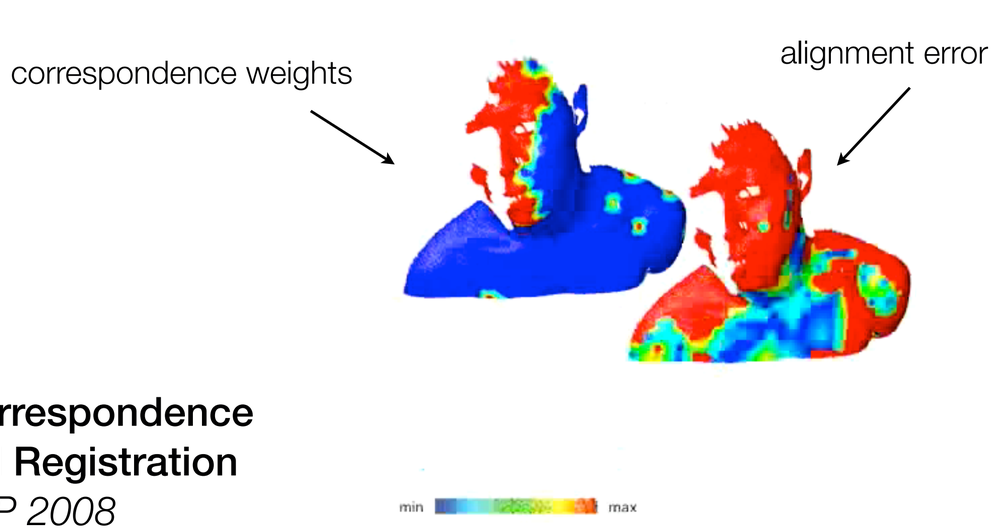

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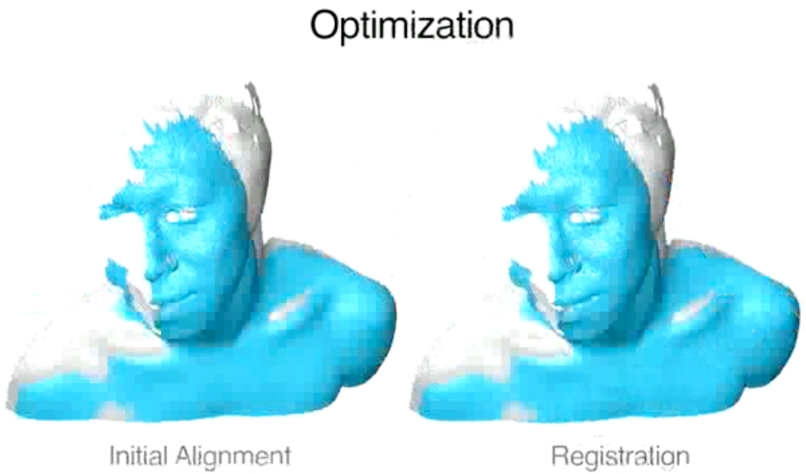

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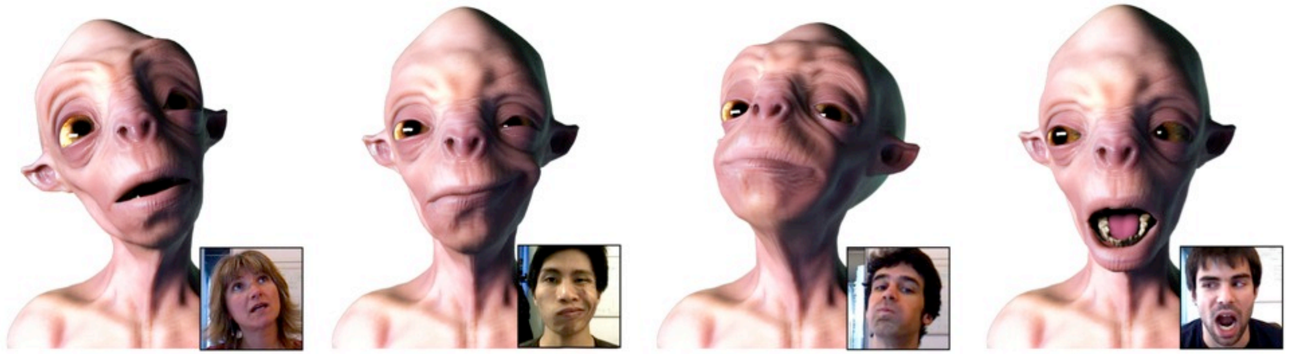
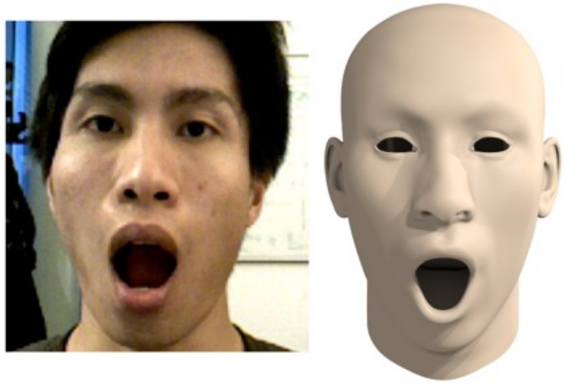


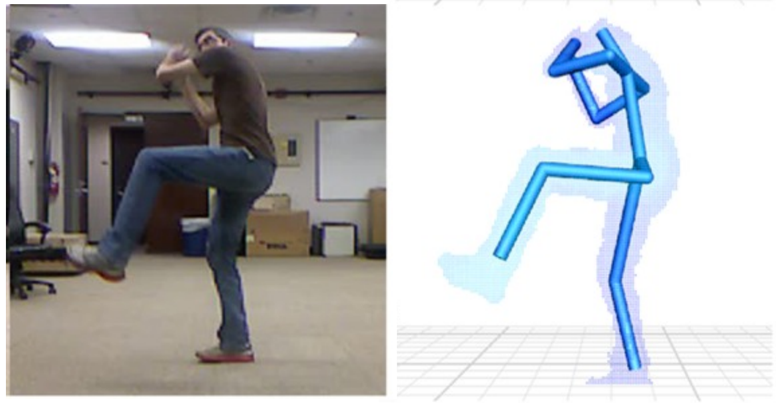
Bouaziz, Wang, Pauly: **Online Modeling For Realtime Facial Animation**, *SIGGRAPH 2013*

Conclusion

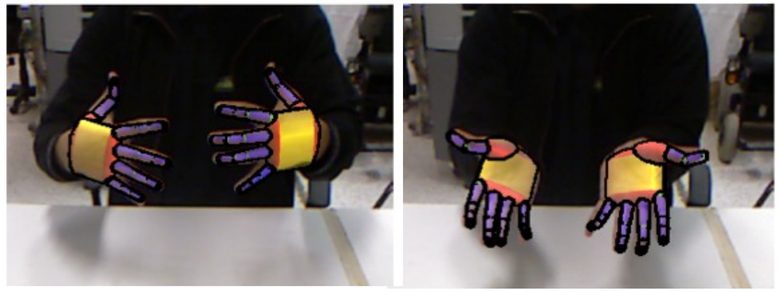


[Bouaziz et al, 2013]

[Newcombe et al, 2011]



[Wei et al, 2012]



[Oikonomidis et al, 2012]

Thanks!

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