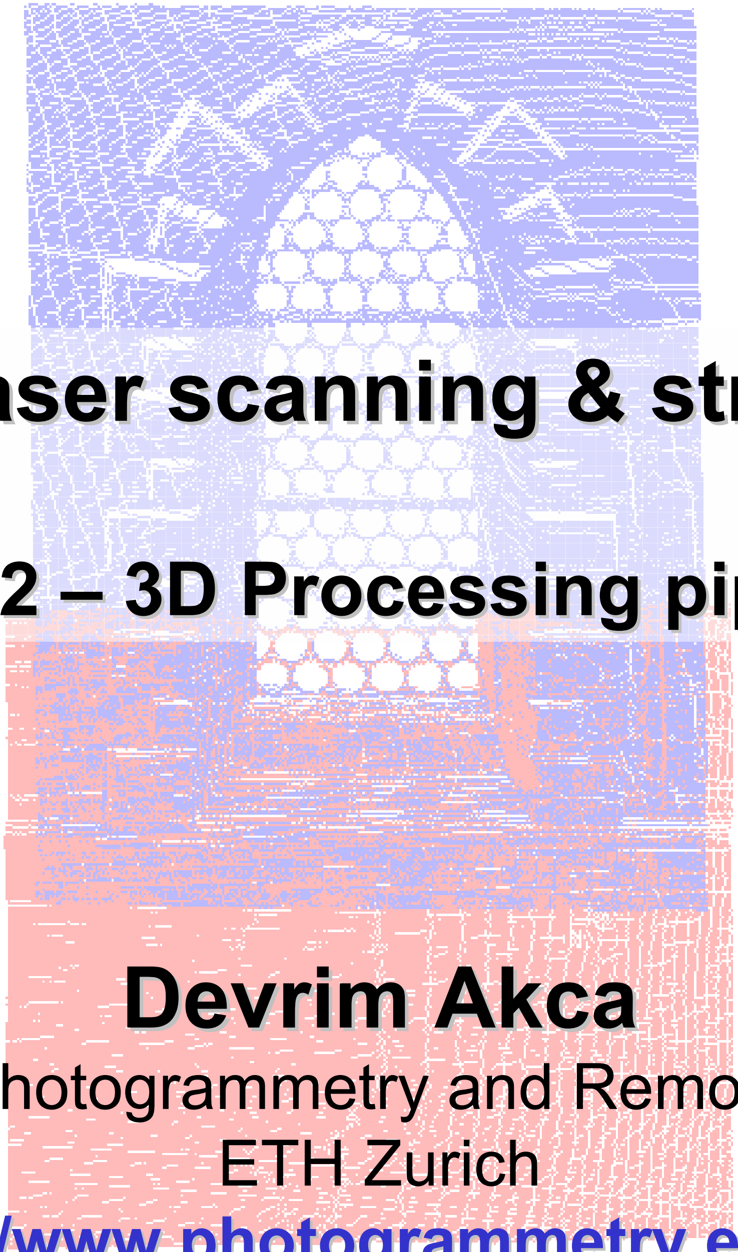


Terrestrial laser scanning & structured light

Part 2 – 3D Processing pipeline

Devrim Akca
Chair of Photogrammetry and Remote Sensing
ETH Zurich
http://www.photogrammetry.ethz.ch

Pointcloud data source: Active sensors (C-R & terrestrial)

+ Triangulation based systems:

++ Single spot (1D)

ShapeGrabber – BIRIS

Small object volume

High accuracy ~ 50-100micron

++ Profile measurement (2D)

KONIKA – Minolta

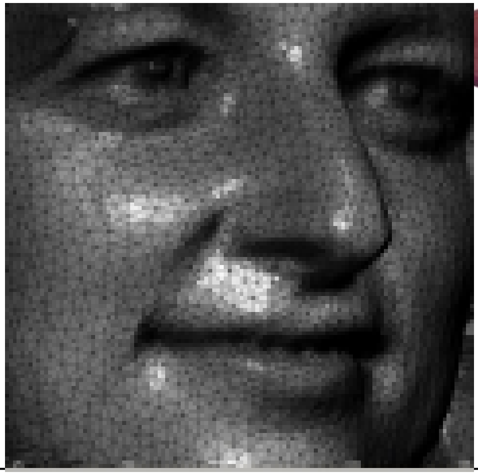
Small object volume

High accuracy ~ 50-100micron

+ Triangulation based systems:

++ Area measurement (2.5D), pattern projection

© 2004 Breuckmann GmbH



Breuckmann
Small object volume
High accuracy ~ 50-100micron

+ Time delay systems:

++ Single spot with mirror-based scanning (time-of-flight, AM or FM)


Zoller + Fröhlich


Leica

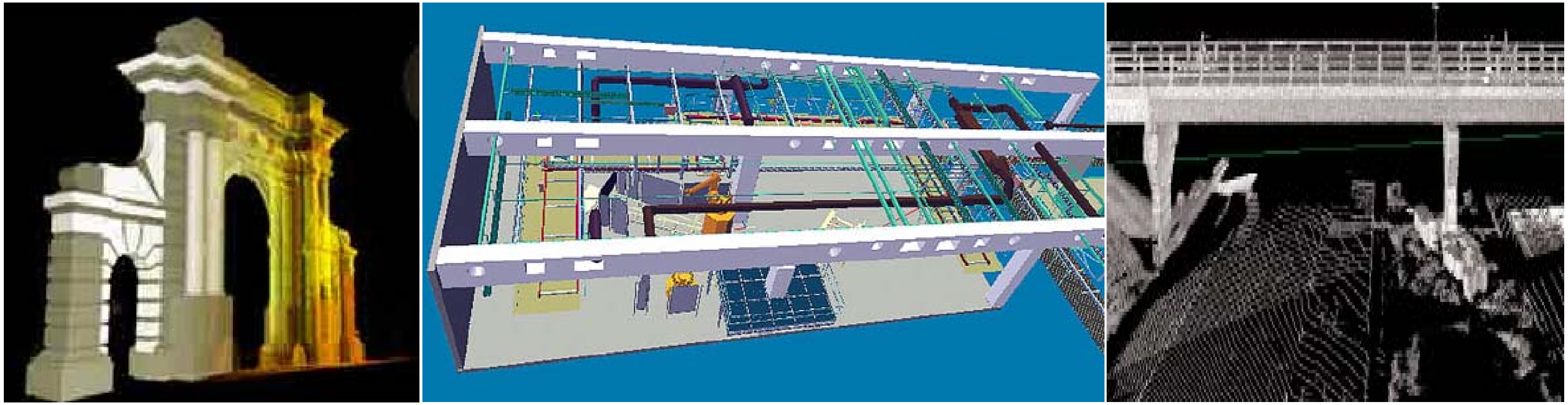

Riegl


Trimble (Mensi)


Optech

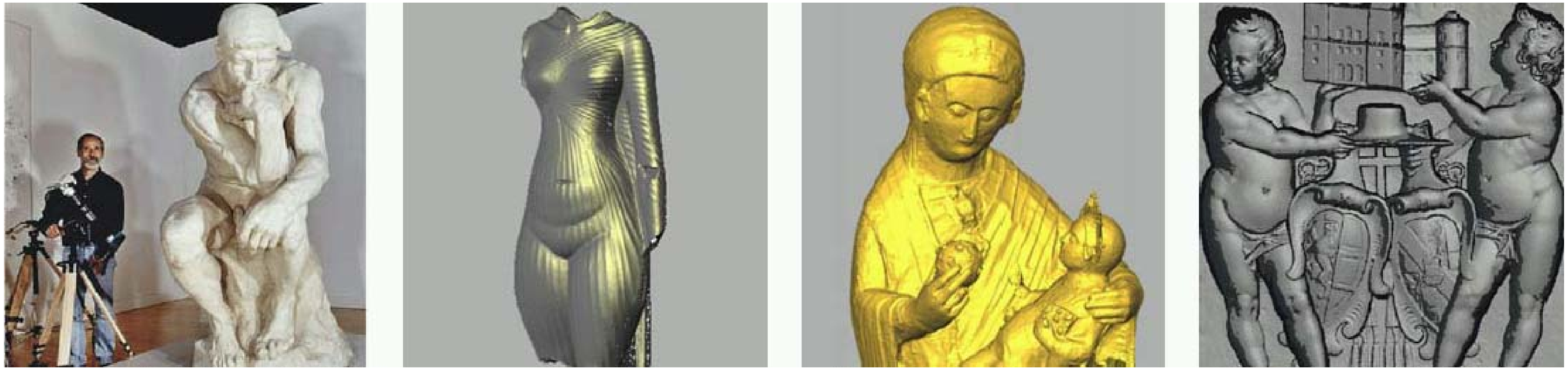
Range:
10-1000m

Accuracy:
2~15mm



Typical data processing chain

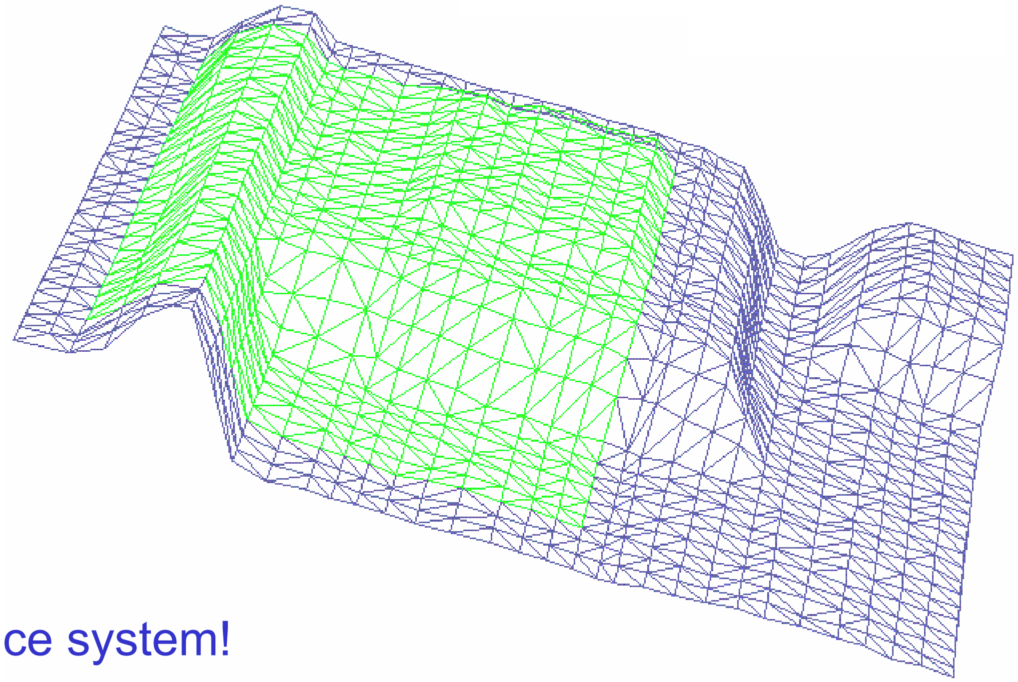
+ data acquisition (scanning)
+ **registration of pointclouds**
+ surface mesh generation and editing
+ texture mapping
+ visualization



What is pointcloud registration?

An object surface may be

- digitized:
  - point by point,
  - or in a different sampling pattern
- using:
  - a laser scanner device,
  - the photogrammetric method,
  - or other techniques..
- acquired:
  - from different stand-points (spatially)
  - at different times (temporally)
- goal:
  - matching the conjugate parts and estimating the 3D transformation



Pointcloud registration:
Bringing pointclouds to the same reference system!

Contents

- Pointcloud registration techniques
    - + Target-based
    - + Surface-based
- Surface registration in Computer Vision
    - + Iterative Closest Point (ICP) algorithm
    - + Variants of the ICP
- Surface registration in Photogrammetry
- Least Squares 3D Surface Matching
    - + Mathematical model
    - + Acceleration strategies
    - + Matching of surface geometry and intensity
- Applications & examples
    - + surface registration
    - + change detection & accuracy analysis

Pointcloud registration techniques:

- Target based registration
- Surface based registration

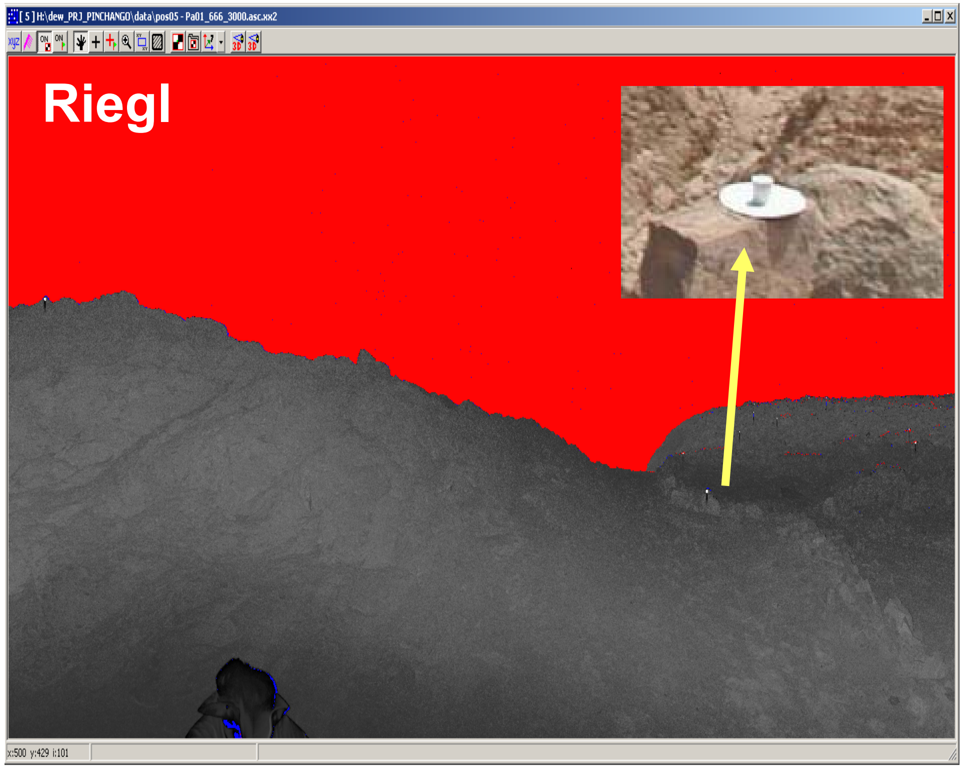
Target based registration:

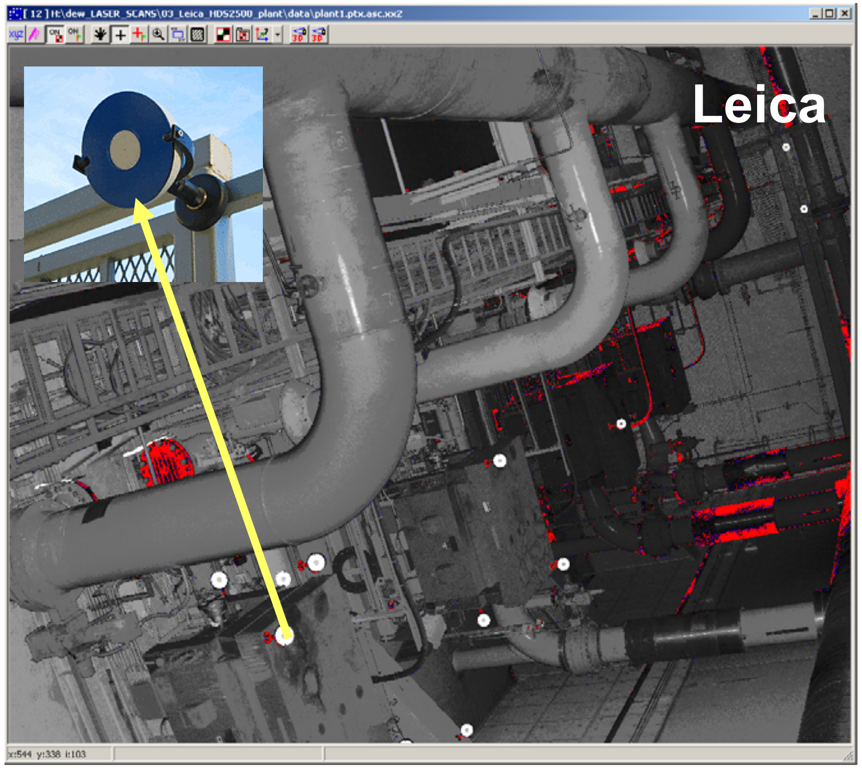
- Target’s coordinates measured by geodesic surveying instruments
- Identify / measure the targets in the pointclouds
- Apply a chained 3D similarity transformation

Pointcloud registration techniques:

Target based registration:

- Vendor supplied special targets used.





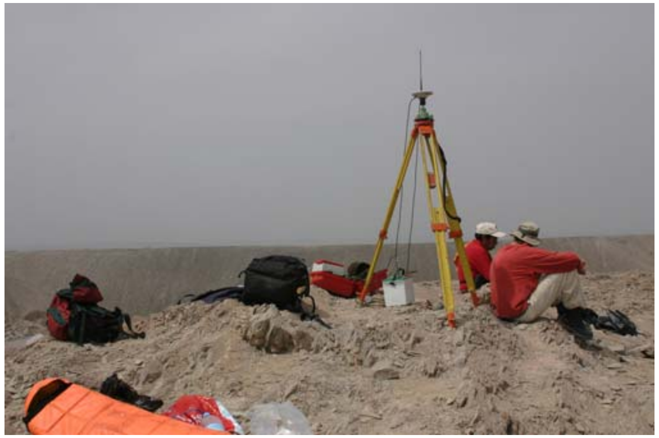
Pointcloud registration techniques: Target based registration

Disadvantages:

- Longer fieldwork time!

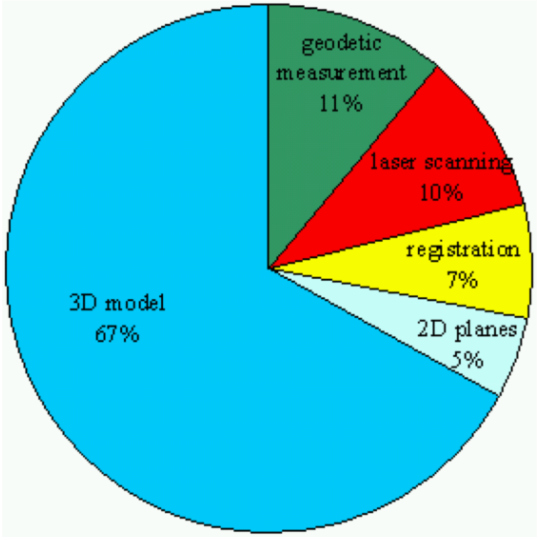
Collapsed CAMC Parking Garage (E.L. Robinson Eng.Co.)

- documentation of a collapsed 1000-car parking garage
- scanning **3** days
- while surveying of GCP **2** days with total station



Pinchango-Alto (Peru)

- documentation of a Cultural Heritage site
- scanning **5** days
- while surveying of GCP **1.5** days with RTK-GPS



Sternberg et al., 2004

- recording of pipelines of the company Boie

Pointcloud registration techniques: Target based registration

Disadvantages (con’t):

- Longer fieldwork time → personnel & equipment cost!
- Accuracy!
    - + Error(geodetic measurement) **>** Error(scanner)
    - + For the sphere/ellipse targets, parametric model fit → modeling error
- Inconvenient for the fieldworks more than 1 day,
    - + Stable targets during the whole scanning campaign!

Advantages:

- Geo-referencing to a higher reference system
- Less computational effort

Pointcloud registration techniques: Surface based registration

Surface based registration:

- Solely pointcloud data used for the registration
- Simply bring strenuous additional fieldwork to the computer in the office

Advantages:

- Better accuracy!
- Optimizing the project cost and duration

Disadvantages:

- Not well-suited for the geo-referencing
- Computationally expensive

Pointcloud registration techniques: Surface based registration

Steps of surface based registration:

- Coarse registration (coarse alignment, crude alignment)
    - \+ surface registration is a non-linear problem
    - \+ approximate registration
    - \+ manual or automatic

- Fine registration (pointcloud co-registration, surface matching)
    - \+ Mostly pairwise
    - \+ Consisting of two sub-parts:
        - ++ correspondence searcher: finds the conjugate surface elements
        - ++ parameter estimator: calculates the 3D transformation
    - \+ fully automatic methods

- Global registration (multiple pointclouds)
    - \+ For multiple pointclouds, mostly an additional step to the fine registration
    - \+ Distributes the residual errors evenly among all pointclouds
    - \+ Considers
        - ++ multiple overlap conditions
        - ++ closure condition, i.e. matching of the last to the first.

Pointcloud registration in Computer Vision literature

Iterative Closest Point (**ICP**) (*Besl & McKay, 1992; Chen & Medioni, 1992; Zhang, 1994*)
Iterative solution based on closed-form LS rigid transformation

Point set **P** with N_p points (data shape, to be transformed)
Point set **X** with N_x points (model shape)

- Initial approximations, initialization
  - + $k = 0$ (iteration number)
  - + $\mathbf{P}_0 = \mathbf{P}$ (initial state of data shape)
  - + $\mathbf{q}_0 = [1, 0,0,0, 0,0,0]^T$ (transformation parameters)
- Iteration:
  - Compute the closest points: $\mathbf{Y}_k = C(\mathbf{P}_k, \mathbf{X})$
  - Compute the transformation: $(\mathbf{q}_k, \mathbf{d}_k) = T(\mathbf{P}_0, \mathbf{Y}_k)$
  - Apply the registration: $\mathbf{P}_{k+1} = \mathbf{q}_k(\mathbf{P}_0)$
  - if($\mathbf{d}_k - \mathbf{d}_{k+1} < \lambda$) terminate, else continue

Monotonic convergence, 30-50 iterations!

Computer Vision literature: Iterative Closest Point (ICP)

Corresponding point set registration by Horn’s (1987) quaternion method:

$\mathbf{q}_R = [q_0\ q_1\ q_2\ q_3]^T$	representing the rotation
$\mathbf{q}_T = [q_4\ q_5\ q_6]^T$	representing the translation
$\mathbf{P} = \{\mathbf{p}\}$	data point set (to be aligned)
$\mathbf{X} = \{\mathbf{x}\}$	model point set

Assuming that each $\mathbf{p}_i$ has a correspondent $\mathbf{x}_i$ with the same index,
The mean square objective function to be minimized:

$$f(q) = \frac{1}{N_p} \sum_{i=1}^{N_p} \left\| \mathbf{x}_i - \mathbf{R}(\mathbf{q}_R)\mathbf{p}_i - \mathbf{q}_T \right\|^2$$

Where **R** is the 3x3 rotation matrix generated by unit rotation quaternion:

$$\mathbf{R} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 + q_2^2 - q_1^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 + q_3^2 - q_1^2 - q_2^2 \end{bmatrix}$$

Computer Vision literature: Iterative Closest Point (ICP)

Corresponding point set registration by quaternion method (con’t)

1) Center of masses of **P** and **X**:

$$\boldsymbol{\mu}_p = \frac{1}{N_p}\sum_{i=1}^{N_p}\mathbf{p}_i \quad , \quad \boldsymbol{\mu}_x = \frac{1}{N_x}\sum_{i=1}^{N_x}\mathbf{x}_i$$

2) Cross-covariance matrix $\boldsymbol{\Sigma}_{px}$ of the sets **P** and **X**:

$$\boldsymbol{\Sigma}_{px} = \frac{1}{N_p}\sum_{i=1}^{N_p}[(\mathbf{p}_i - \boldsymbol{\mu}_p)(\mathbf{x}_i - \boldsymbol{\mu}_x)^T] = \frac{1}{N_p}\sum_{i=1}^{N_p}[\mathbf{p}_i\mathbf{x}_i] - \boldsymbol{\mu}_p\boldsymbol{\mu}_x^T$$

3) Form such a symmetric 4x4 matrix $\mathbf{Q}(\ \boldsymbol{\Sigma}_{px}\ )$:

$$\mathbf{Q} = \begin{bmatrix} Q_{11}+Q_{22}+Q_{33} & Q_{32}-Q_{23} & Q_{13}-Q_{31} & Q_{21}-Q_{12} \\ Q_{32}-Q_{23} & Q_{11}-Q_{22}-Q_{33} & Q_{12}+Q_{21} & Q_{31}+Q_{13} \\ Q_{13}-Q_{31} & Q_{12}+Q_{21} & -Q_{11}+Q_{22}-Q_{33} & Q_{23}+Q_{32} \\ Q_{21}-Q_{12} & Q_{31}+Q_{13} & Q_{23}+Q_{32} & -Q_{11}-Q_{22}+Q_{33} \end{bmatrix}$$

Computer Vision literature: Iterative Closest Point (ICP)

Corresponding point set registration by quaternion method (con’t)

4) Calculation of rotation:
The unit quaternion $\mathbf{q}_R = [q_0\ q_1\ q_2\ q_3]^T$ corresponds to;
the unit eigenvector of the maximum eigenvalue of the matrix **Q**.

5) Calculation of the translation vector:

$$\mathbf{q}_T = \boldsymbol{\mu}_x - \mathbf{R}(\mathbf{q}_R)\boldsymbol{\mu}_p$$

Straightforward to implement!
A closed-form solution,
But, does not directly give the precisions of the estimated parameters!

Computer Vision literature: Iterative Closest Point (ICP)

Variants of the ICP

- Data representation

Point-to-point (*Besl & McKay, 1992; Zhang, 1994*)
Point-to-surface (*Chen & Medioni, 1992; Bergevin et al., 1996; Pulli, 1999*) → better!

- Error detection

Rejection of point pairs based on:

+ constant distance threshold (*Turk & Levoy, 1994*)
+ variable (Robust Est.) distance threshold (*Masuda & Yokoya, 1995*)
+ orientation threshold for surface normals (*Zhang, 1994; Guehring, 2001*)
+ on the mesh boundaries (*Turk & Levoy, 1994; Pulli, 1999*)
+ reciprocal correspondence (*Pajdla & Van Gool, 1995*)
+ the worst %n of pairs (*Pulli, 1999*)
+ LMedS estimator (*Masuda & Yokoya, 1995*)
+ the Least Trimmed Squares estimator (*Chetverikov et al., 2005*)
+ etc..

Computer Vision literature: Iterative Closest Point (ICP)

Variants of the ICP (con’t)

- Parameter estimation

  Mainly, closed-form solutions:

    + Quaternion methods (*Horn, 1987; Faugeras & Hebert, 1986*)
    + SVD method (*Arun et al., 1987; Horn et al., 1988*)

  Eggert et al. (1997) gives an extensive review on the issue.

  A few gradient-descent algorithms

    + Levenberg-Marquardt (*Szeliski & Lavallee, 1996; Neugebauer, 1997*)
    + Gauss-Helmert (*Williams et al., 1999*)
    + Gauss-Markoff (*Gruen & Akca, 2005*)

  Substantially less number of iterations!

Computer Vision literature: Iterative Closest Point (ICP)

Variants of the ICP (con’t)

- Acceleration strategies
  - \+ reducing the number of iterations
    - ++ convergence: monotonic → quadratic
    - ++ manipulation of the parameter vector in the parameter space ??
  - \+ reducing number of points
    - ++ resolution hierarchy (coarse-to-fine)
    - ++ sub-sampling
      - +++ points at smooth surfaces (*Chen & Medioni, 1992*)
      - +++ points with hi-intensity gradients (*Weik, 1997*)
      - +++ random sampling (*Masuda & Yokoya, 1995*)
      - +++ regular sampling (*Guehring, 2001*), etc..
  - \+ reducing the correspondence search time (restricting search space)
    - ++ multi z-buffer (*Benjemaa & Schmitt, 1997*)
    - ++ *k*-D search tree (*Bentley, 1975*)
    - ++ 3D boxing (bucketing, Elias) (*Rivest, 1974*)
    - ++ etc..

Computer Vision literature: Iterative Closest Point (ICP)

Variants of the ICP (con't)

- Surface geometry + intensity

When surface geometry either homogeneous or isotropic (plane, sphere)!

+ reflectance images as complementary to range images (*Maas, 2001*)
+ feature based methods (*Roth, 1999; Vanden Wyngaerd & Van Gool, 2003*)
    - interest point extraction on reflectance images
    - registration with range information
+ intensity extra distance under ICP (*Weik, 1997; Johnson & Kang, 1999; Godin et al., 2001*)
+ Simultaneous orientation of brightness, range and intensity information by object space Least Squares matching (*Wendt & Heipke, 2006*)

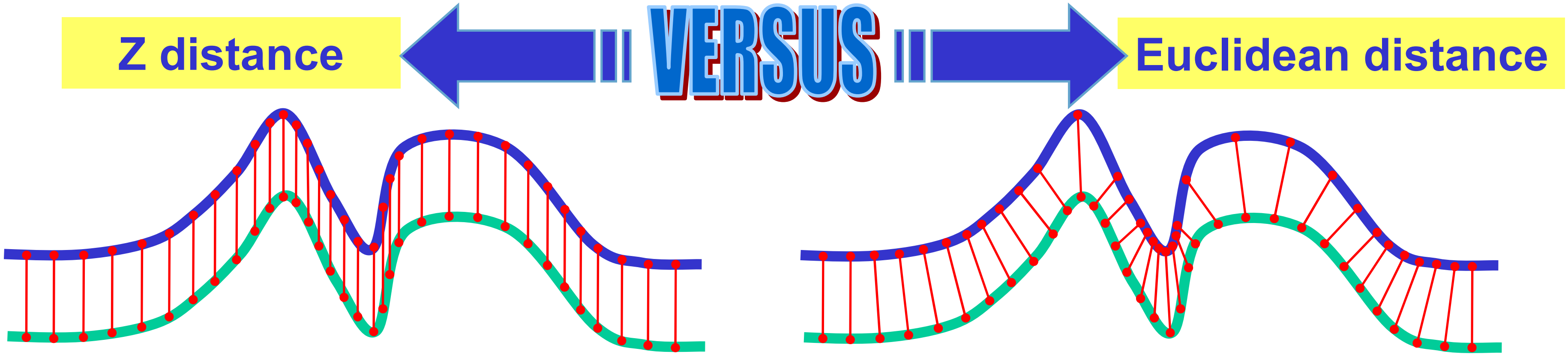
Surface registration in Photogrammetry

Least Squares Matching (LSM) (Grün, 1985)

- Surface matching first was addressed as a straight extension of LSM

DEM Matching (Ebner & Müller, 1986; Ebner & Strunz, 1988; Rosenholm & Torlegard, 1988)

- Minimizes height differences along Z-axis by LSs (corresponds to LSM)
- It has been used for:
  - + absolute orientation of stereo models
  - + block triangulation
  - + registration of airborne laser scanner strips



- Valid for **2.5D** surfaces, cannot work with **3D** surfaces!

Least Squares 3D Surface Matching Method

Motivation: to develop such a surface matcher,

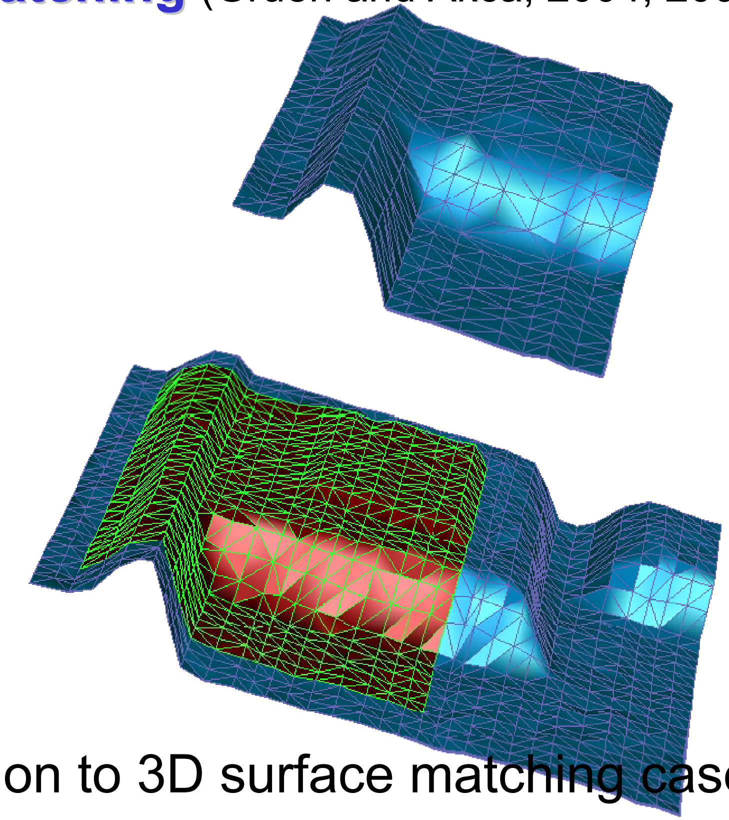
- Matching of fully 3D surfaces (as opposed to 2.5D)
- Rigorous mathematical model for high accuracy demands
- Flexible mathematical model for further algorithmic extensions
- Mechanisms and statistical tools for internal quality control
- Capability of matching of data sets in different quality and resolution

Least Squares 3D Surface Matching Method: Background

LS Image Matching (Grün, 1984; 1985)

LS Cuboid (Voxel) Matching (Maas, 1994; Maas and Grün, 1995)

LS 3D Surface Matching (Gruen and Akca, 2004; 2005)



Generalization to 3D surface matching case

The basic estimation model: Observation equations

Two partial surfaces of an object:

- template surface f(x,y,z) and search surface g(x,y,z) (to be transformed)
- surface representation in a piecewise form
- f(x,y,z) and g(x,y,z) stand for any surface element

3D transformation of the search surface g(x,y,z) to be estimated.
In a ideal case,

$$f(x,y,z) = g(x,y,z) \qquad (1)$$

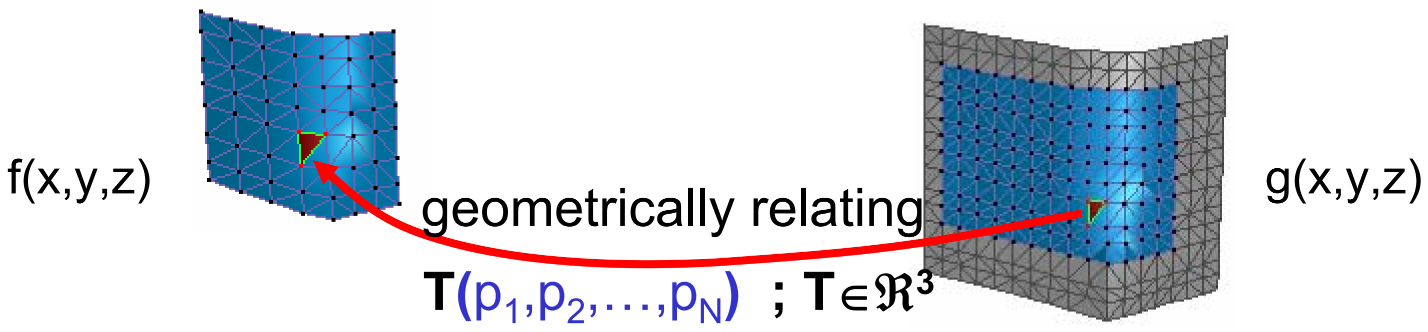
Considering the stochastic discrepancies,

$$f(x,y,z) - e(x,y,z) = g(x,y,z) \qquad (2)$$

Equation (2) is observation equations, which functionally relate the observations f(x,y,z) to the parameters of g(x,y,z).

The goal function: $[d_E d_E] = \min$
The final location of g(x,y,z) is estimated w.r.t. an initial position $g^0(x,y,z)$

The basic estimation model: Geometric relationship



Geometric relationship: 7-parameter 3D similarity transformation

$$x = t_x + m(r_{11}x_0 + r_{12}y_0 + r_{13}z_0)$$
$$y = t_y + m(r_{21}x_0 + r_{22}y_0 + r_{23}z_0) \qquad (3)$$
$$z = t_z + m(r_{31}x_0 + r_{32}y_0 + r_{33}z_0)$$

Depending on the geometric deformation between the surfaces, any other kind of 3D transformation can be used: (3D affine, tri-linear, etc..)

The basic estimation model: Functional model

Non-linear functional model,

$$f(x,y,z)-e(x,y,z)=g(x,y,z) \qquad (2)$$

Numerical derivatives

Linearization by Taylor Expansion,

$$f(x,y,z)-e(x,y,z)=\underbrace{g^0(x,y,z)}_{\text{Initial state (approximations)}}+\overbrace{\frac{\partial g^0(x,y,z)}{\partial x}}^{g_x}\underbrace{dx}+\overbrace{\frac{\partial g^0(x,y,z)}{\partial y}}^{g_y}\underbrace{dy}+\overbrace{\frac{\partial g^0(x,y,z)}{\partial z}}^{g_z}\underbrace{dz} \qquad (4)$$

$$dx = dt_x + a_{10}\,dm + a_{11}\,d\omega + a_{12}\,d\varphi + a_{13}\,d\kappa$$

$$dy = dt_y + a_{20}\,dm + a_{21}\,d\omega + a_{22}\,d\varphi + a_{23}\,d\kappa$$

$$dz = dt_z + a_{30}\,dm + a_{31}\,d\omega + a_{32}\,d\varphi + a_{33}\,d\kappa$$

Differentiation terms

The basic estimation model: Functional model

Final functional model in linearized form:

$$\begin{aligned} -e(x,y,z) = {} & g_x dt_x + g_y dt_y + g_z dt_z \\ & + (g_x a_{10} + g_y a_{20} + g_z a_{30}) dm \\ & + (g_x a_{11} + g_y a_{21} + g_z a_{31}) d\omega \\ & + (g_x a_{12} + g_y a_{22} + g_z a_{32}) d\varphi \\ & + (g_x a_{13} + g_y a_{23} + g_z a_{33}) d\kappa \\ & - (f(x,y,z) - g^0(x,y,z)) \end{aligned} \qquad (5)$$

The functional model in matrix notation:

$$-\mathbf{e} = \mathbf{A}\,\mathbf{x} - \ell \quad , \quad \mathbf{P} \qquad (6)$$

weight matrix	**P**
design matrix	**A**
parameter vector	**x**T = [dtx dty dtz dm dω dφ dκ]
discrepancies vector	ℓ = f(x,y,z)–g0(x,y,z)

The unknown parameters as stochastic quantities,

$$-\mathbf{e}_b = \mathbf{I}\mathbf{x} - \ell_b \quad , \quad \mathbf{P}_b \qquad (7)$$

The basic estimation model: Mathematical model

The total system is a Generalized Gauss-Markoff model:

$$-\mathbf{e} = \mathbf{A}\,\mathbf{x} - \ell \quad , \quad \mathbf{P} \tag{8}$$

$$-\mathbf{e}_b = \mathbf{I}\mathbf{x} - \ell_b \quad , \quad \mathbf{P}_b \tag{9}$$

The Least Squares solution of the joint system gives as:

Solution vector: $$\hat{\mathbf{x}} = (\mathbf{A}^T\mathbf{P}\mathbf{A} + \mathbf{P}_b)^{-1}(\mathbf{A}^T\mathbf{P}\ell + \mathbf{P}_b\ell_b) \tag{10}$$

Variance factor: $$\hat{\sigma}_0^2 = \frac{\mathbf{v}^T\mathbf{P}\mathbf{v} + \mathbf{v}_b^T\mathbf{P}_b\mathbf{v}_b}{r} \tag{11}$$

The solution is iterative. At each iteration:

- search surface is transformed to a new state: $g^t(x,y,z) \Rightarrow g^{t+1}(x,y,z)$
- **A** and ℓ are re-evaluated.

The iteration stops if each element of the alteration vector $\hat{\mathbf{x}}$ falls below a certain limit:

$$|dp_i| < c_i \quad , \quad i = \{1,2,\ldots,7\} \tag{12}$$

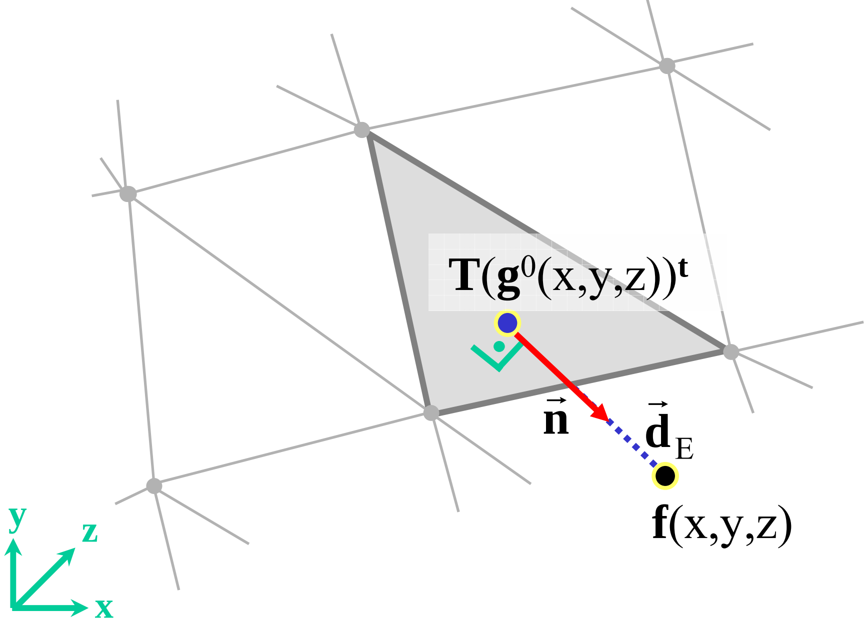
The basic estimation model: Numerical derivative terms

Numeric derivative terms $\{g_x , g_y , g_z\}$ are defined as local surface normals. Their calculation depends on the analytical representation of search surface elements.

Two kind of piecewise forms optionally:

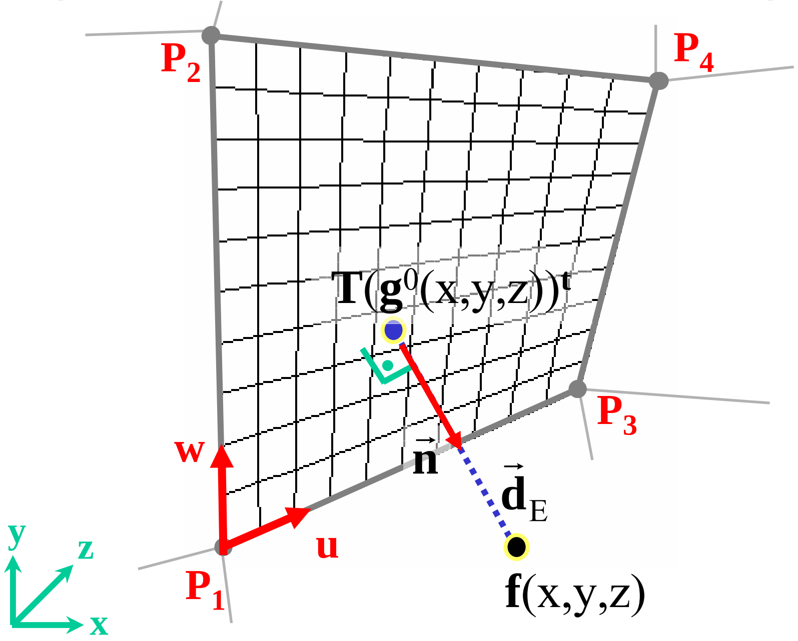
Triangle mesh form

(with planar surface elements)



Grid mesh form

(with bi-linear surface elements)



Both of them are 1st degree C^0 continuous piecewise surface representations.

Precision and Reliability

- $\mathbf{K}_{xx}$ gives useful information on the stability of the system & quality of the data content

$$\mathbf{K}_{xx} = \hat{\sigma}_0^2\,\mathbf{Q}_{xx} = \hat{\sigma}_0^2\,\mathbf{N}^{-1} = \hat{\sigma}_0^2\,(\mathbf{A}^T\mathbf{P}\mathbf{A} + \mathbf{P}_b)^{-1}$$

- A simple weighting scheme adapted from Robust Estimation Methods is used in order to eliminate occluded parts and large outliers

$$(\mathbf{P})_{ii} = \begin{cases} 1 & \text{if} \quad |(\mathbf{v})_i| < K\sigma_0 \\ 0 & \text{else} \end{cases} \quad , \quad K > 10 \quad \text{(according to a given confidence level)}$$

Convergence of Solution Vector

- Typical convergence rate is 5-6 iterations in a good data configuration case.
- It depends on the quality of initial approximations and data content.

Computational Aspects

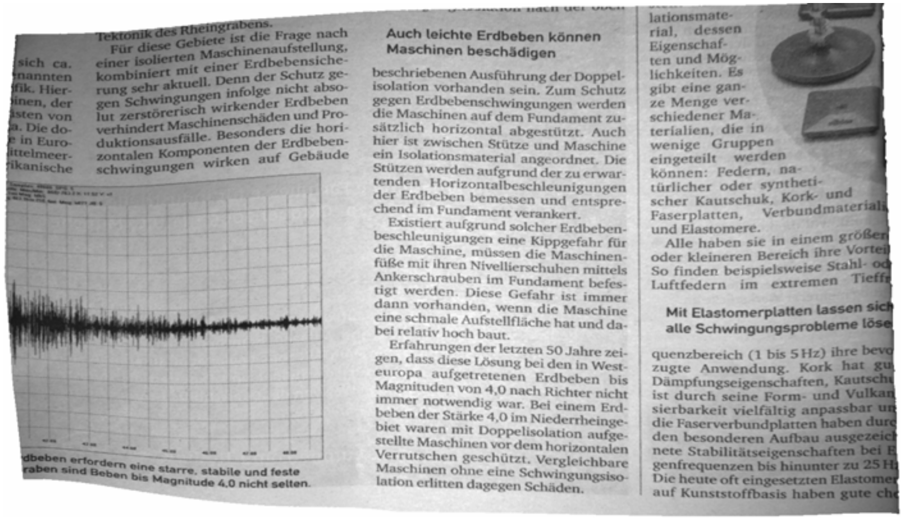
- Adjustment part is very small (Cholesky decomposition + back-substitution)

> 95% of the computational effort is for searching the correspondence.

- Correspondence search is guided by a boxing structure from Chetverikov (1991)
- Originally 2D, straightforwardly extended to 3D

Experimental results: Newspaper

- **object:** a newspaper
- **scanner:** stereoSCAN^{3D} (Breuckmann)
- **average point spacing:** ~150microns.

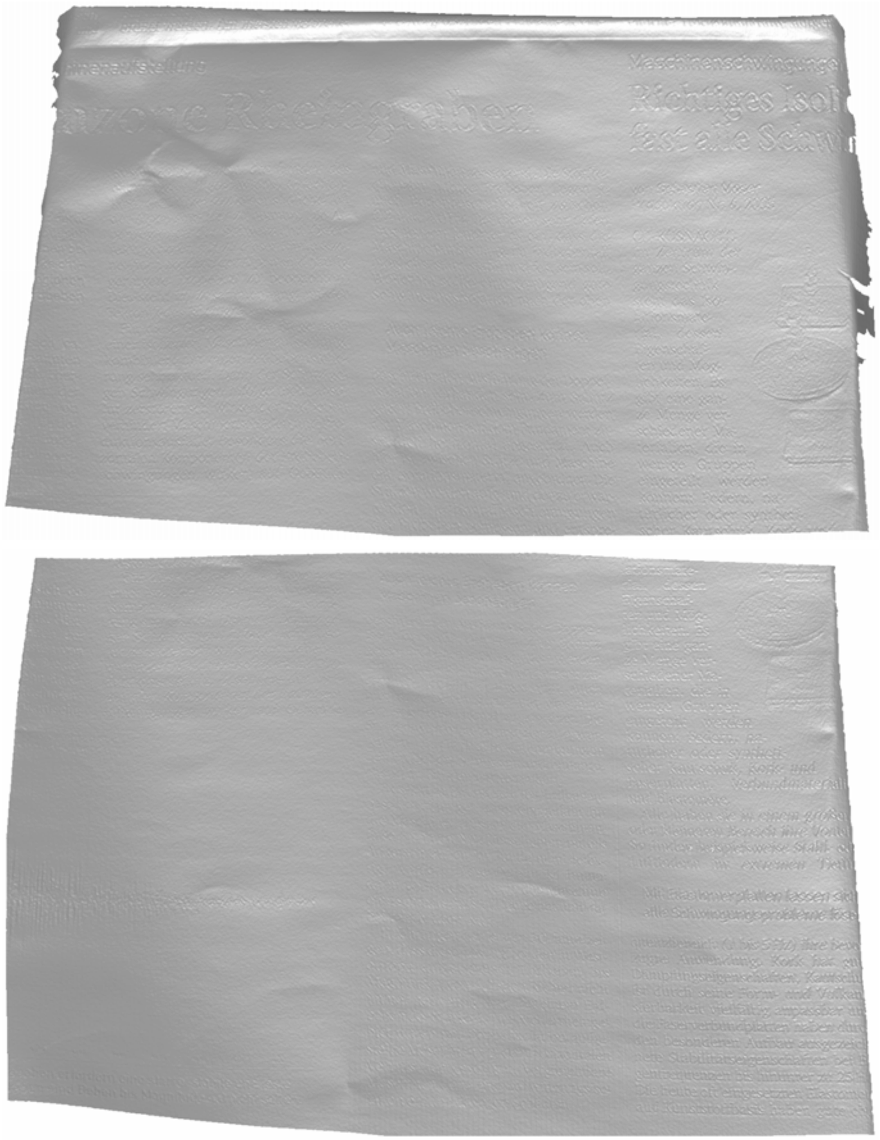


This example:

- Difficult case due to little surface information
- Little changes in surface curvature, almost a plane

Data set is courtesy of Breuckmann GmbH (Germany), http://www.breuckmann.com

Experimental results: Newspaper



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This example:

- Difficult case due to little surface information
- Little changes in surface curvature, almost a plane

Data set is courtesy of Breuckmann GmbH (Germany), http://www.breuckmann.com

Experimental results: Newspaper

Result of the LS3D surface matching is successful, in spite of being a difficult case due to very little changes in surface curvature.

No. points	377K
No. iterations	13
Sigma naught	**11.3 microns**
Time	36.7 seconds

ordnet werden. Am meisten verbreitet

hinenaufstellung

nzone Rheingraben

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müssen
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ikanische

Küstenzone, Italien, die Länder des ehemaligen Jugoslawiens, Griechenland, die Türkei sowie der südliche Teil der Alpen sind hier zu nennen. Die Alpenregionen der Schweiz und Österreich gehören mit zu dieser Einflusszone. Auch nördlich der Alpen sind häufig geringere Erdbeben zu beobachten. Dies steht im Zusammenhang mit der Tektonik des Rheingrabens.

Für diese Gebiete ist die Frage nach einer isolierten Maschinenaufstellung, kombiniert mit einer Erdbebensicherung sehr aktuell. Denn der Schutz gegen Schwingungen infolge nicht absolut zerstörerisch wirkender Erdbeben verhindert Maschinenschäden und Produktionsausfälle. Besonders die horizontalen Komponenten der Erdbebenschwingungen wirken auf Gebäude und Maschinen zerstörend. Die Störfrequenzen infolge Erdbeben liegen je nach Bodenbeschaffenheit zwischen 0,2 und 2,0 Hz. Bei diesen sehr tiefen Frequenzen leuchtet es ein, dass die Maschinenaufstellung im Erdbebenfall möglichst starr, stabil und fest sein soll. Weiterhin sollte eine genügend gute Schwingungsisolation nach der oben beschriebenen Ausführung der Doppelisolation vorhanden sein. Zum Schutz gegen Erdbebenschwingungen werden die Maschinen auf dem Fundament zusätzlich horizontal abgestützt. Auch hier ist zwischen Stütze und Maschine ein Isolationsmaterial angeordnet. Die Stützen werden aufgrund der zu erwartenden Horizontalbeschleunigungen der Erdbeben bemessen und entsprechend im Fundament verankert.

Auch leichte Erdbeben können Maschinen beschädigen

Existiert aufgrund solcher Erdbebenbeschleunigungen eine Kippgefahr für die Maschine, müssen die Maschinenfüße mit ihren Nivellierschuhen mittels Ankerschrauben im Fundament befestigt werden. Diese Gefahr ist immer dann vorhanden, wenn die Maschine eine schmale Aufstellfläche hat und dabei relativ hoch baut.

Erfahrungen der letzten 50 Jahre zeigen, dass diese Lösung bei den in Westeuropa aufgetretenen Erdbeben bis Magnituden von 4,0 nach Richter nicht immer notwendig war. Bei einem Erdbeben der Stärke 4,0 im Niederrheingebiet waren mit Doppelisolation aufgestellte Maschinen vor dem horizontalen Verrutschen geschützt. Vergleichbare Maschinen ohne eine Schwingungsisolation erlitten dagegen Schäden.

dbeben erfordern eine starre, stabile und feste
raben sind Beben bis Magnitude 4,0 nicht selten.

Maschinenschwingungen

Richtiges Isoli
fast alle Schwi

von Sebastian Moser
Produktion Nr. 6, 2005

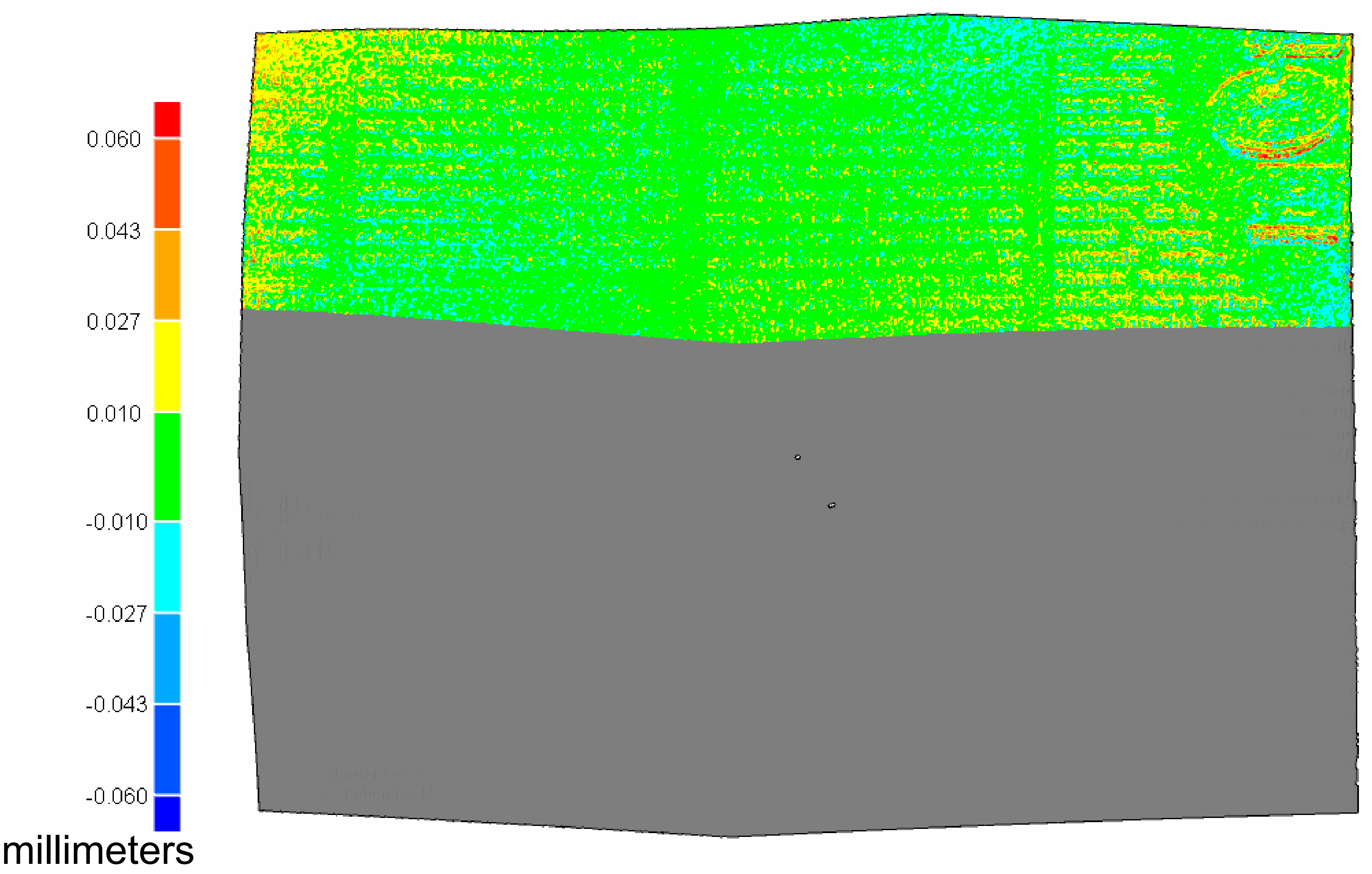
CH-KÜSNACHT. Im Zentrum der ganzen Schwingungstechnik steht das Isolationsmaterial, dessen Eigenschaften und Möglichkeiten. Es gibt eine ganze Menge verschiedener Materialien, die in wenige Gruppen eingeteilt werden können: Federn, natürlicher oder synthetischer Kautschuk, Kork- und Faserplatten, Verbundmateriali und Elastomere.

Alle haben sie in einem größer oder kleineren Bereich ihre Vortei So finden beispielsweise Stahl- od Luftfedern im extremen Tieffr

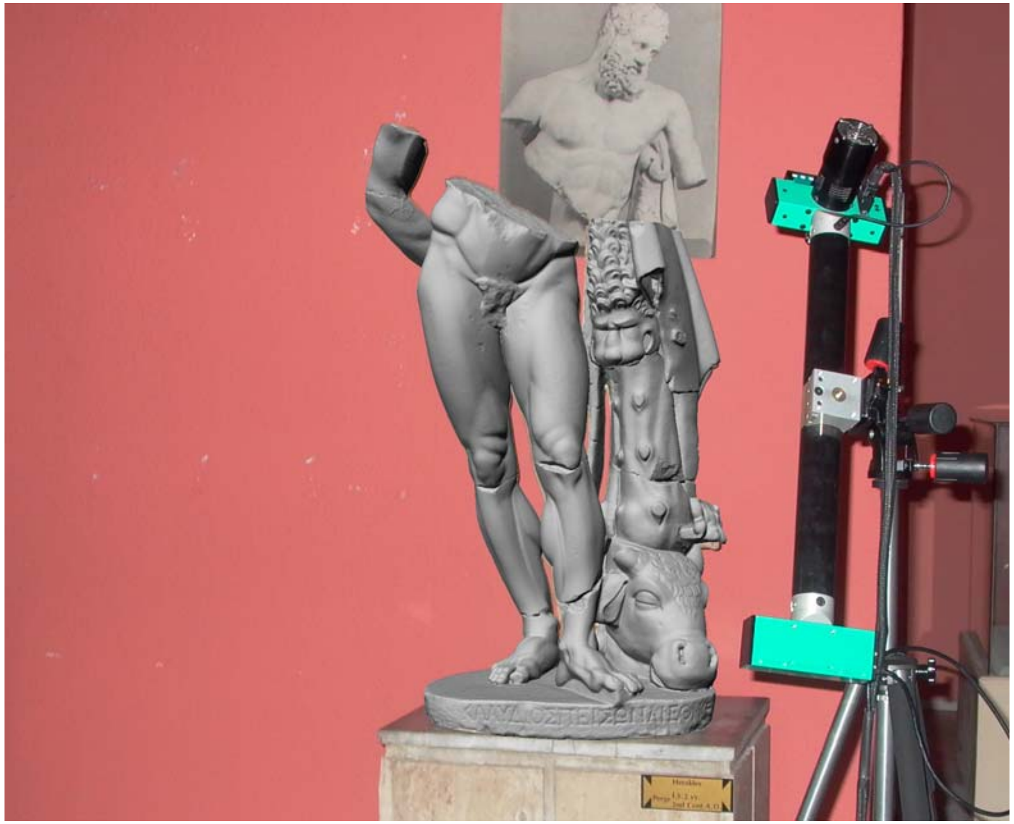
Mit Elastomerplatten lassen sich alle Schwingungsprobleme löse

quenzbereich (1 bis 5 Hz) ihre bevo zugte Anwendung. Kork hat gu Dämpfungseigenschaften, Kautsch ist durch seine Form- und Vulkan sierbarkeit vielfältig anpassbar u die Faserverbundplatten haben durc den besonderen Aufbau ausgezeich nete Stabilitätseigenschaften bei E genfrequenzen bis hinunter zu 25 H Die heute oft eingesetzten Elastomer auf Kunststoffbasis haben gute ch

Experimental results: Newspaper



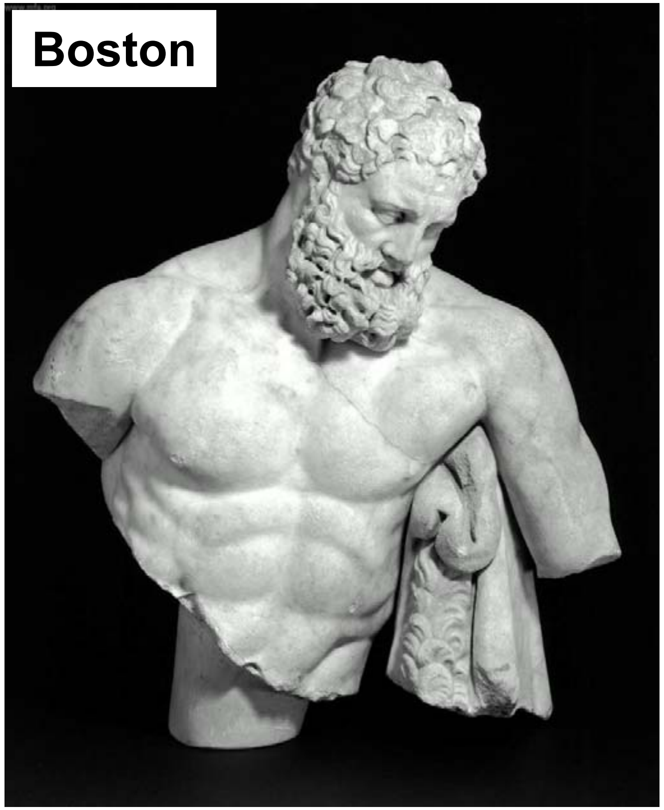
Residuals after LS3D surface matching method



3D modeling of the Weary Herakles statue with a coded structured light system

http://www.photogrammetry.ethz.ch/research/herakles/

The Weary Herakles Statue - Story



- Marble statue of the Greek demi-god Herakles (2nd c.AD).
- Copy of the original bronze statue of famous sculptor Lyssipos of Sicyon (4th c.BC)
- Broken in two parts.
- The upper half, seen in the USA in the early 1980s (Boston Museum of Fine Arts).
- The lower half, excavated in Perge (Antalya, TR) in 1980 by Prof. J. Inan, (now in the Antalya Museum).

The Weary Herakles Statue - Story

- According to Turkish law, Turkish antiquities state property since Ottoman times 1906.
- The Turkish government asked the upper half.
- The Boston MFA refused the petition, saying that:

“the statue may have broken in ancient times and the upper torso may have been taken from Turkey before the year 1906”.

Aim of the Project


Photo: O Acar

The Aim

- To record and model both the lower and the upper part and
- **bring these partial models together in the computer**,
- so that at least there the complete statue could be seen, appreciated and analyzed.

- The lower part in the Antalya Museum was scanned in September 2005.

- Access to the upper part in the Boston MFA was denied.

The Project

In cooperation with

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

breuckmann

info(+)TRON "Birlikte Geleceği Yaratıyoruz"

Data Acquisition

- Digitization in the Antalya Museum in September 2005
- Breuckmann optoTOP-HE coded structural light system

Coded Structural Light System

Coded Structural Light Technique:

- A kind of active stereo triangulation technique for surface measurement
- Replacing one of the cameras with a pattern projector

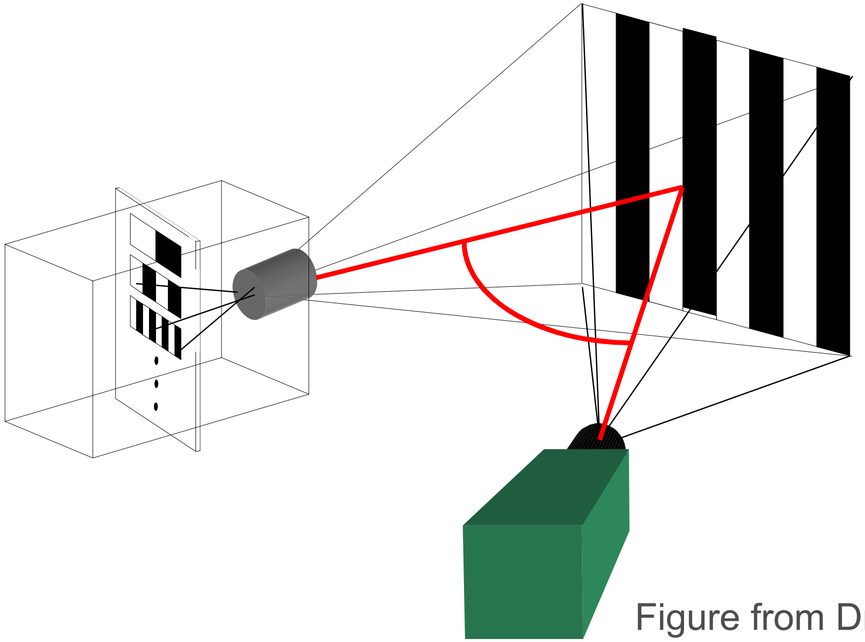
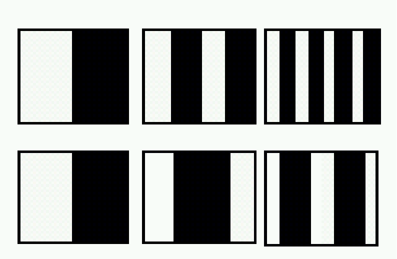


Figure from Dr. B. Breuckmann

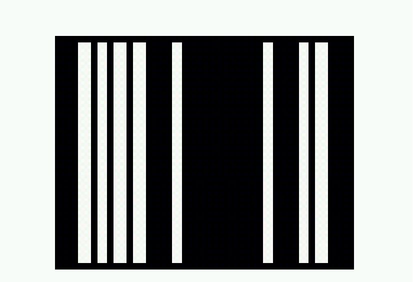
- Projecting a set of known patterns onto object
- Grabbing the images with the other camera
- Correspondence problem solved by system calibration parameters & known geometry of the patterns (decodification)

Coded Structural Light System - Pattern encoding techniques



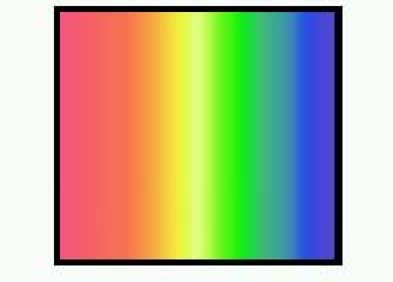
Time-multiplexing

- Binary codes
- n-ary codes
- **Gray code + phase shifting** (Breuckmann)
- Hybrid methods



Spatial codification

- Non-formal codification
- De Bruijn sequences
- M-arrays



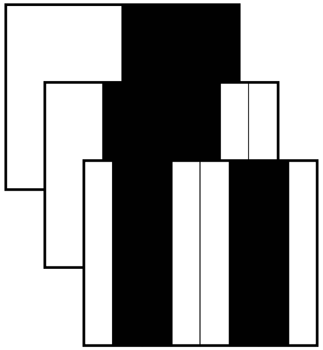
Direct Codification

- Grey levels
- Color

Salvi et al., 2003

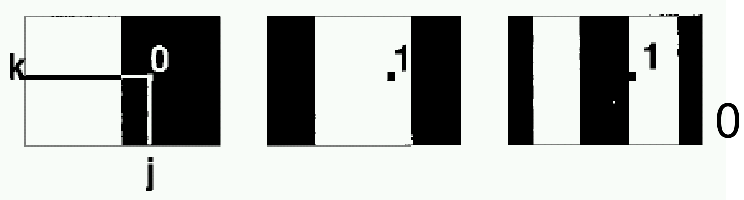
http://eia.udg.es/~jpages/ReportCodedLight03.pdf

Coded Structural Light System - Gray code + phase shifting



Gray code: (Frank Gray, 1953)

- A sequence of (Gray encoded) binary fringe patterns are projected, dividing into sections.
- A codeword is associated for each pixel, establishing the correspondence: image pixel -> projector stripe no

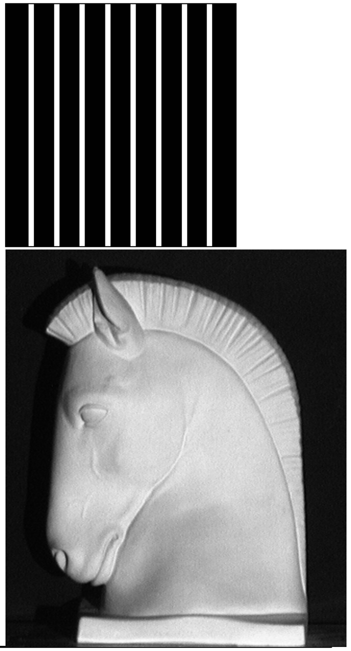


011

- 3D coordinates by triangulation
- Resolution limit, half size of the finest pattern

Phase shifting:

- A periodical pattern (sinusoidal) is projected several times by shifting it in one direction
- Phase unwrapping
- Each camera pixel -> projector stripe number (sub-stripe accuracy)



http://eia.udg.es/~jpages/examples/examples.html

Figure: Line shifting, Gühring, 2001

The Scanner: Breuckmann optoTOP-HE / SE

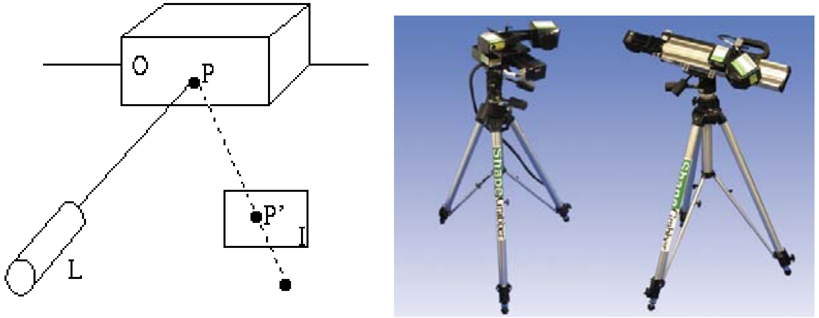
	optoTOP -HE	optoTOP -SE
Field of View (mm)	**480x360**	**400x315**
Depth of View (mm)	**320**	**260**
Decodification principle	**Gray code + phase shifting**	
Acquisition time (sec)	**ca 1**	
Weight (kg)	**2-3**	
Digitization (points)	**1380x1040**	**1280x1024**
Base length (mm)	**600**	**300**
Triangulation angle (deg)	**30^0**	
Projector	**128 order sinus patterns**	
Lamp	**100 W halogen**	
Lateral resolution (µm)	**~360**	**~340**
Depth accuracy (µm)	**~45**	**~50**

http://www.breuckmann.com

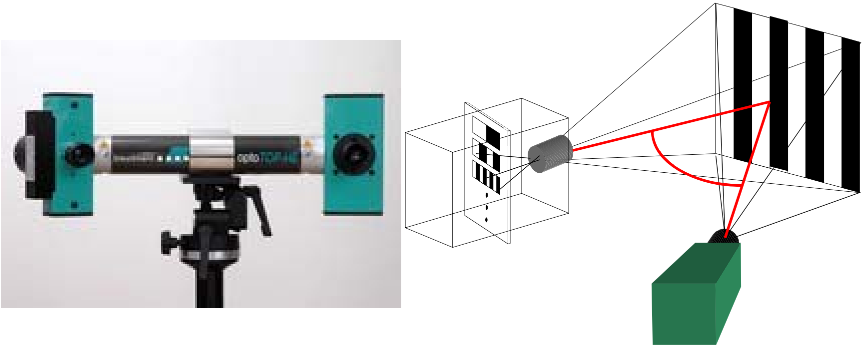
3D modeling of Cultural Heritage objects

Active Sensors – Triangulation based systems

Triangulation based systems	**Laser light**	**Coded structured light**
Weight and price	Identical	Identical
Speed		Faster
Sensitivity to ambient light	Less	
Speckle noise		Less
Penetration into object surface		No
Imaging for texture mapping		Yes
Depth of view	Larger	
Eye safety		Better



Laser light



Coded structured light

Scanning in the Antalya Museum

- Breuckmann optoTOP-HE system
- 1 ½ days on site work with 67 scans (56+11)
- Each scan 1.25M points
- Totally 83.75M points

preparation

scanning

Scanning in the Antalya Museum

optoTOP-HE, very flexible system

Postprocessing Workflow

- Registration
  - + Pairwise registration
  - + Global registration

LS3D v2.0.8 (LS3D)

- Point cloud editing
  - + Cropping the Area Of Interest
  - + Noise reduction
  - + Down-sampling

Geomagic Studio 6 (Geomagic Studio 6)

- Surface triangulation and editing

Geomagic Studio 6 (Geomagic Studio 6)

- Texture Mapping

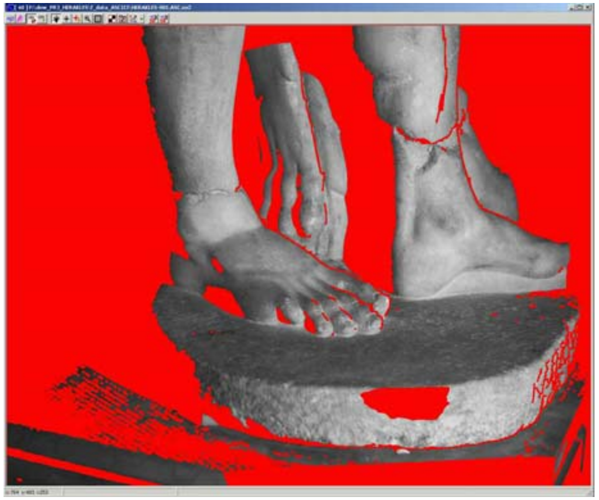
(VCLab's 3D Scanning Tool, CNR, Pisa)

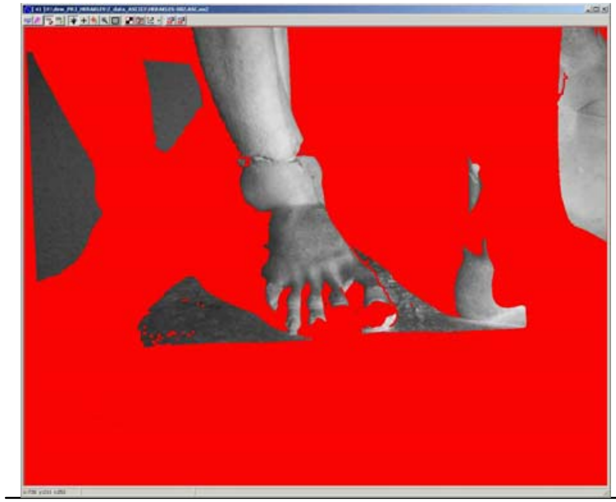
- Visualization

PolyWorks 9.0.2 (PolyWorks 9.0.2)

Registration – Pairwise registration

- 234 consecutive pairwise LS3D matching. The average sigma naught is **81 microns**.



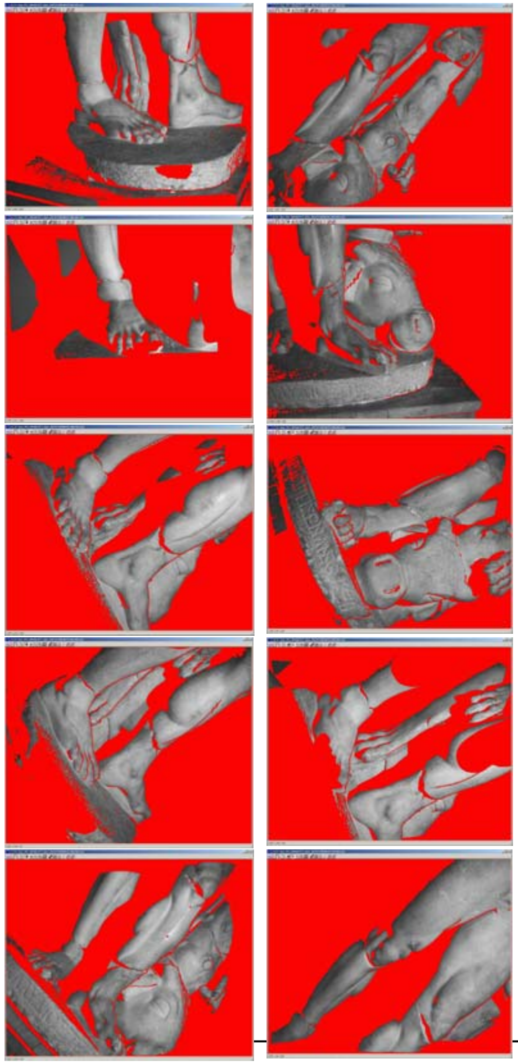


Example: Registration of 1st and 2nd scans

Note: 3x3 down-sampling for better visualization

Registration – Global registration

- Global registration with the block adjustment by independent models solution
- Sigma naught **47 microns**, in agreement with the system specifications

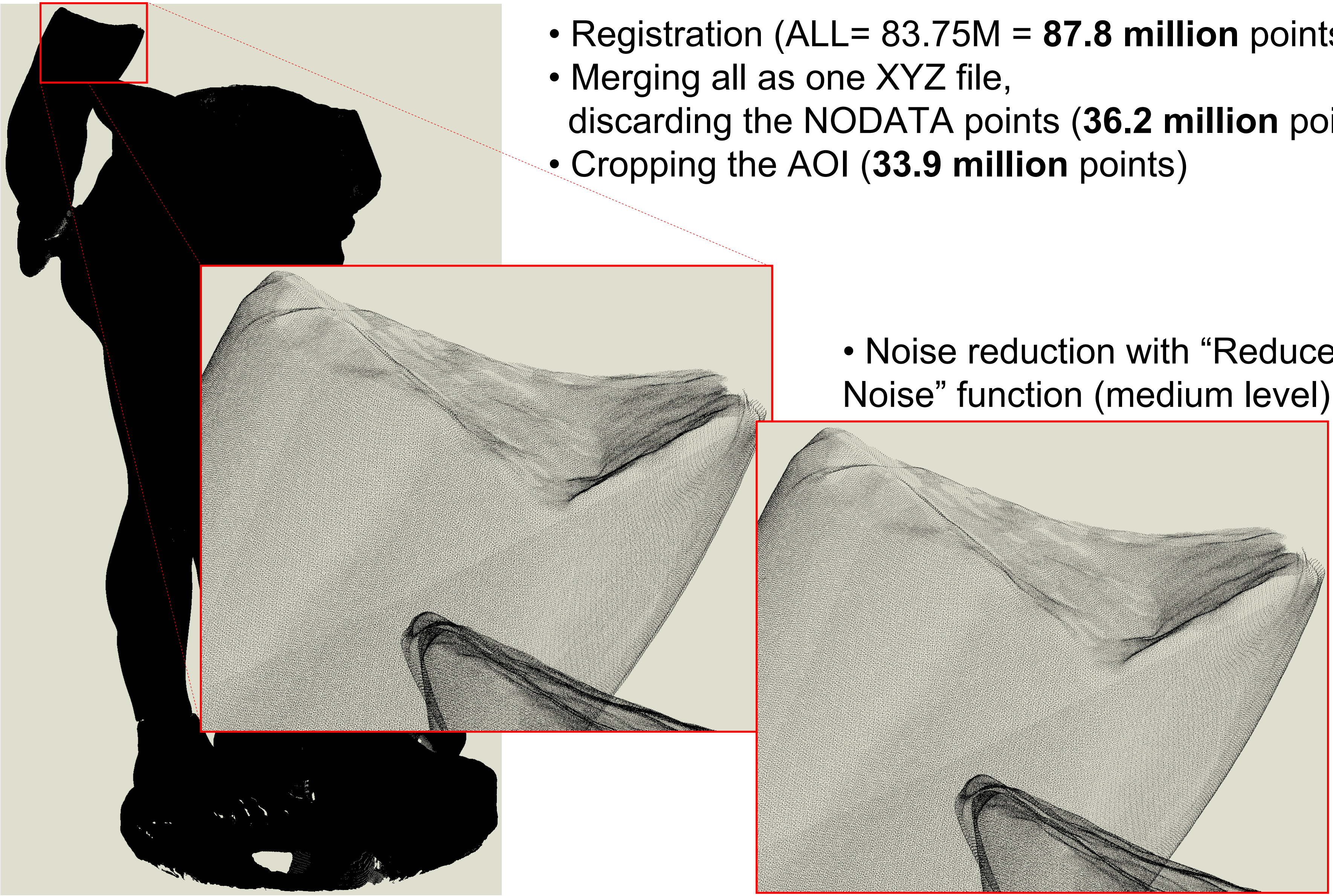


Example: Registration of first 10 scans

Note: 3x3 down-sampling for better visualization

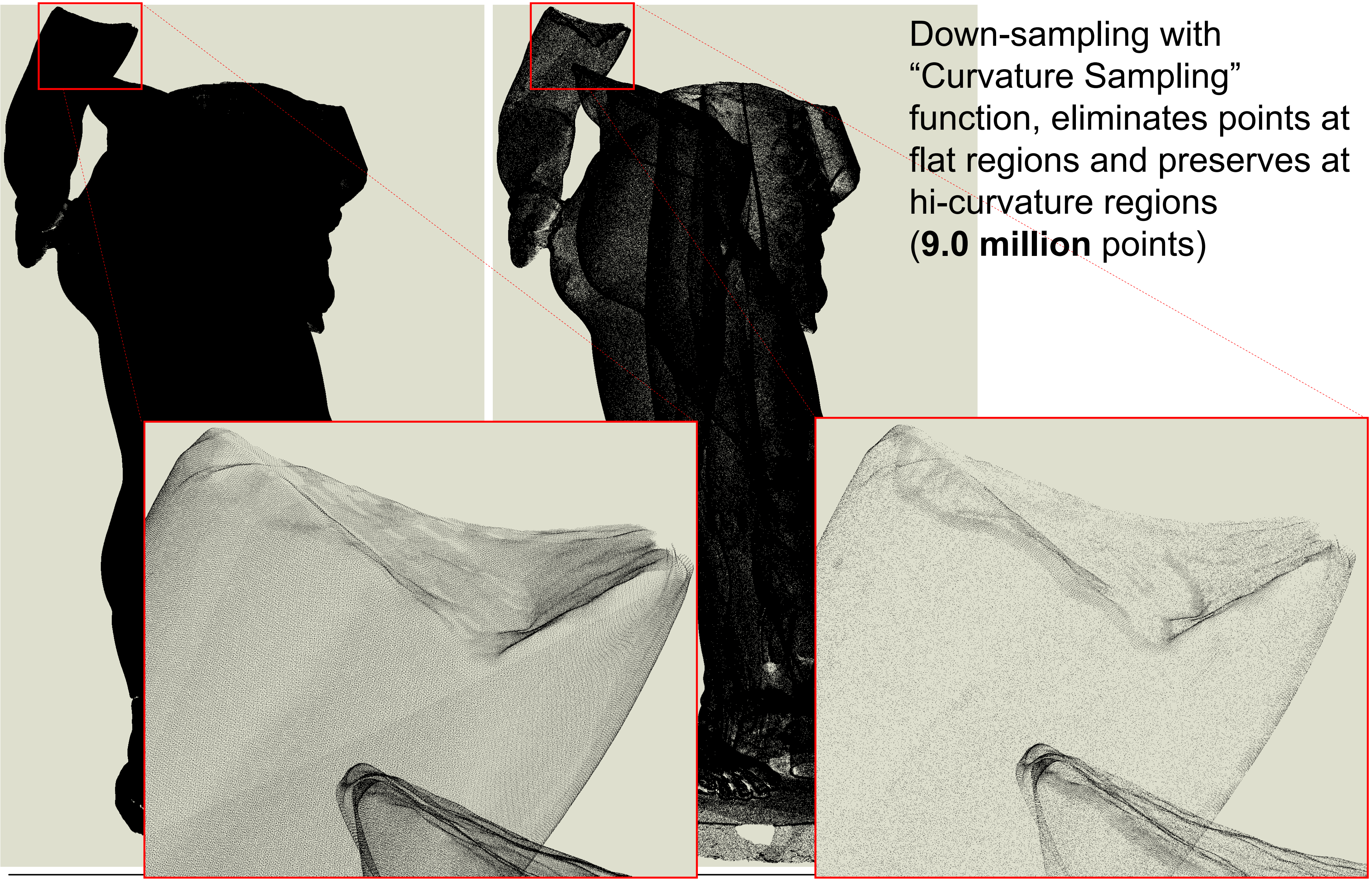
Point Cloud Editing – Noise reduction

- Registration (ALL= 83.75M = **87.8 million** points)
- Merging all as one XYZ file, discarding the NODATA points (**36.2 million** points)
- Cropping the AOI (**33.9 million** points)



- Noise reduction with “Reduce Noise” function (medium level)

Point Cloud Editing – Down-sampling

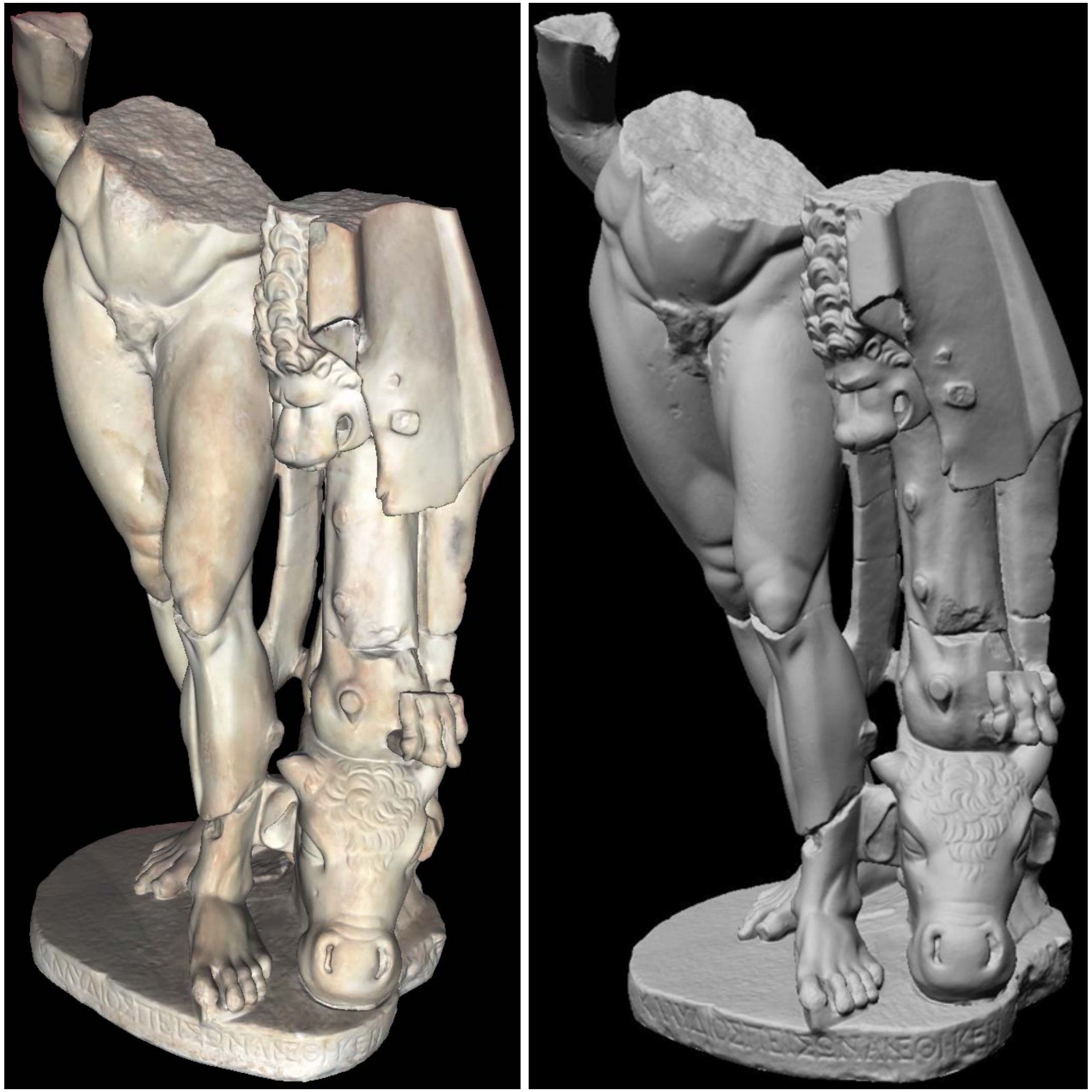


Down-sampling with “Curvature Sampling” function, eliminates points at flat regions and preserves at hi-curvature regions (**9.0 million** points)

Surface Triangulation and Editing

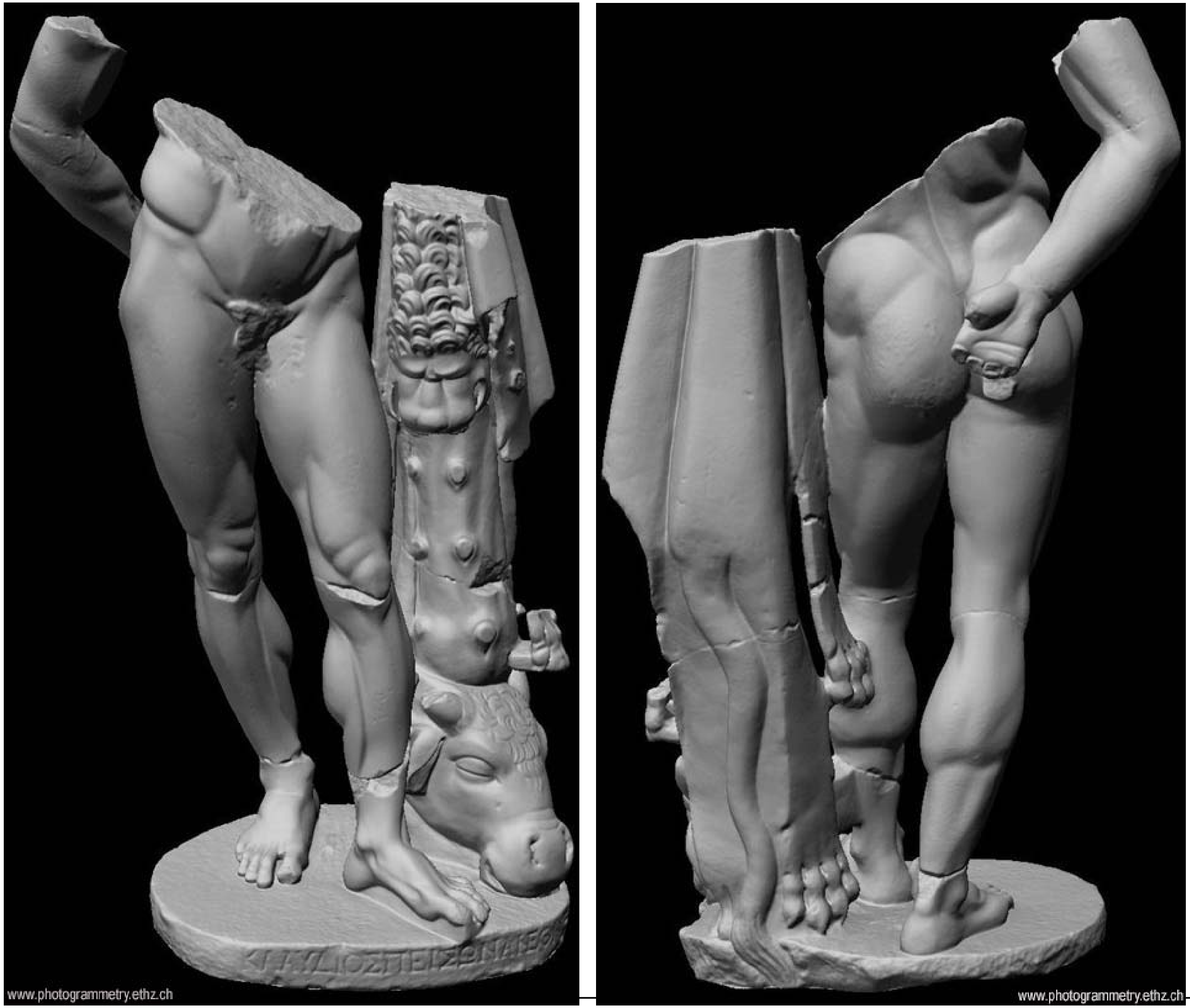
- Finally **9.0 million points => 5.2 million triangles**
- Memory problems with Geomagic if greater number of target triangles, e.g. 10 million
- Data holes due to complexity & inner concave parts
- Filling the holes is the most tedious step of the project

Texture Mapping



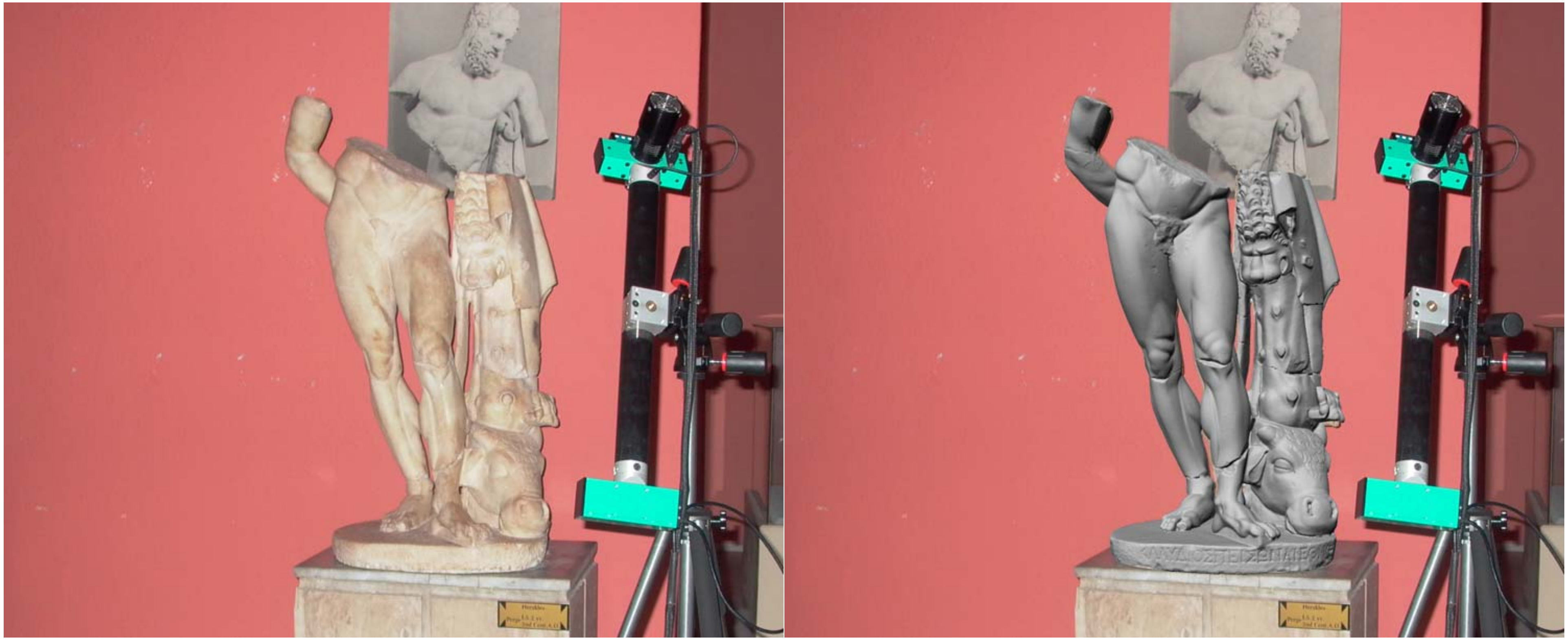
- Leica Digilux1, 4Mpixel CCD camera
- The Veawer module of VCLab‘s 3D Scanning Tool (ISTI-CNR, Pisa, Italy)

Visualization – (gray shaded)



- Better lighting & shading with PolyWorks IMView.

Visualization



Back projection of the 3D model into image space

http://www.photogrammetry.ethz.ch/research/herakles/

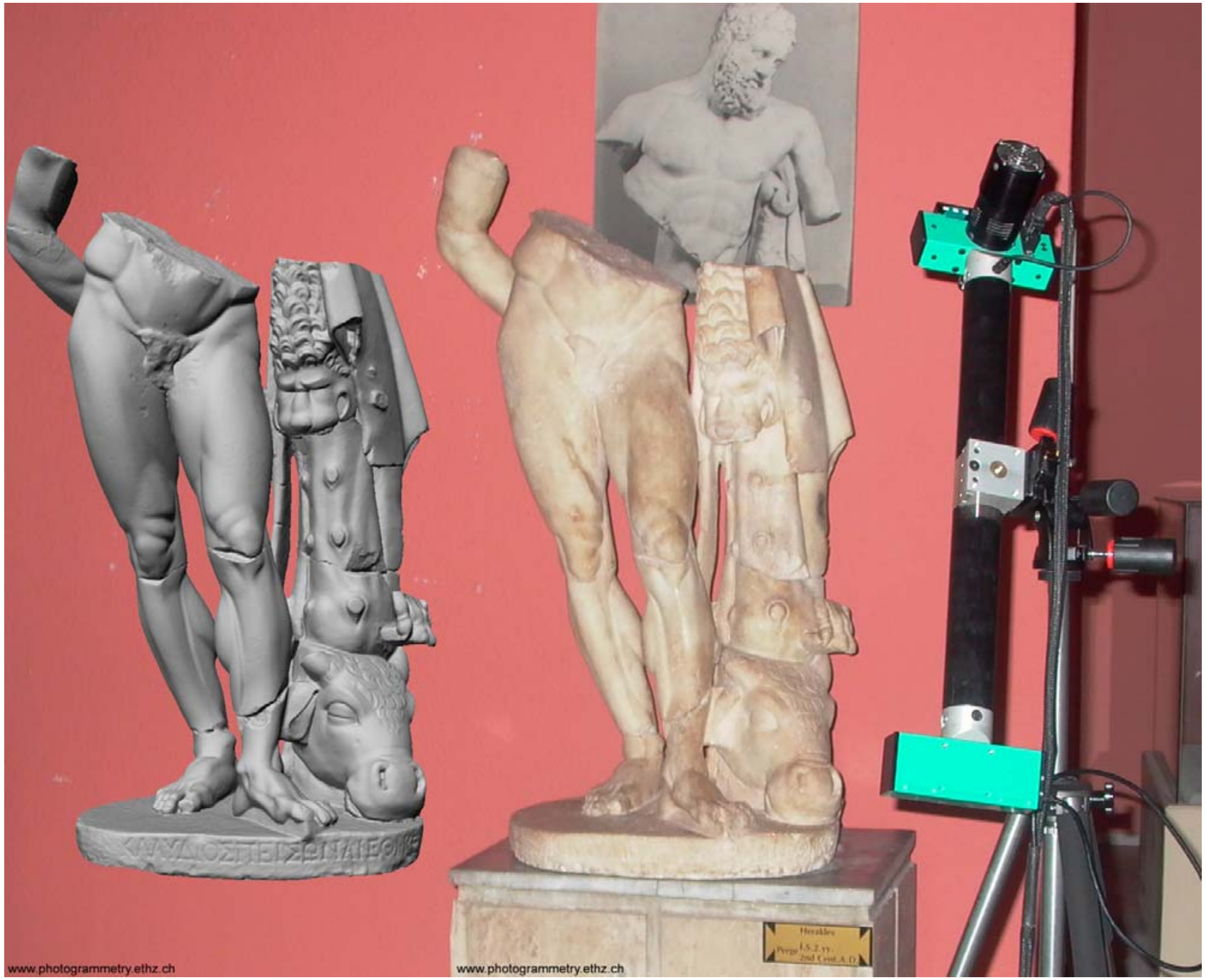
Gained experiences

- The coded structural light system is a mature technology and allows high resolution documentation of cultural heritage objects.
- The hardware component, optoTOP-HE worked well.

- Editing the surface is the most tedious step of the whole modeling pipeline. Need for sophisticated algorithms & software.
- Texture mapping is not fully available in either software.

http://www.photogrammetry.ethz.ch/research/herakles/

Result



http://www.photogrammetry.ethz.ch/research/herakles/

3D Modeling of a Khmer Head

http://www.photogrammetry.ethz.ch/research/khmer/

The Khmer head project

- Bodhisattva Head
- Cambodia - Khmer period
- Bayon style, 12th-13th a.c.
- 28 cm in height
- Sandstone
- Collection of Rietberg Museum, Zurich

The Scanner: Breuckmann optoTOP-HE / SE

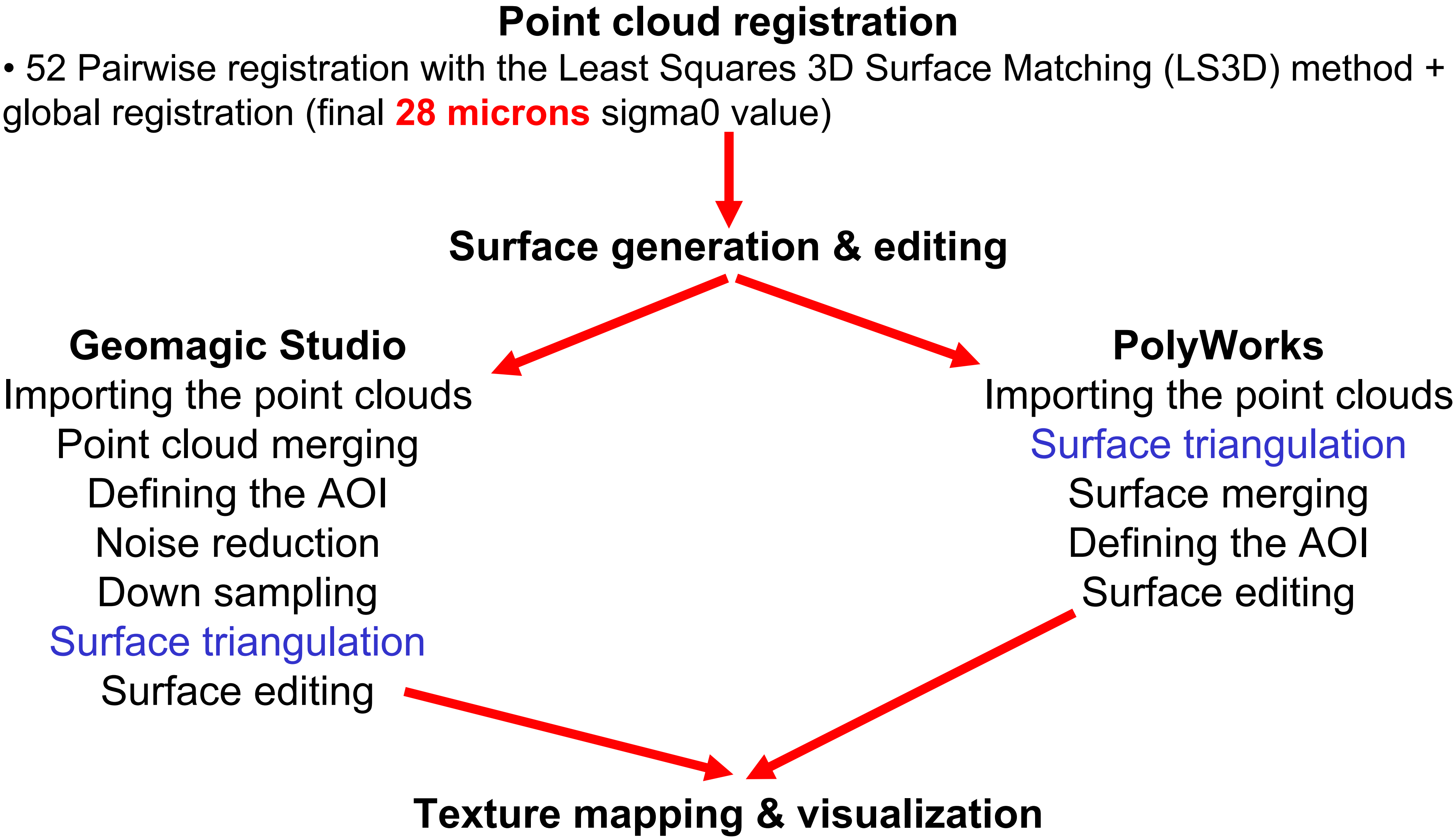
	optoTOP -HE	optoTOP -SE
Field of View (mm)	**480x360**	**400x315**
Depth of View (mm)	**320**	**260**
Decodification principle	**Gray code + phase shifting**	
Acquisition time (sec)	**ca 1**	
Weight (kg)	**2-3**	
Digitization (points)	**1380x1040**	**1280x1024**
Base length (mm)	**600**	**300**
Triangulation angle (deg)	**30^0**	
Projector	**128 order sinus patterns**	
Lamp	**100 W halogen**	
Lateral resolution (µm)	**~360**	**~340**
Depth accuracy (µm)	**~45**	**~50**

http://www.breuckmann.com

The Khmer head project – Data acquisition

- Data acquisition: 3-4 hours on site work
- Breuckmann OptoTOP-SE coded structural light system
- 18 scans, each scan 1.3 million points (totally 23.6 million points)

The Khmer head project – Data processing



Point cloud registration

- 52 Pairwise registration with the Least Squares 3D Surface Matching (LS3D) method + global registration (final **28 microns** sigma0 value)

Surface generation & editing

Geomagic Studio
Importing the point clouds
Point cloud merging
Defining the AOI
Noise reduction
Down sampling
Surface triangulation
Surface editing

PolyWorks
Importing the point clouds
Surface triangulation
Surface merging
Defining the AOI
Surface editing

Texture mapping & visualization

The Khmer head project – Data processing

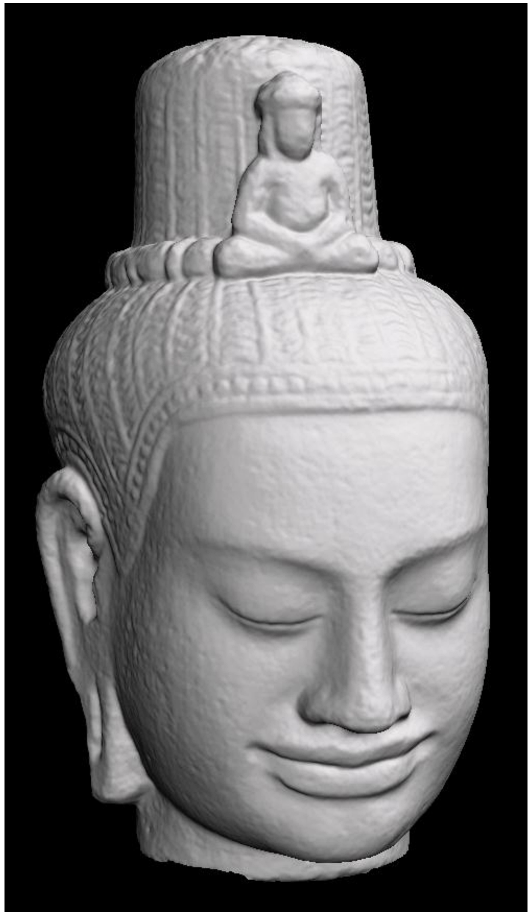
Geomagic Studio

- Full automatic import functionality

- Import
& merge all the pointclouds
& noise reduction
& pointcloud down-sampling

- Surface triangulation: fully 3D and automatic, limited user interaction

- Preserve the high frequency details of the object geometry successfully by considering all points in one processing sweep

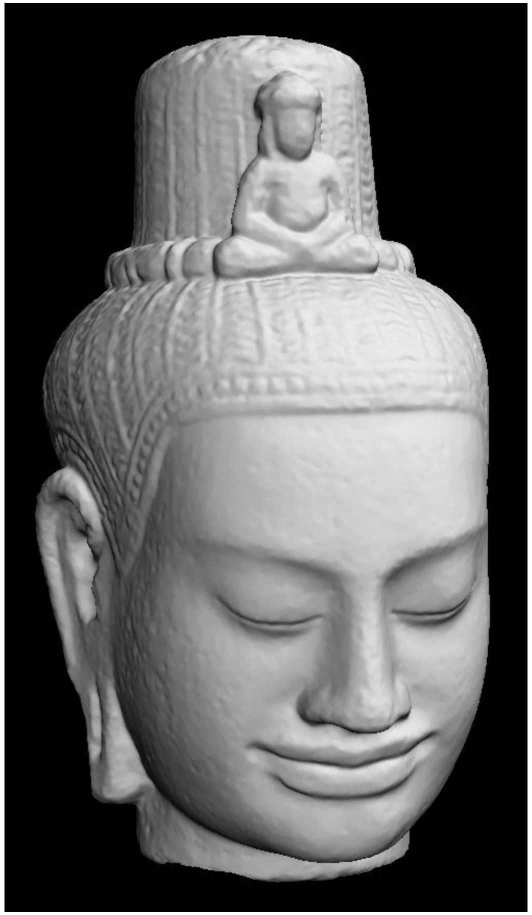


The Khmer head project – Data processing

PolyWorks

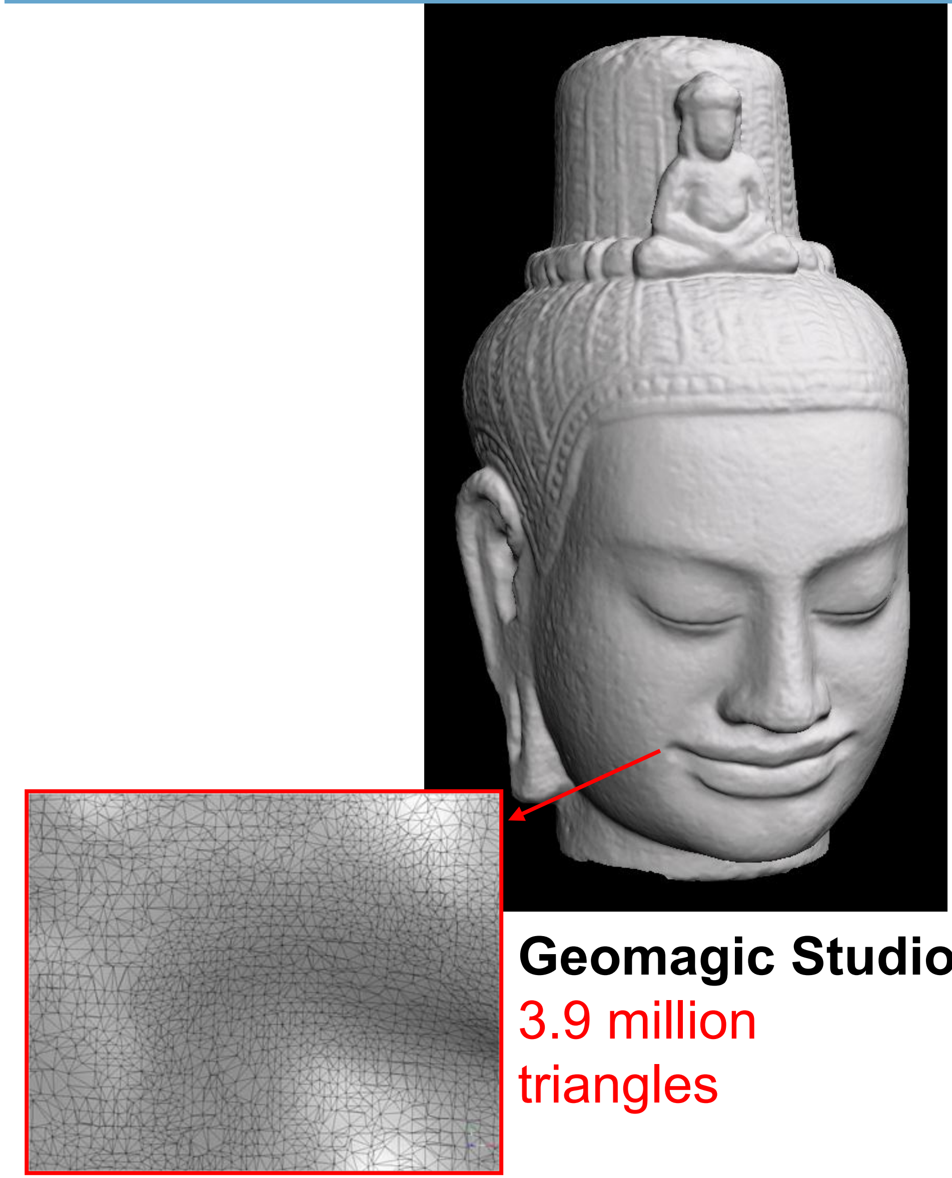
- Data import is not automatic

- Each pointcloud individually imported,
subsequently converted to surface by 2.5D triangulation.
Each pointcloud interactively rotated to the viewing angle of the data acquisition instant.
+ Advantage: less topological errors
-Disadvantage: partial processing, not one processing sweep



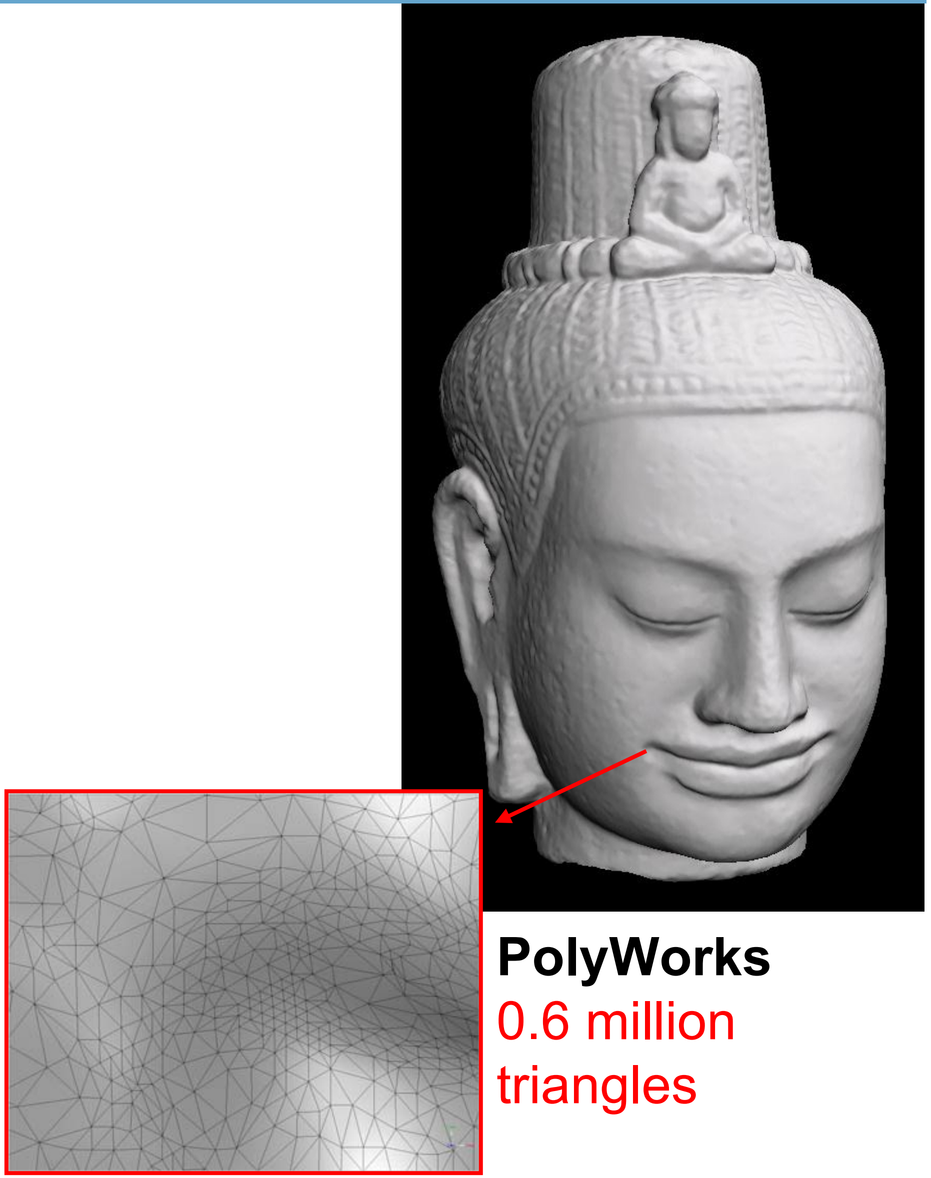
- Merge individual 2.5D surface → 3D manifold
- Noise reduction

The Khmer head project – Data processing



Geomagic Studio

3.9 million triangles



PolyWorks

0.6 million triangles

The Khmer head project – Data processing

	PolyWorks	**Geomagic**
Data import	Manual	Automatic
Triangulation		
Type	2.5D	3D
Optimality	Better	
Detail preservation		Better
Topological correctness	Better	
Automatisation		Better
Editing capabilities		Better
Performance	Better	
Visualization	Better	
User friendliness		Better
Stability	Better	

PolyWorks
9.0.2

Geomagic
Studio 6

The Khmer head project – Texture mapping & Viz

- Special illumination to avoid shadows
- Diffuse reflection

The Khmer head project – Texture mapping & Viz

Texture mapping procedure

- Image orientation with self-calibrating bundle adjustment
  - \+ Common points measured both on images & 3D model (intensity images)
  - \+ images → 3D model coordinate system

- Visibility analysis: (for each image)
  - \+ re-triangulate the partly occluded triangles into visible and occluded parts

- Select the optimal texture for every triangle
  - \+ according to best viewing angle criteria (the image with the most perpendicular viewing direction)
  - \+ Another criteria could be area of the projected triangles

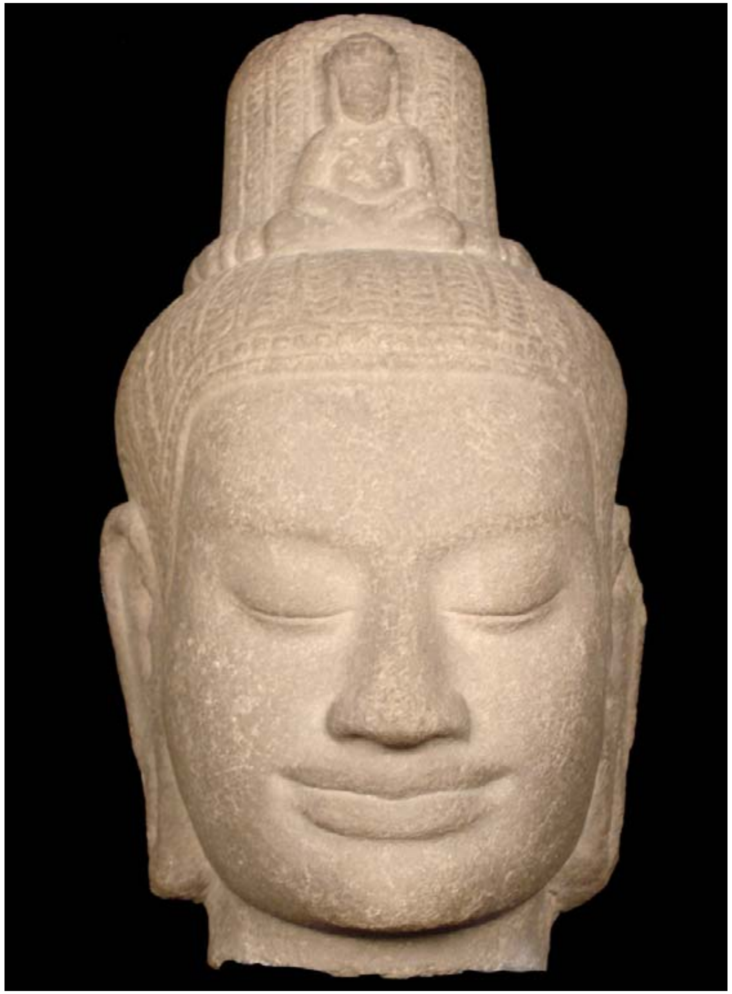
- Rendering for movie & animation

The Khmer head project – Texture mapping & Viz

Grey shaded model

Texture mapped model (T.Hanusch)

The Khmer head project – Texture mapping & Viz



Picture

3D model (T. Hanusch)

The Khmer head project – Comments

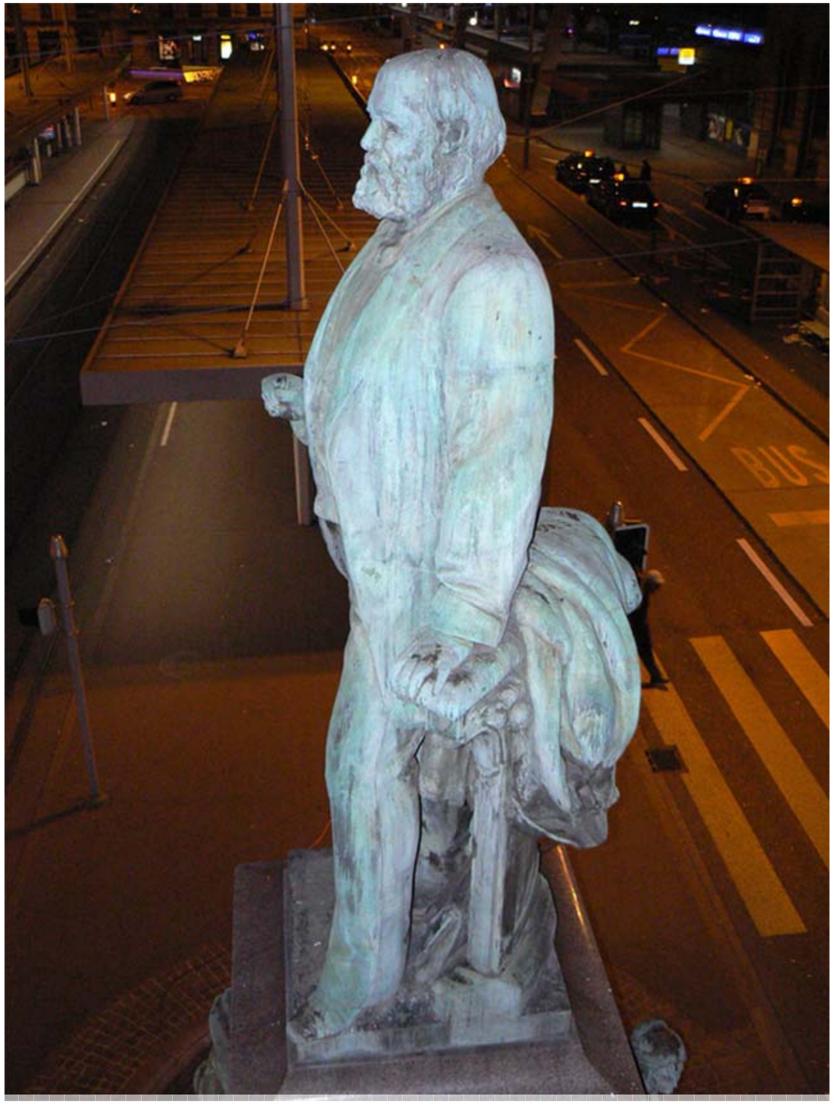
- Coded structural light systems are a good solution for fast and precise object recording and modeling

- Hardware component worked properly with the surface material (sandstone)

- Reached accuracy (ca 30-50 micron) might be not necessary in some archaeological applications

- Recovered 3D digital models useful for documentation or physical replica

- Employed modeling Software produced reasonable results
but any of them is not fully superior to others
=> multiple software is the optimum solution!



3D Modeling of Alfred Escher statue in Zurich

http://www.photogrammetry.ethz.ch/research/escher/

The Alfred Escher project

- Scanner: FARO LS880 HE80
- Range: 0.6-76 meters
- FOV: 320^0x360^0
- Accuracy: ±3 mm @ 10 meters

The Alfred Escher project

The Alfred Escher project

- Scanning in 2 nights:
  - 30 March 2007, Friday, 01:00am – 05:15am
  - 1 April 2007, Sunday, 01:00am – 05:00 am
- 36 scans with 4.4 million points in the AOI

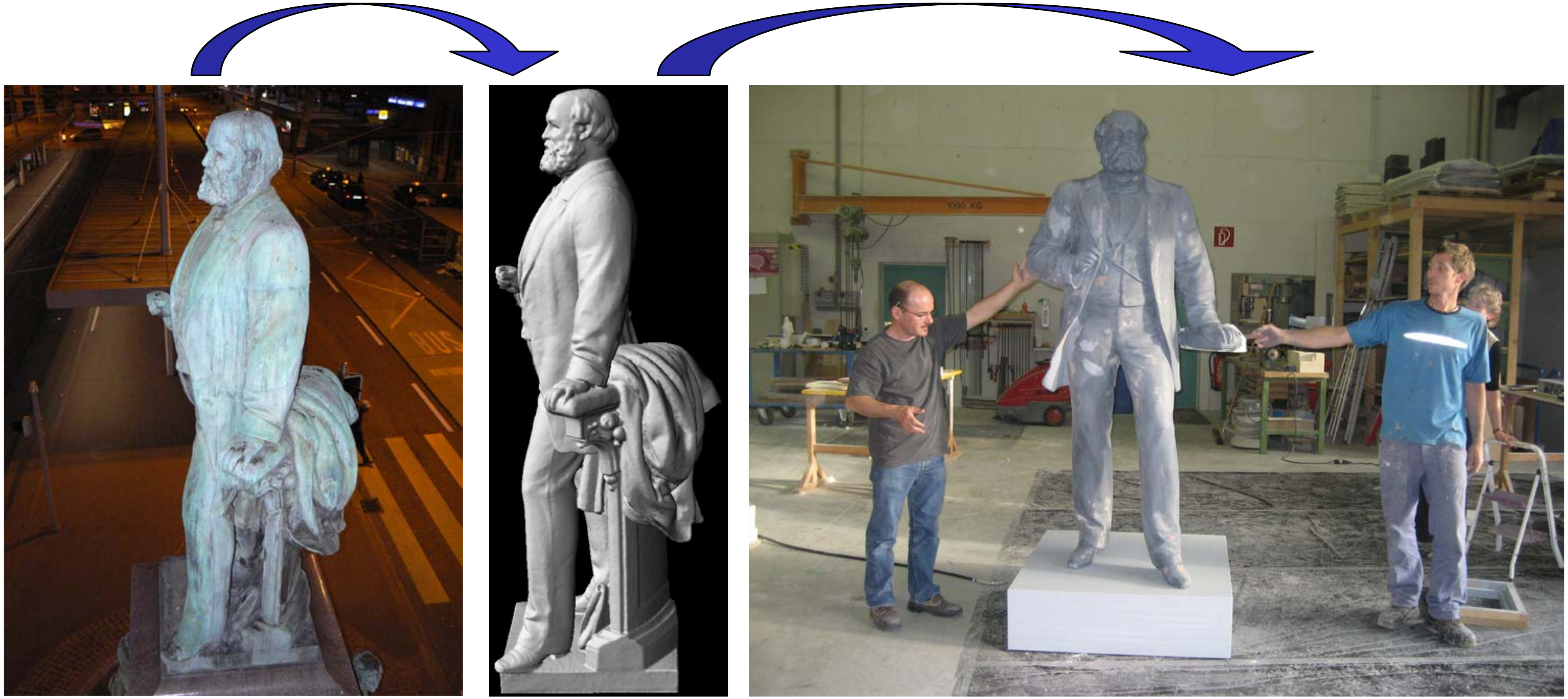
The Alfred Escher project

Intensity image of a scan

The Alfred Escher project

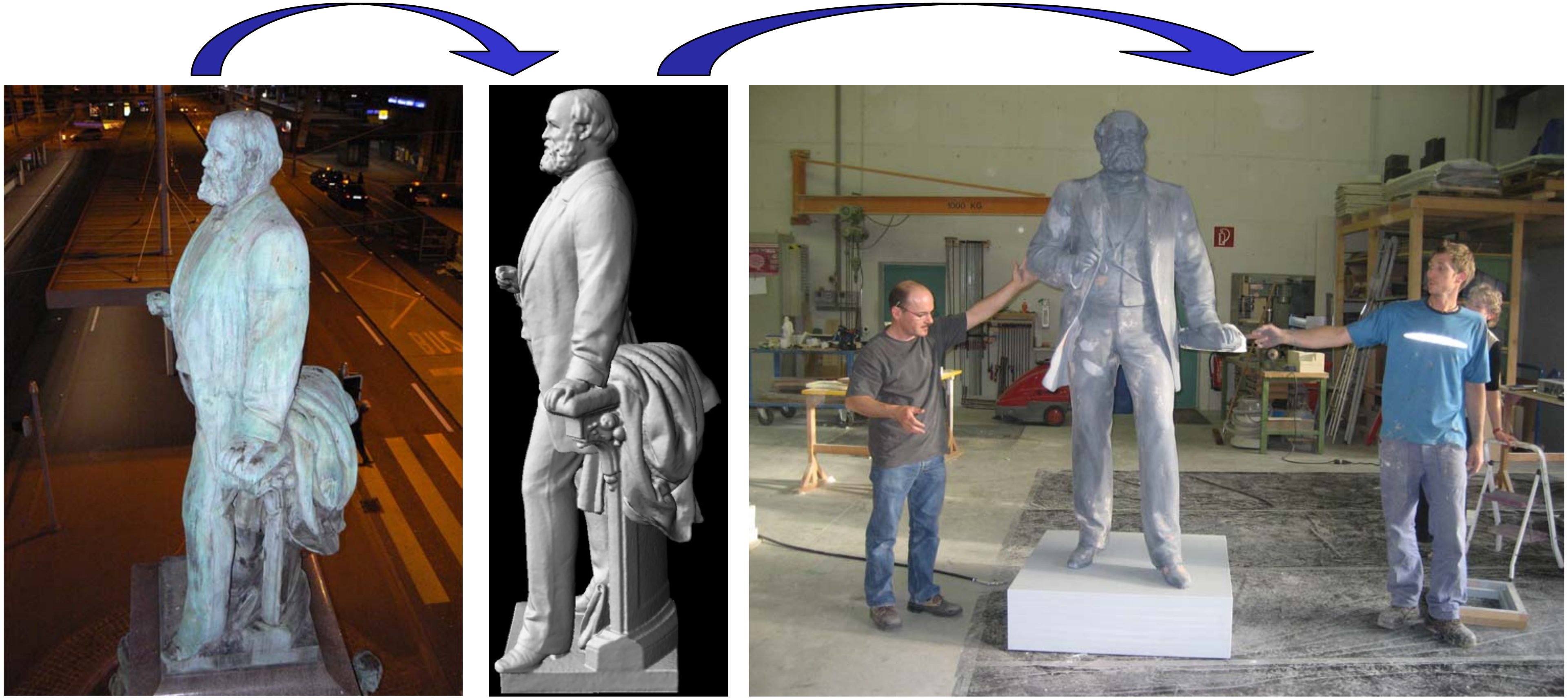
Modeling with Geomagic Studio

Why 3D modeling of Cultural Heritage objects?
Case of physical replica



Why 3D modeling of Cultural Heritage objects?

Case of physical replica



The Alfred Escher project

Physical replica production (scale 1/2)