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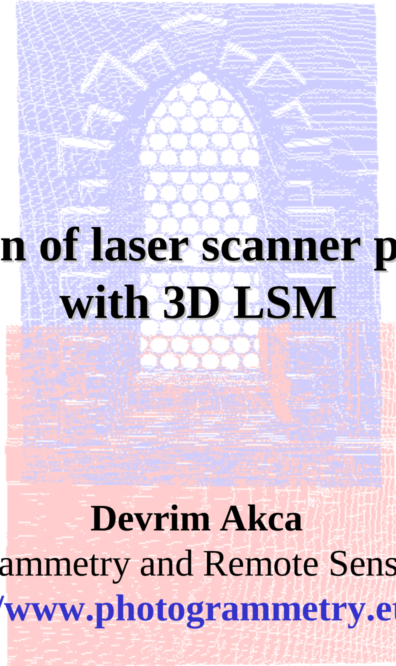

Registration of laser scanner point clouds with 3D LSM

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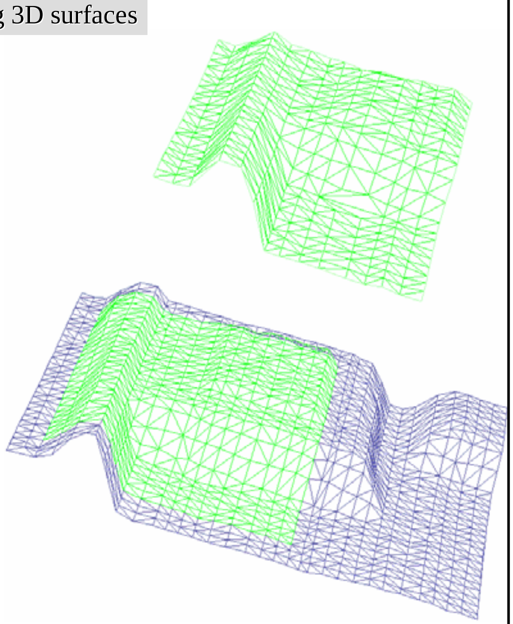
The Subject: Registration of overlapping 3D surfaces

<u>An object surface may be</u>

- 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)
- problem statement:
  - + matching the conjugate parts and estimating the 3D transformation



Contents:

Introduction: Previous work

Least Squares Matching (LSM) (*Grün, 1985*)
- Surface matching first was addressed as a straight extension of LSM

DEM Matching (*Ebner and Müller, 1986; Ebner and Strunz, 1988; Rosenholm and Torlegard, 1988*)
- It minimizes height differences along Z-axis by LSs (corresponds mathematically to LSM)
- It has been used for:
  - + absolute orientation of stereo models
  - + block triangulation
  - + registration of airborne laser scanner strips

Iterative Closest Point (**ICP**) (*Besl and McKay, 1992; Chen and Medioni, 1992; Zhang, 1994*)
- Iterative solution based on closed-form LS rigid transformation
- It converges slowly
- It has lack of internal quality indicators

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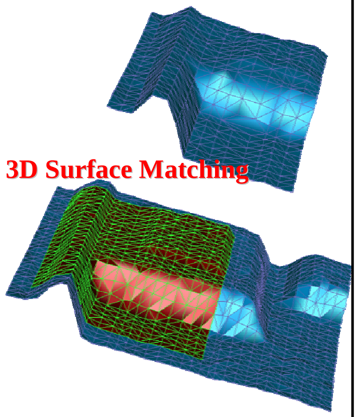
Introduction: Our proposed method LS 3D Surface Matching (LS3D)

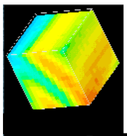
LS Image Matching *(Grün, 1984, 1985)*

Straightforward extension

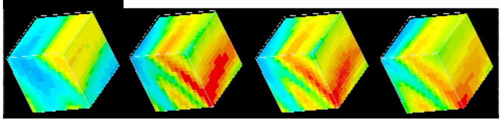
another extension



LS 3D Surface Matching



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



From H.G. Maas, 1994, P+F, IGP, ETH-Zürich
http://www.photogrammetry.ethz.ch/research/flotomo/flotomo.html

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The Basic Estimation Model: Observation equations

Two different partial surfaces of the same object

f(x,y,z) : template
g(x,y,z) : search (to be transformed)
} (discrete 3D representations of the real surface)

The problem statement is estimating the final 3D transformation of search surface g(x,y,z)

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

Considering the stochastic discrepancies, a true error vector e(x,y,z) has to be added

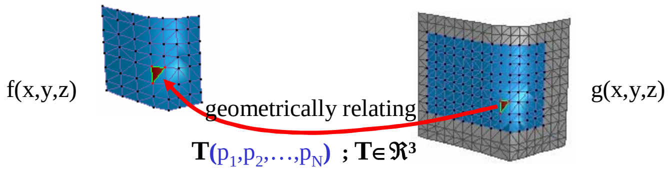
$$f(x,y,z) - e(x,y,z) = g(x,y,z) \quad (2)$$

Equation (2) is considered as observation equations

The goal function: $[d_E d_E] = \min$ (3) d_E:Euclidean distance

The final location of g(x,y,z) is estimated with respect to an initial position $g^0(x,y,z)$

The Basic Estimation Model: Geometric relationship



- Geometric relationship: 7-parameter 3D similarity transformation

$$\begin{aligned} x &= t_x + m(r_{11}x_0 + r_{12}y_0 + r_{13}z_0) \\ y &= t_y + m(r_{21}x_0 + r_{22}y_0 + r_{23}z_0) \\ z &= t_z + m(r_{31}x_0 + r_{32}y_0 + r_{33}z_0) \end{aligned} \qquad (4)$$

- Any other kind of 3D transformation can be also used: (3D affine, tri-linear, etc..)

The Basic Estimation Model: Functional model

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

The functional model is non-linear. It is linearized by Taylor Expansion.

Differentiation terms

$$f(x,y,z) - e(x,y,z) = g^0(x,y,z) + \frac{\partial g^0(x,y,z)}{\partial x}dx + \frac{\partial g^0(x,y,z)}{\partial y}dy + \frac{\partial g^0(x,y,z)}{\partial z}dz \qquad (5)$$

$\mathbf{g_x}$ $\mathbf{g_y}$ $\mathbf{g_z}$

Initial state (by approximations) *Numerical derivatives*

Final functional model in linearized form:

$$\begin{aligned} -e(x,y,z) = {} & g_x dt_x + g_y dt_y + g_z dt_z + (g_x a_{10} + g_y a_{20} + g_z a_{30})dm + (g_x a_{11} + g_y a_{21} + g_z a_{31})d\omega + \\ & (g_x a_{12} + g_y a_{22} + g_z a_{32})d\varphi + (g_x a_{13} + g_y a_{23} + g_z a_{33})d\kappa - (f(x,y,z) - g^0(x,y,z)) \end{aligned} \qquad (6)$$

The functional model in matrix notation:

$$-\mathbf{e} = \mathbf{A}\,\mathbf{x} - \ell \quad , \quad \mathbf{P} \qquad (7)$$

A design matrix
$\mathbf{x}^T = [dt_x\ dt_y\ dt_z\ dm\ d\omega\ d\varphi\ d\kappa]$ parameter vector
$\ell = f(x,y,z) - g^0(x,y,z)$ constant vector (Euclidean distances)

$$-\mathbf{e}_b = \mathbf{I}\,\mathbf{x} - \ell_b \quad , \quad \mathbf{P}_b \qquad (8)$$

The unknown parameters are added as stochastic quantities

The Basic Estimation Model: Mathematical model

The total system is a Generalized Gauss-Markoff model:

$$-\mathbf{e} = \mathbf{A}\,\mathbf{x} - \ell \quad , \quad \mathbf{P} \tag{7}$$

$$-\mathbf{e}_b = \mathbf{I}\,\mathbf{x} - \ell_b \quad , \quad \mathbf{P}_b \tag{8}$$

The Least Squares solution of the joint system gives as:

Solution vector: $$\hat{\mathbf{x}} = (\mathbf{A}^T\mathbf{P}\mathbf{A} + \mathbf{P}_b)^{-1}(\mathbf{A}^T\mathbf{P}\ell + \mathbf{P}_b\ell_b) \tag{9}$$

Variance factor: $$\hat{\sigma}_0^2 = \frac{\mathbf{v}^T\mathbf{P}\mathbf{v} + \mathbf{v}_b^T\mathbf{P}_b\mathbf{v}_b}{r} \tag{10}$$

The solution is iterative. At each iteration:

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

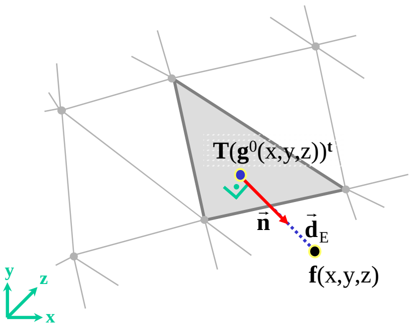
The iteration stops if each element of the alteration vector $\hat{x}$ falls below a certain limit:

$$|dp_i| < c_i \quad , \quad i = \{1,2,\ldots,7\} \tag{11}$$

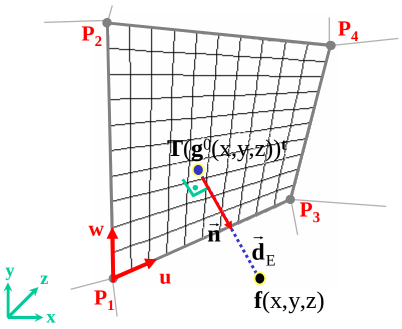
The Basic Estimation Model: Numerical derivative terms

Numeric derivative terms $\{\mathbf{g_x}, \mathbf{g_y}, \mathbf{g_z}\}$ are defined as local surface normals.
Their calculation depends on the analytical representation of search surface elements.
We represented them in two kind of piecewise forms optionally:

Triangle plane representation



Parametric bi-linear representation



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

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Precision and Reliability

- $\mathbf{K}_{xx}$ gives useful information on the stability of the system and 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

$$(\boldsymbol{P})_{ii} = \begin{cases} 1 & \text{if} \quad |(\boldsymbol{v})_i| < K\sigma_0 \\ 0 & \text{else} \end{cases}$$

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.

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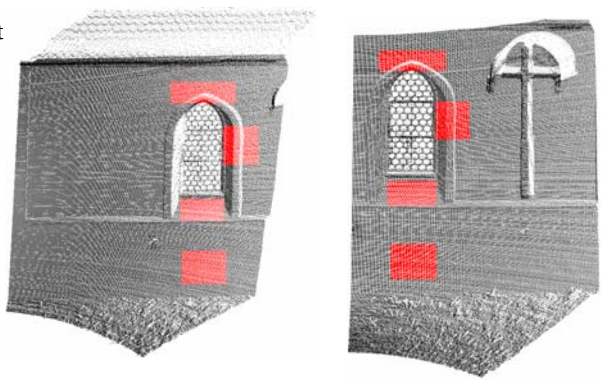
Further Extension: Simultaneous multi-subpatch matching

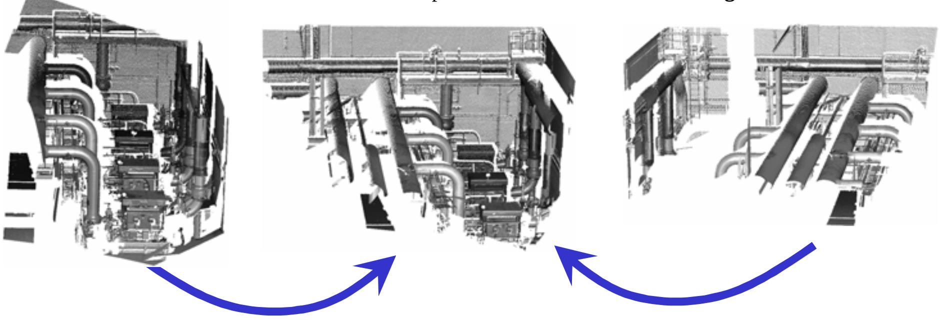
- Suppose that two scans are subject to matching
- Straightforward way is matching the whole overlapping area
- Another way is matching of only some cooperative subpatches



+ Subpatches are manually selected
+ Joined to the system by the same 3D transformation parameters
+ Individual subpatches may not include sufficient information, but together they provide a computationally effective solution.

Experimental Results (#1): Plant

Left search surface | **Centre** template surface | **Right** search surface



- object: plant area
- scanner: Leica HDS 2500
- average point spacing ~ 12 mm.

Data set is courtesy of Leica Geosystems HDS Inc.

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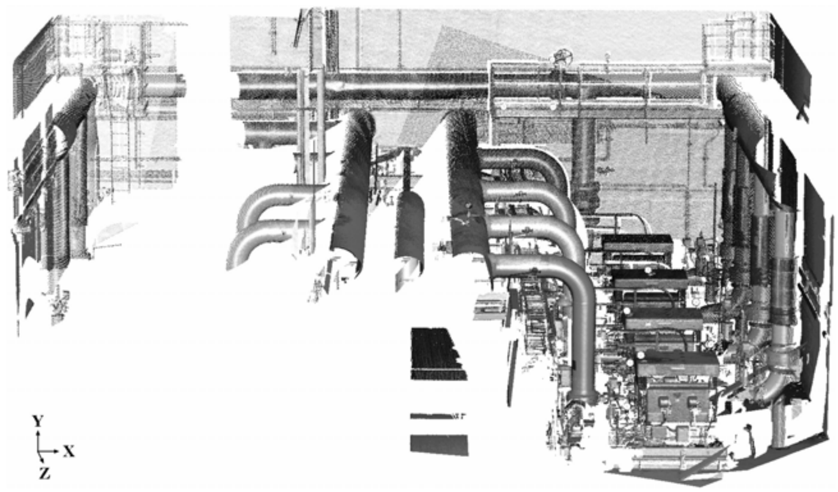
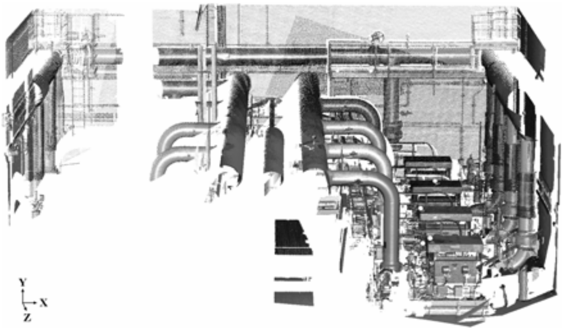
Experimental Results (#1): Plant

Result of LS3D surface matching method:



Experimental Results (#1): Plant



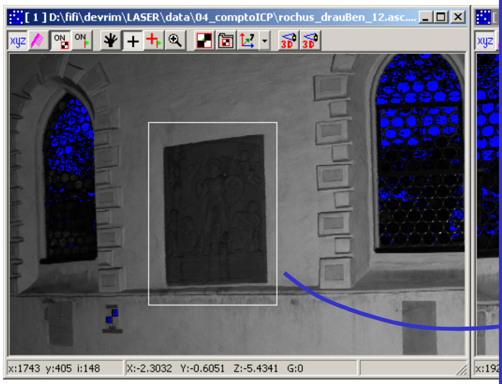
Numerical results of “plant”

#		Σpoints	Iter.	$\hat{\sigma}_0$ (mm)
I	LEFT	245041	6	**2.78**
II	RIGHT	323936	7	**2.54**

Numerical results of “plant” (multi-subpatch approach)

#		Σsub-patches	Σpoints	Iter.	$\hat{\sigma}_0$ (mm)
III	LEFT	5	20407	6	**2.11**
IV	RIGHT	7	37983	8	**2.01**

Experimental Results (#2): Comparison to ICP



- object: A bas-relief on the wall of a chapel (Wan
- scanner: Z+F IMAGER 5003
- average point spacing ~ 11 mm.

Data set is courtesy of Zoller+Fröhlich GmbH Elektrotechnik.

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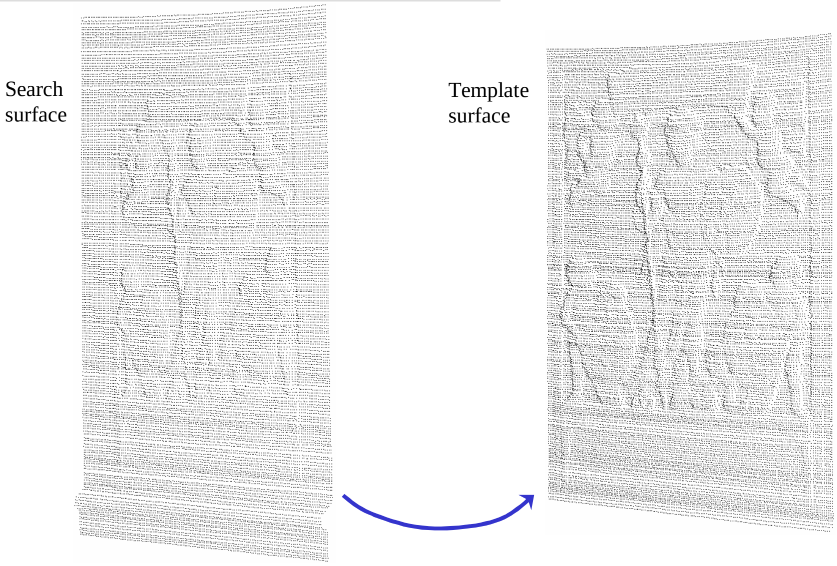
Experimental Results (#2): Comparison to ICP



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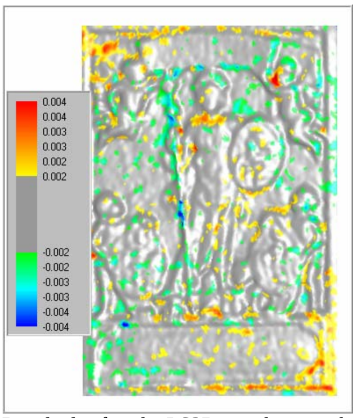
Experimental Results (#2): Comparison to ICP

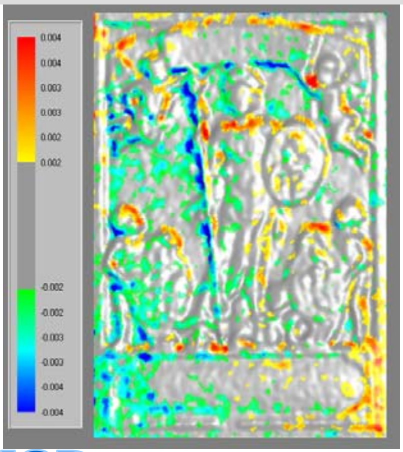
Result of LS3D surface matching method:

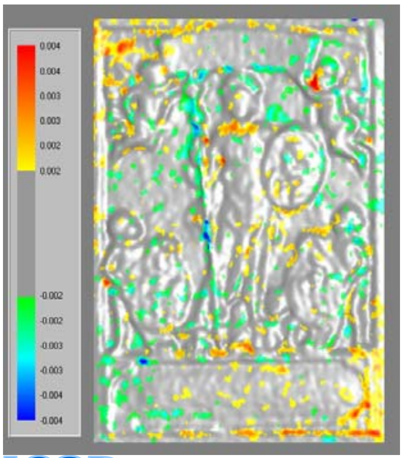


Residuals after the LS3D matching method

no. points	31520
iterations	10
spacing (mm)	~11
sigma0 (mm)	**2.45**

Experimental Results (#2): Comparison to ICP





ICP **Geomagic Studio v.4.1**
Statistical results: N/A

RMSE: 2.55 mm

LS3D

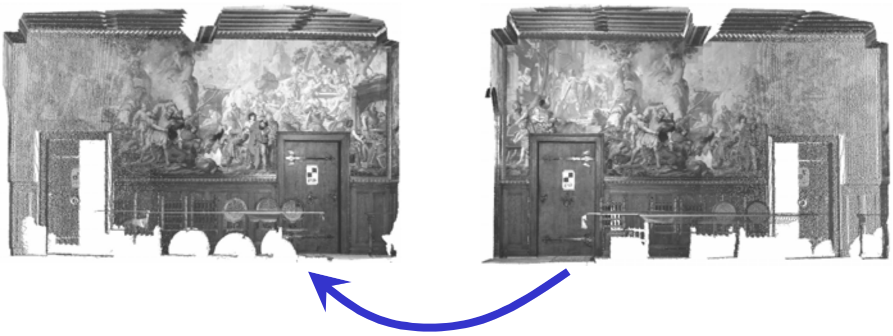
RMSE: 2.40 mm

Comparing distribution and magnitude of the residuals, LS3D gives slightly better results than the ICP.

Experimental Results (#3): "Room"

Template surface

Search surface

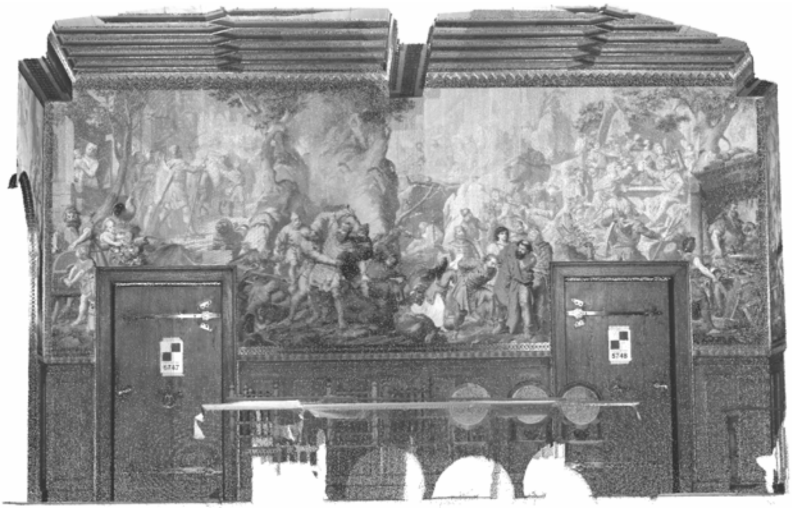


- object: a room in Neuscahwanstein Castle in Bavaria (Germany)
- scanner: Zoller+Fröhlich IMAGER 5003
- average point spacing ~ 5 mm.

Data set is courtesy of Zoller+Fröhlich GmbH Elektrotechnik.

Experimental Results (#3): "Room"

Result of LS3D surface matching method:



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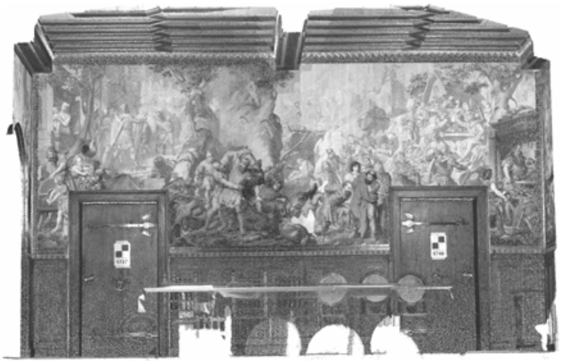
Experimental Results (#3): "Room"



#	Σsub-patches	Σpoints	Iterations	Time (sec.)	$\hat{\sigma}_0$ (mm)	
I	1	1,155,502	10	142.5	**3.69**	Basic model
II	7	279,088	8	25.8	**3.60**	Multi-subpatch approach

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Experimental Results (#4): "wooden Buddha"

- **object**: An Indonesian Buddha
- **material**: polished wooden, shiny!
- **scanner**: Breuckmann triTOS-HE based on fringe projection technique
- **average point spacing** ~ 0.3-0.5 mm.

Remondino et al., 2005. 3D Modeling of close-range objects: photogrammetry or laser scanning? Videometrics VIII, SPIE vol. 5665, pp. 216-225.

Data set is courtesy of Fabio Remondino (ETH Zurich) and Breuckmann GmbH.

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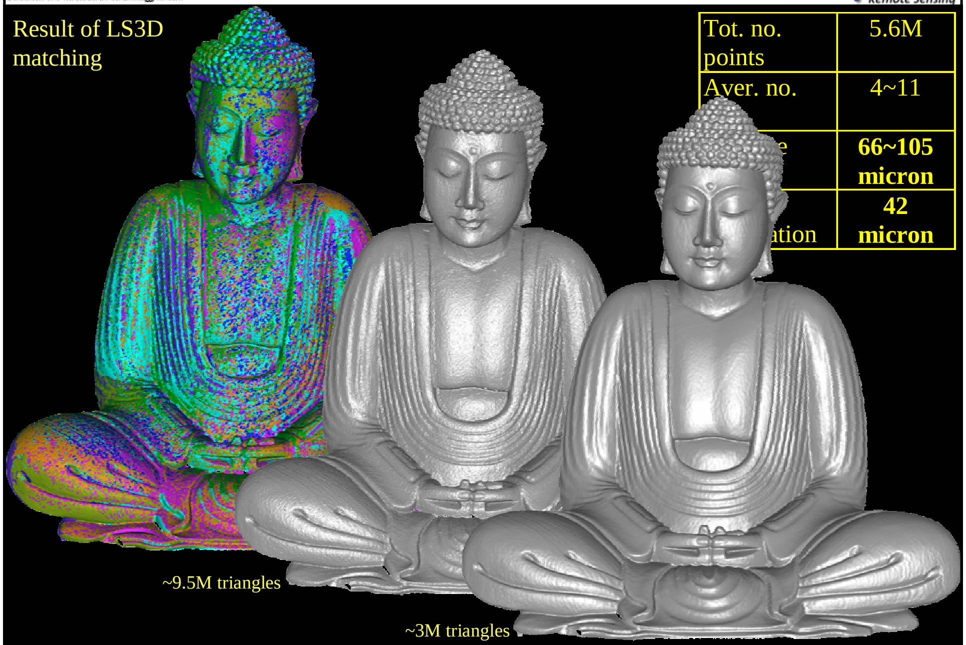

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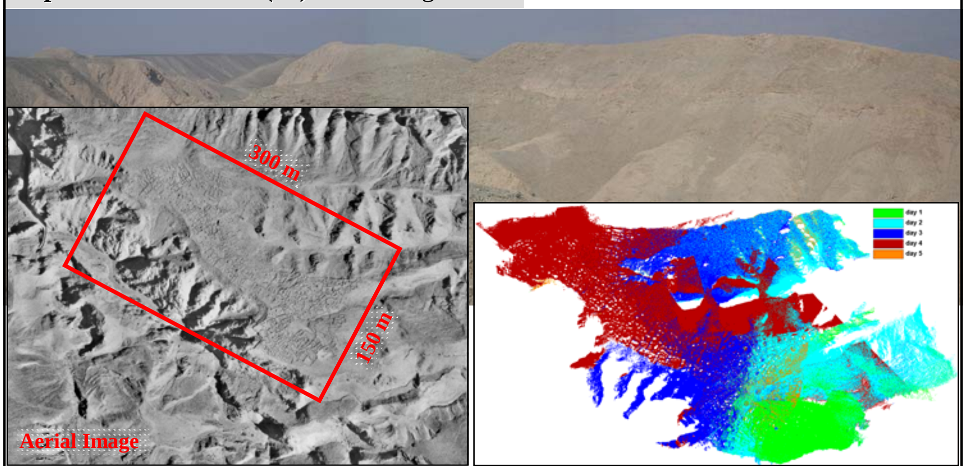
Experimental Results (#5): "Pinchango Alto"



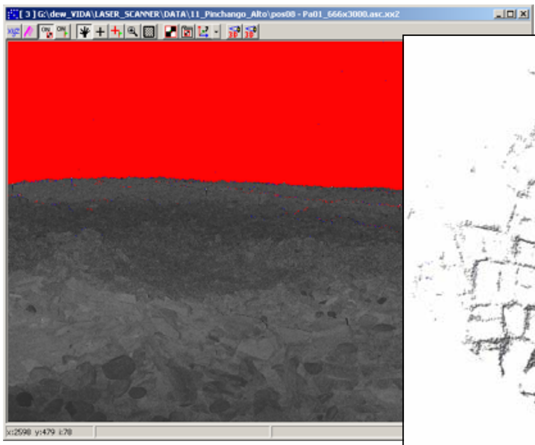
- area: Pinchango Alto, a pre-Inkaic site in Peru
- scanner: Riegl LMS Z-420*i*
- average point spacing 1~30 cm, changing with range

Data set is courtesy of Riegl GmbH.

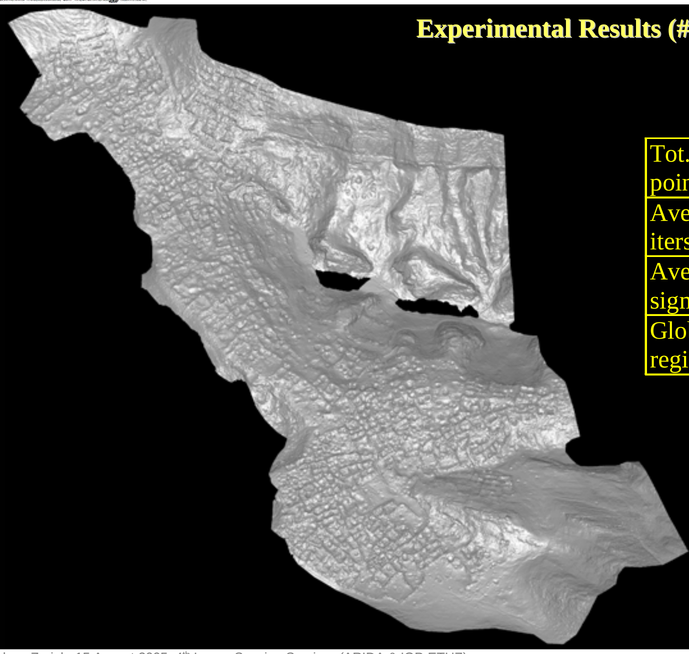
Experimental Results (#5): "Pinchango Alto"

The data set:

- large data set (57 scans with 144 million points)
- large occlusions due to topography



Experimental Results (#5): "Pinchango Alto"



Tot. no. points	144M
Aver. no. iters.	~7-8
Average sigma	**~1 cm**
Global registration	**0.5 cm**

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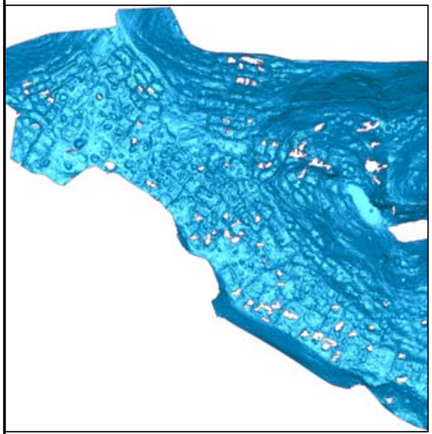
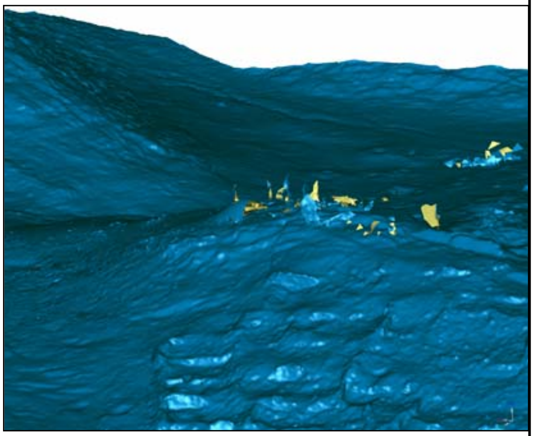
Experimental Results (#5): "Pinchango Alto"

Difficulties in modelling:
• Geomagic Studio 6, memory limitations in surface wrapping
• data holes due to occlusions of walls and hollows
• non-static objects on the site during 5 days field work





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Conclusions

• LS3D is a generalisation of the least squares 2D image matching concept

• Non-linear functional model, need for initial approximations
• Generalized Gauss-Markoff model for the estimation
• Monitoring capabilities for internal quality control

• It can solve the point cloud registration task without using special targets.

Thank you for your attention!