Overview of TLS systems, overall processing and applications

Theory and Application of Laser Scanning

ISPRS Summer School 2007

Ljubljana, Solvenia

information from imagery

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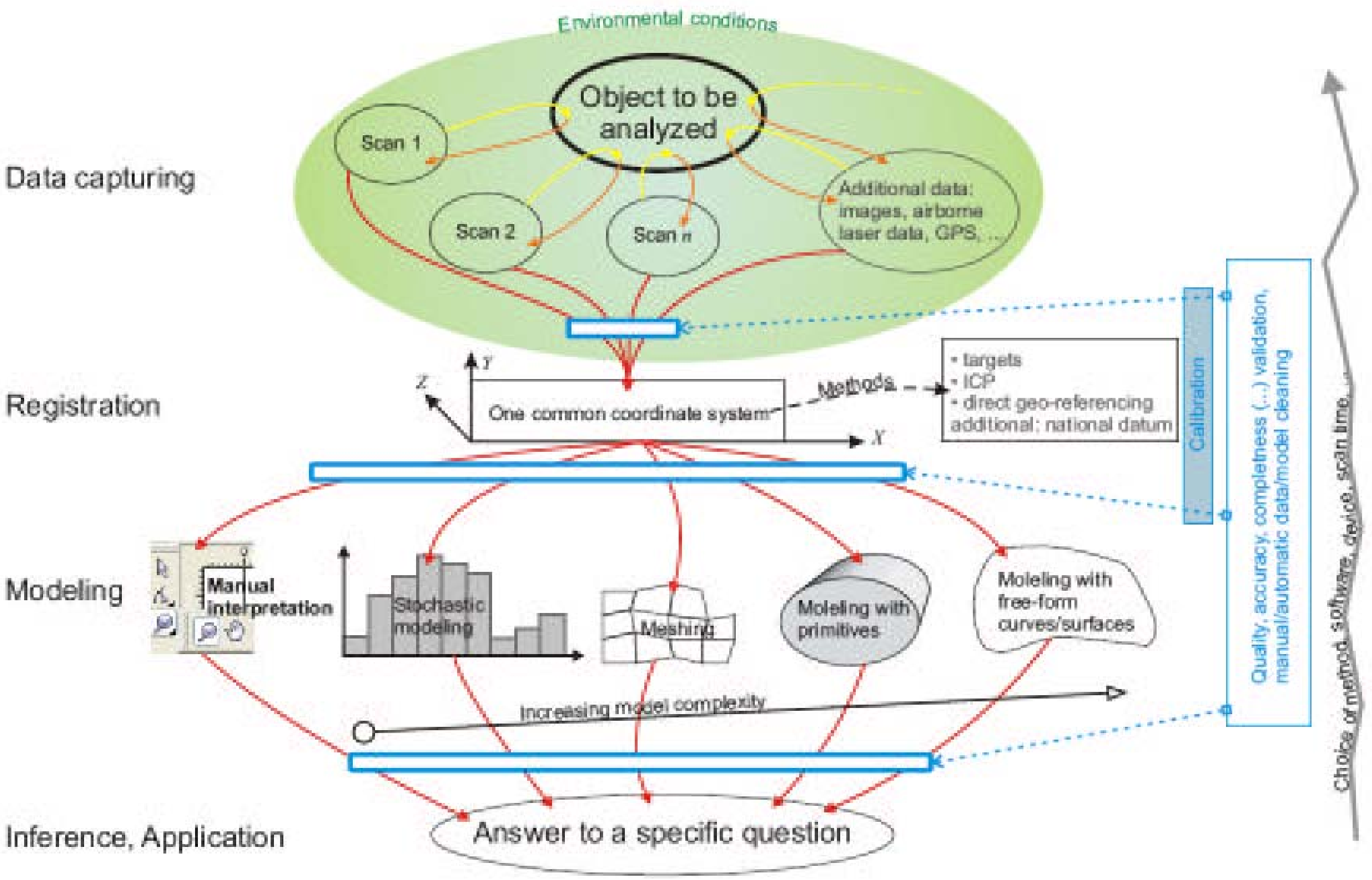
Lecture outline

- Definition: Laser Scanning
- Measurement principles
- Presentation of different instruments
- Comparison to other techniques
- Registration overview
- Modeling overview
- Application overview

N.B., material partly taken from

- Kraus, 2004. Photogrammetrie, 7th ed., Dümmler, Germany.
- Boehler, Marbs: 3D Scanning Instruments. CIPA WG6 Internat. Workshop, Scanning for Cultural Heritage Recording, Corfu, Greece, 2002.
- Websites of device producers: Riegl, Trimble, Hexagon, Optech



Competing Complementing Measurement Tools

Definitions

- Definition: TLS
  = Terrestrial Laser Scanning
  data point of view
- TLS systems
  = Terrestrial Laser Scanner
  component point of view

Terrestrial Laser Scanning Definition

Terrestrial Laser Scanning

- is a technique
- using laser light
- for measuring
- in a regular pattern
- directly
- 3D coordinates
- of points
- on surfaces
- from a terrestrial position

measurement errors

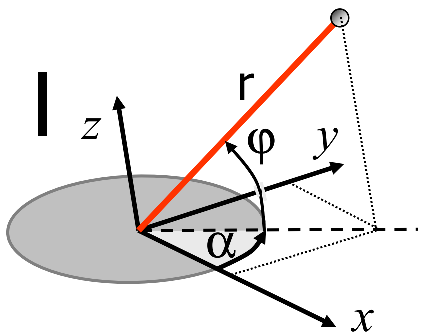
Photogrammetry
direct: 2D coordinates
compute: 3D coordinates

no corners, no edges

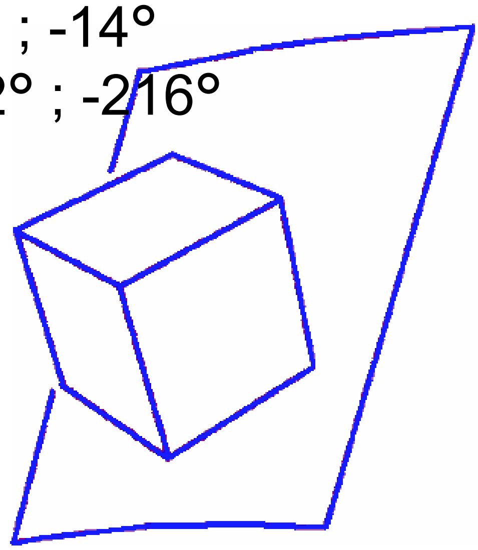
Tacheometry +
Photogrammetry:
corners and edges

ground, building, car, ...

synthetic Example - I



- measure polar coordinates
  φ, α, r (3D coordinates)
- regular pattern
  $\varphi_{i+1} - \varphi_i = 1°$ φ min ; max = -30° ; -14°
  $\alpha_{j+1} - \alpha_j = 1°$ α min ; max = -232° ; -216°
- measure range r for all φ_i , α_j



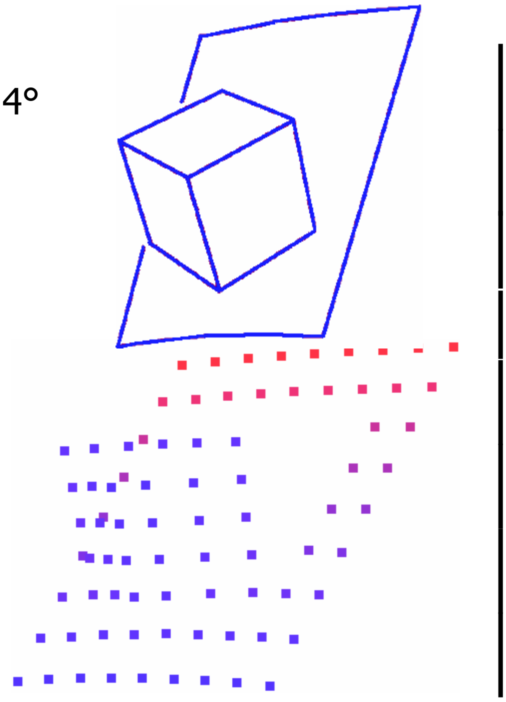
- object (surfaces) measured
  in this example:
  cube and base plane

synthetic Example - I I

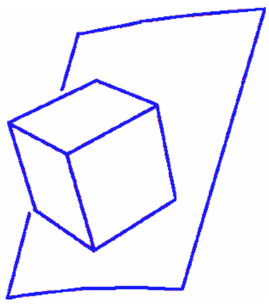
distance color coded and written in meter

	horizontal angle									
	12,4	12,4	12,4	12,4	12,4	12,4	12,4	12,4	12,40	φ=-14°
	10,9	10,9	10,9	10,9	10,9	10,9	10,9	10,9	10,88	
	9,71	6,54	6,47	6,47	6,47	6,47	6,54	9,71	9,71	
vertical angle	8,77	6,62	6,36	6,13	6,13	6,36	6,62	8,77	8,77	
	8,01	6,71	6,45	6,21	6,21	6,45	6,71	8,01	8,01	
	7,38	6,81	6,54	6,3	6,3	6,54	6,81	7,38	7,38	
	6,84	6,84	6,65	6,41	6,41	6,65	6,84	6,84	6,84	
	6,39	6,39	6,39	6,39	6,39	6,39	6,39	6,39	6,39	
	6,00	6,00	6,00	6,00	6,00	6,00	6,00	6,00	6,00	φ=-30°

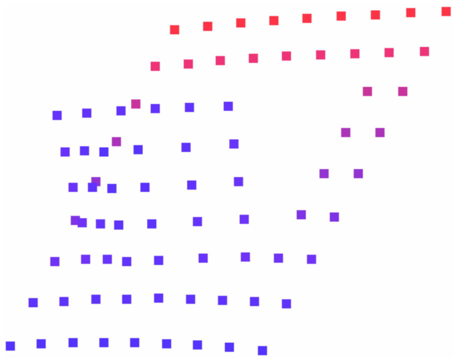
α=-216° α=-232°



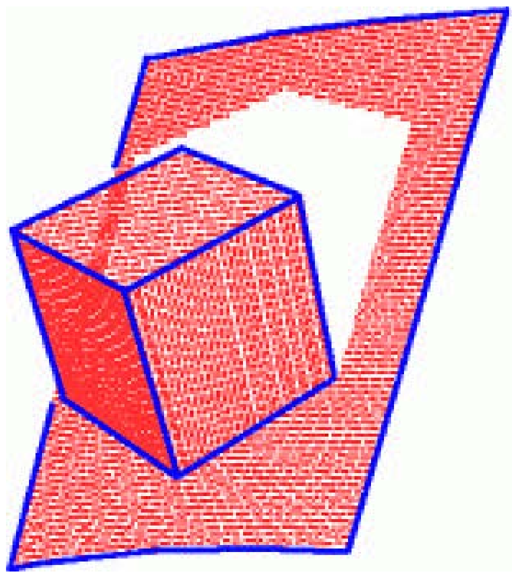
synthetic Example - I I I



Object



low resolution scan



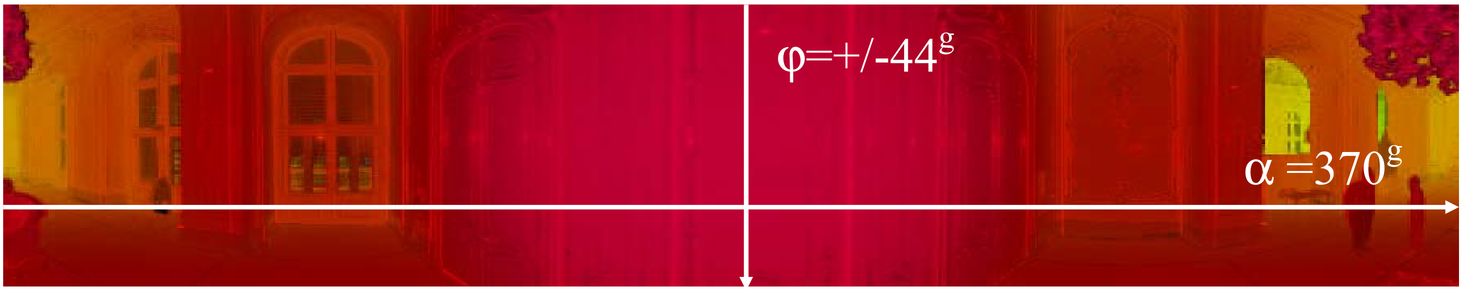
high resolution scan

- Varying point density
- Shadows
- Edges *not* measured

real Example

Field of View (FoV)

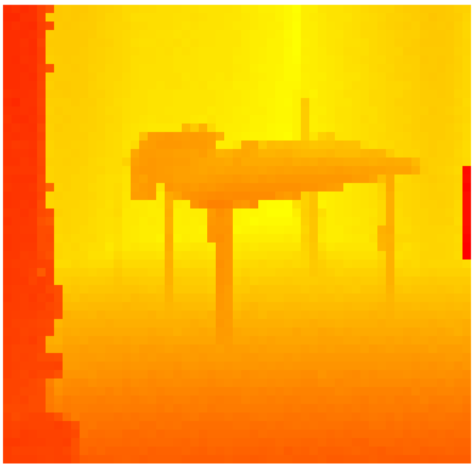
- φ min ; max = -40° ; 40° $\varphi_{i+1} - \varphi_i = 0.25°$
- α min ; max = 0° ; 333° $\alpha_{j+1} - \alpha_j = 0.25°$
- r close ; far away = pink–red–orange–yellow–green
  50cm – 10m
- 422,400 measurements of φ, α, r
- Measurement frequency: 2kHz (2000 measurements per second)
- Time for measurement: < 4 minutes



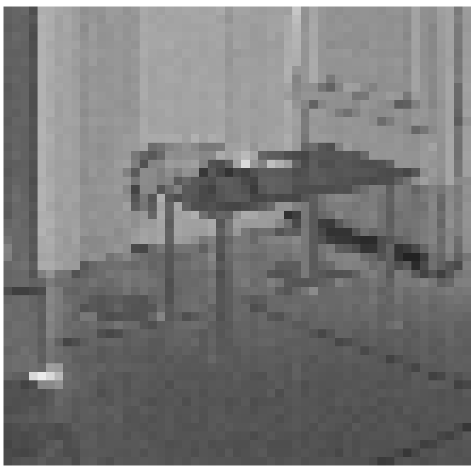
real Example

Small detail from one scan

- Range image
  regular φ, α – raster



- Point cloud in 3D
  in Cartesian coordinate system
- Additional measurement
  not only range to surface
  but **also** *brightness* of surface



improved Definition Terrestrial Laser Scanning

Terrestrial Laser Scanning

- is a technique
- using laser light
- for measuring
- **with high speed**
- in a **dense** regular pattern
- directly
- 3D coordinates
- of points
- on surfaces
- **and surface brightness**
- from a terrestrial position

Terrestrial Laser Scanners System components

- So far: data description from terrestrial laser scanning
- Now: How are the measurements performed?
- Concentration on φ, α, r (not brightness)

- Range r
  pulse round trip – phase comparison – triangulation
- Laser beam angles φ, α
  rotating mirrors – rotating instrument

Measurement principles

- Distance measurement
  - Round trip time of a pulse
  - Phase comparison of a continuous wave

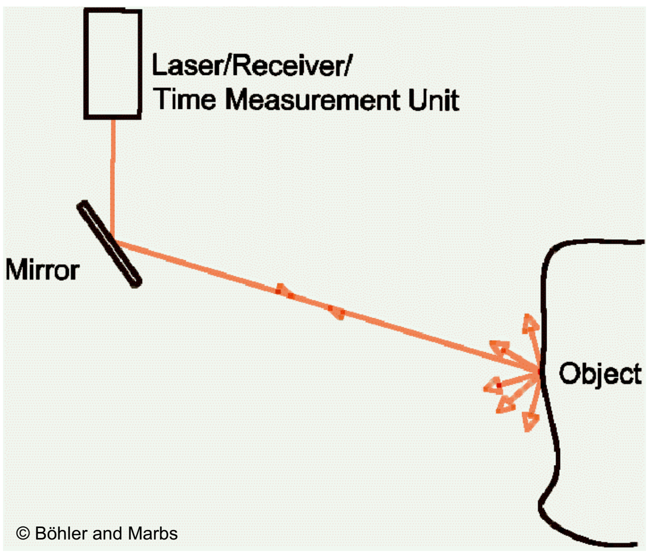
- Triangulation

& laser beam angle measurement

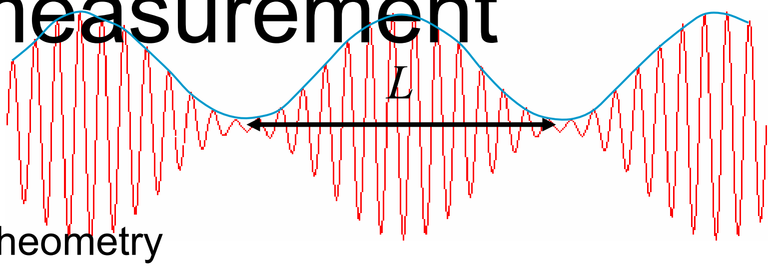
Distance measurement

Pulse round trip:

- measure time lapse between sent and received pulse
- 1cm =   ns (nano-seconds)
- round trip time for 10m
  between scanner and object =   ns
- accuracy (almost) independent of distance
- suitable for longer ranges
  (using higher pulse energies)
- increase accuracy by
  averaging of multiple shots
- accuracy depends on strength
  of backscattered signal:
  object reflectivity + distance

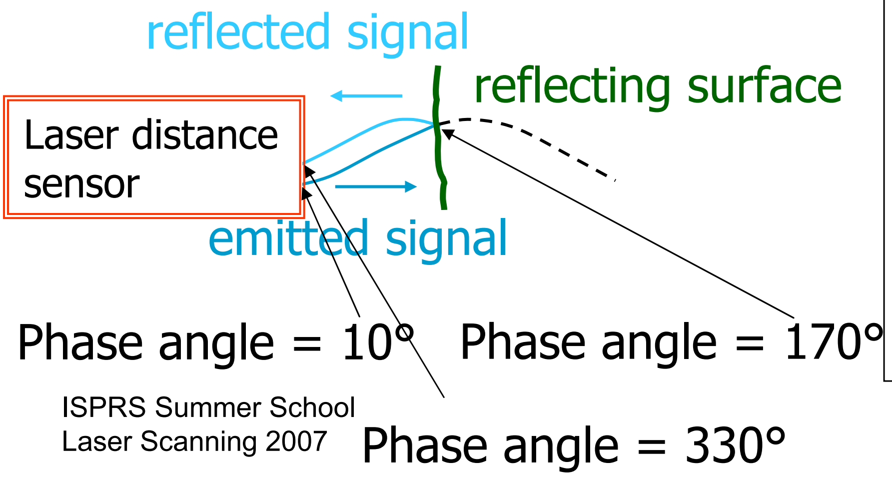


Distance measurement



Phase comparison:

- Similar to electronic
  distance measurement in tacheometry
- modulate laser light with harmonic signal
  (image: amplitude modulation)
- measure phase difference
  between emitted and received modulated signal



Example:
Phase difference =
= 330° - 10° = 320°
L = 100m
Distance =
= 320°/360° * L / 2 =
= 44.4m

Distance measurement

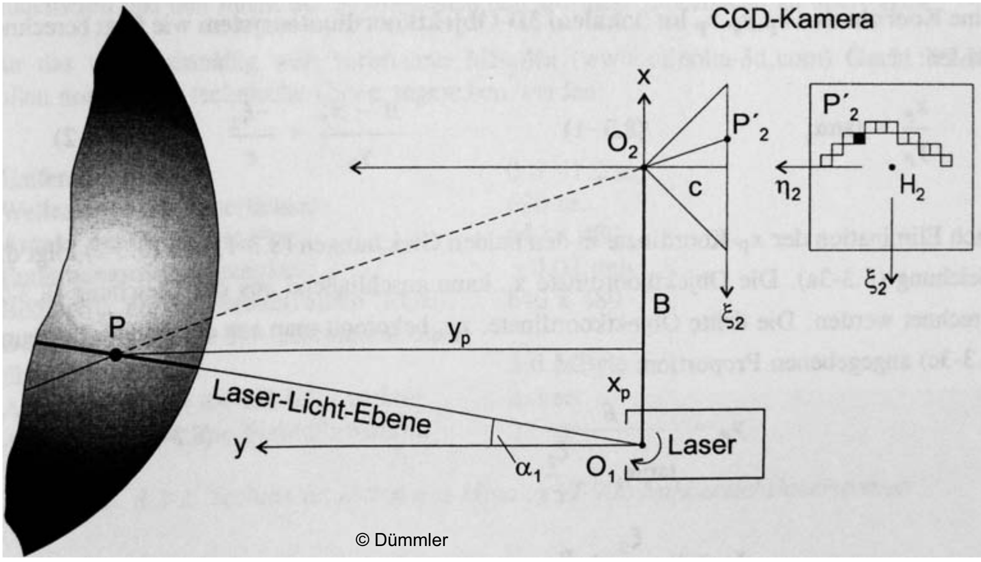
Phase comparison (2):

- uniqueness range = ½ modulation wave length L
  reflecting surfaces in distances d and $d + L/2$
  return the same signal
- measure distances ‘continuously’ … fast
- increase accuracy by
  using shorter modulation wave lengths
- Use multiple modulation waves of different length
  longest wave length defines uniqueness range
- accuracy depending on (shortest) modulation wave length,
  but depending also on object reflectivity

Triangulation

Similar to photogrammetric normal case

- plane of (laser) light
  sweeps over object: angle $\alpha = \alpha(t)$
- light plane — object
  intersection mapped in digital image
- light plane — bundle of mapped curved points
  forward intersection
- for each plane (α)
  set of 3D points



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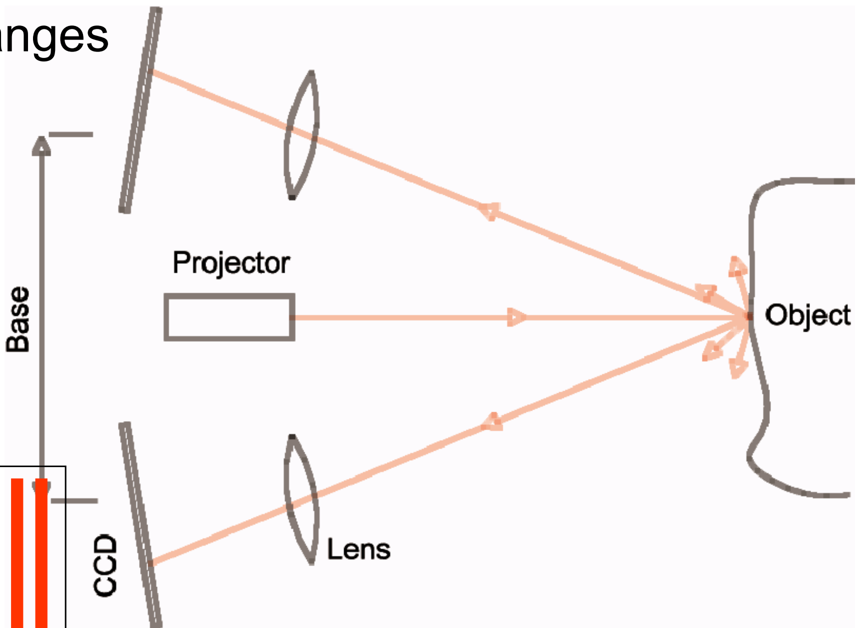
Triangulation

- accuracy depends on intersection quality
  base length vs. object distance
- accuracy decreases with distance^2
- suitable for short ranges

Alternatives:

- use laser beam
  (i.e., no plane)
- use 2 cameras
  and one projector



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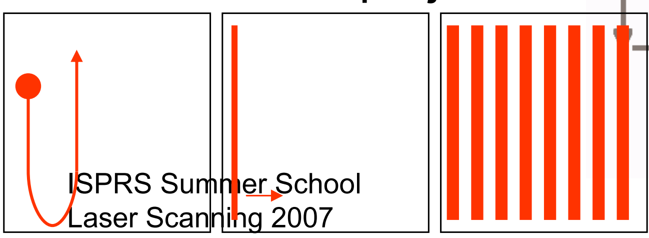
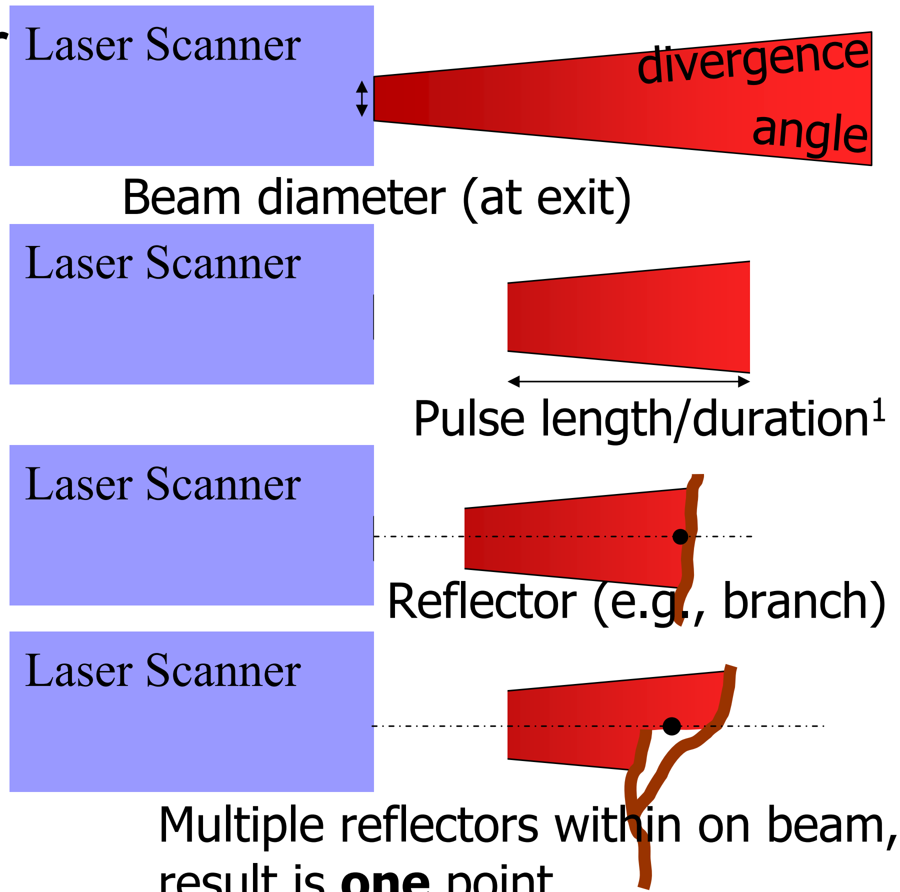


Beam diameter and Pulse length

- Effect …
  … next slide

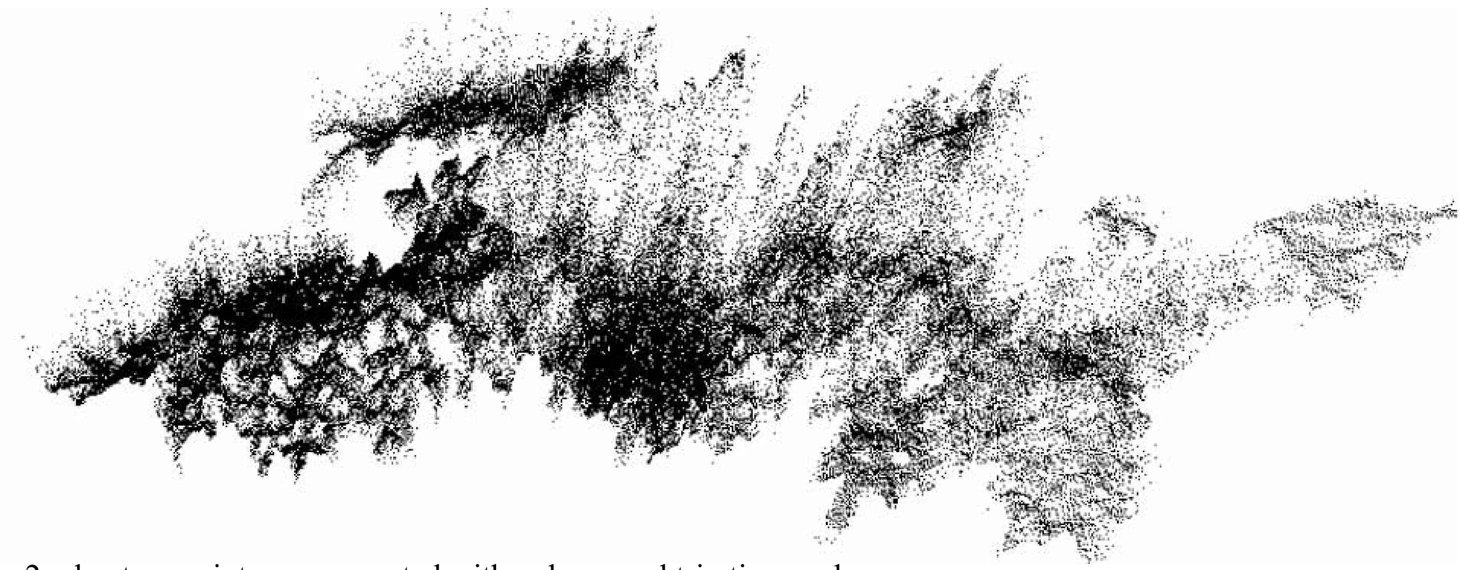
Pulse round trip time scanners CAN (theoretically) differentiate first and last echo.



1: applies to pulse round trip time scanners. Phased based distance measurement uses a permanent signal.

… Effect

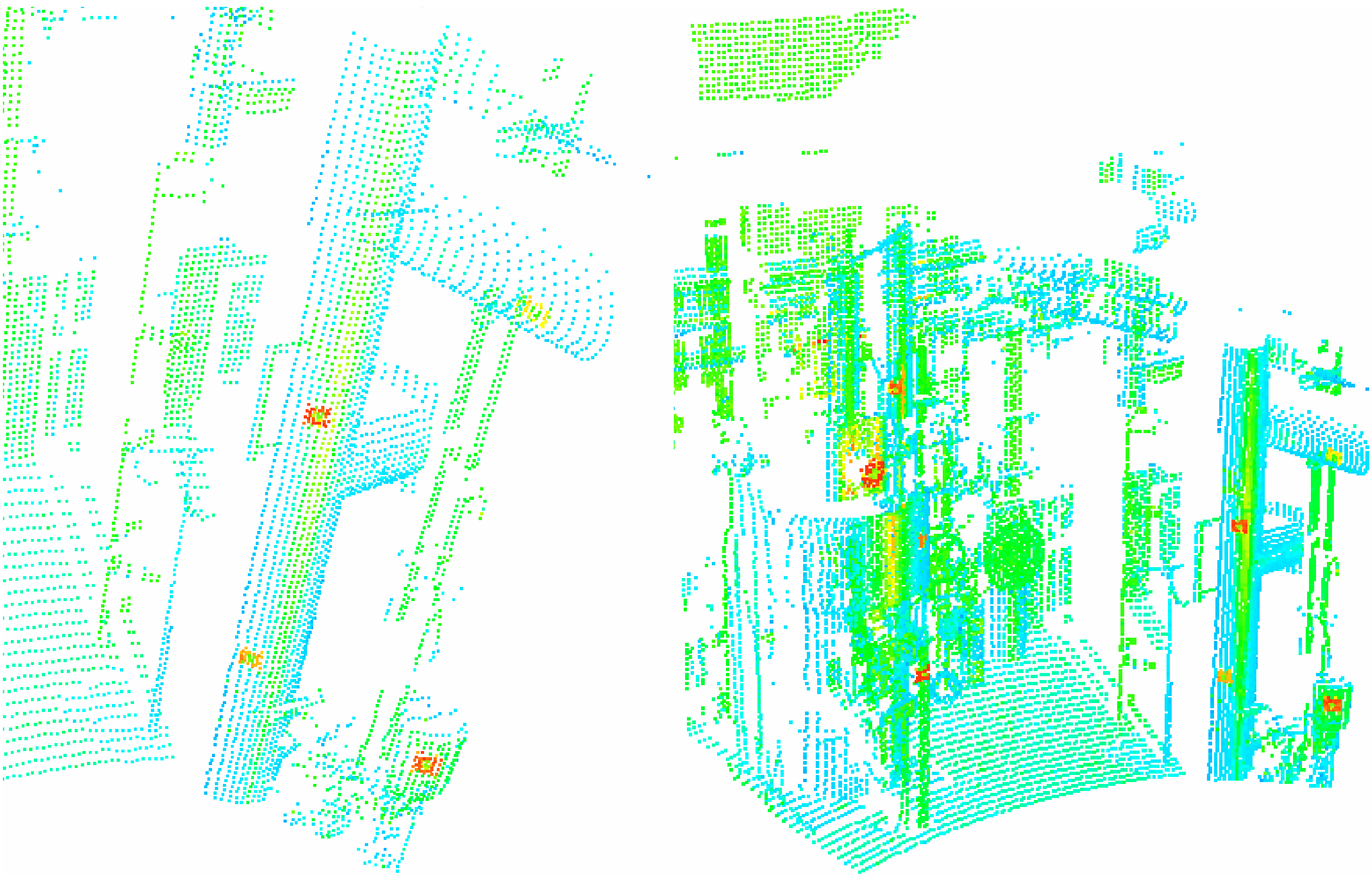
on measurement: Phantom points[2]



2: phantom points are generated with pulse round trip time and phased based distance measurement scanners.

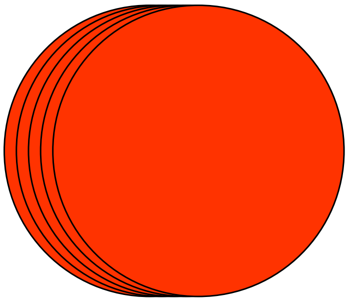
Example 1
Leica HDS2500

- Principle: pulse round trip, laser wavelength: 532nm
- Range: up to 100m
  Range accuracy: ±4mm
- Beam deflection: 2 mirrors
- Field of view: max 40° x 40° : “window” system
  Angular accuracy: 0.00006rad
  (3mm@50m)
- Spot size $\leq$6mm up to 50m
- Max scanning density:
  0.25mm point-to-point spacing @50m
- Speed: 1000 pts/sec
- Max points: 1000col/2000row

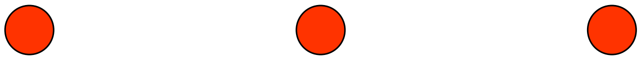


Example data set

Example 1
Leica HDS2500



For distance 50m
- Point accuracy $(\sigma_x^2+\sigma_y^2+\sigma_z^2)^{0.5} = \pm$ mm
- Spot size 6mm and point-to-point spacing 0.25mm
- 1000 points over 40°: point-to-point spacing 36mm



Speed
- 2000000 points in ½ hour
- Other factors

  10 scans for 1 panorama

  Moving equipment: 20kg + 7kg power supply + laptop

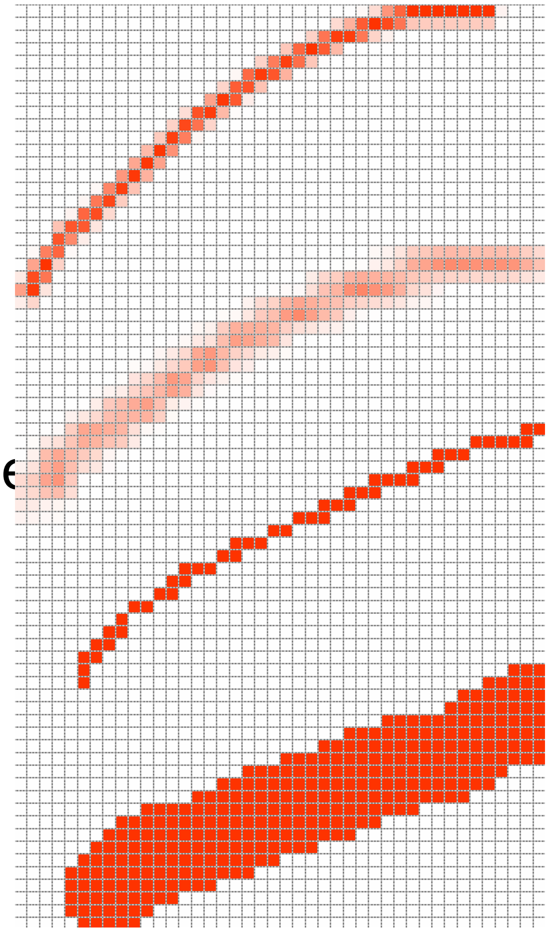
Example 2
Minolta Vivid 900

- Principle: triangulation with ligh
- Laser wavelength: 690nm
- Digital camera
  - CCD 640x480 pixels RGB
    Pixel size: ~3.5µm
  - Focal length: 25mm, 14mm, 8mm
- Range: max 2.5m
- Scan time: 2.5 seconds
- Captures color!

Example 2
Minolta Vivid 900

- For good color good lightning necessary
- How to find map of laser plane in digital image?
  … see images on next slide

- Map of laser plane should be as thin as possible.
- How to achieve this?



Finding the map of the laser light in the digital image

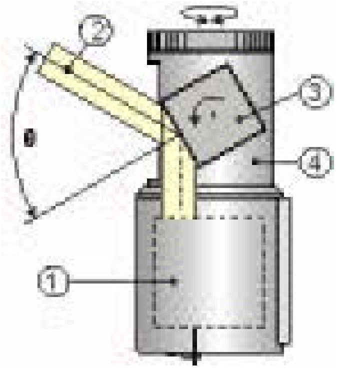
Image without laser beam

Image with laser beam

Difference image

Extracted line

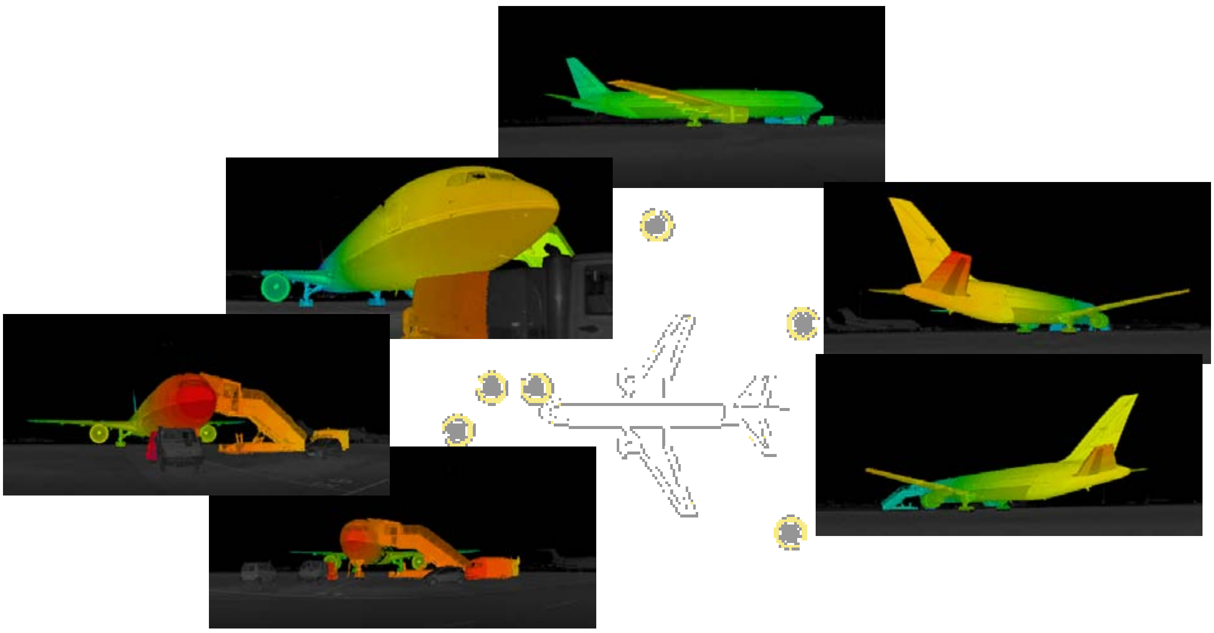
Example 3,4,5



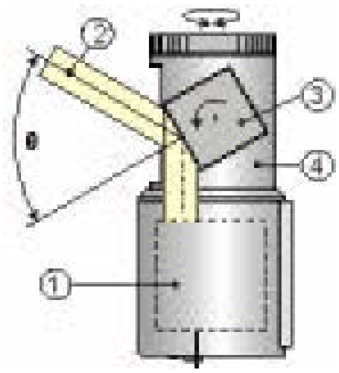
Riegl LMS Z420i

Pulse round trip,
rotating mirror +
instrument rotation

LMS Z210



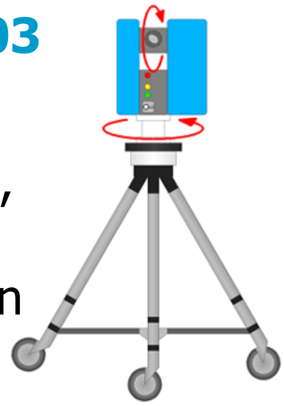
Example 3,4,5



Riegl LMS Z420i

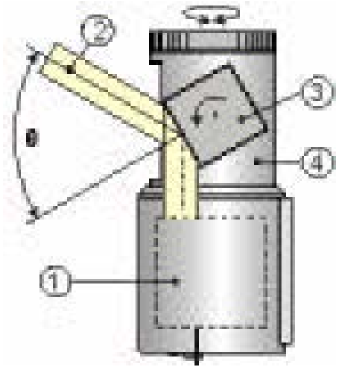
Pulse round trip,
rotating mirror +
instrument rotation

Z+F Imager 5003
LARA 53500



Phase comparison,
rotating mirror +
instrument rotation

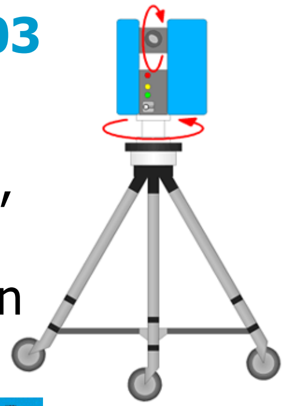
Example 3,4,5



Riegl LMS Z420i

Pulse round trip, rotating mirror + instrument rotation

Z+F Imager 5003 LARA 53500

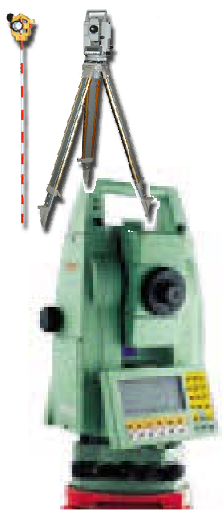


Phase comparison, rotating mirror + instrument rotation

Mensi S10

Triangulation with laser beam in plane, + instrument rotation

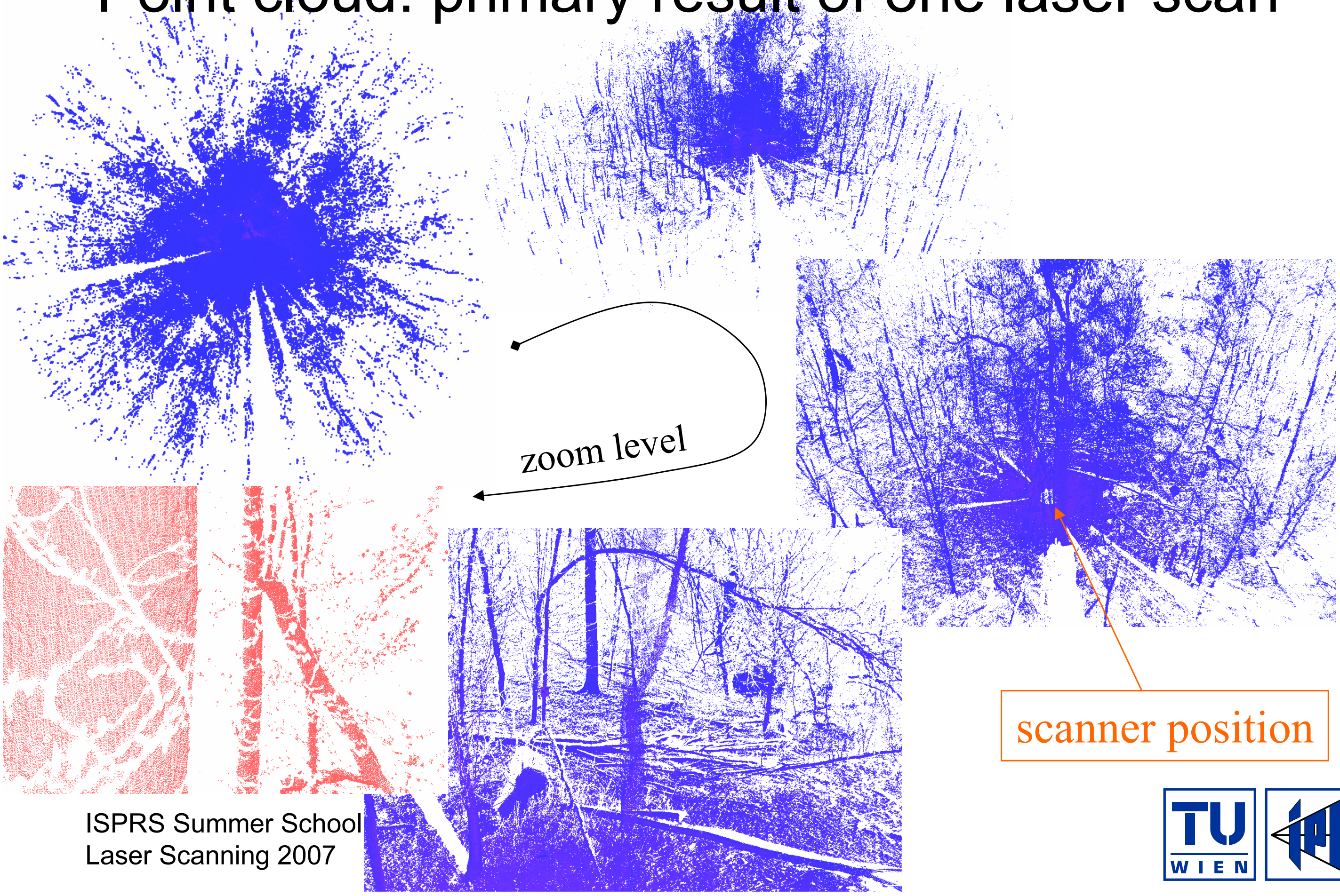
Competing Complementing Measurement Tools

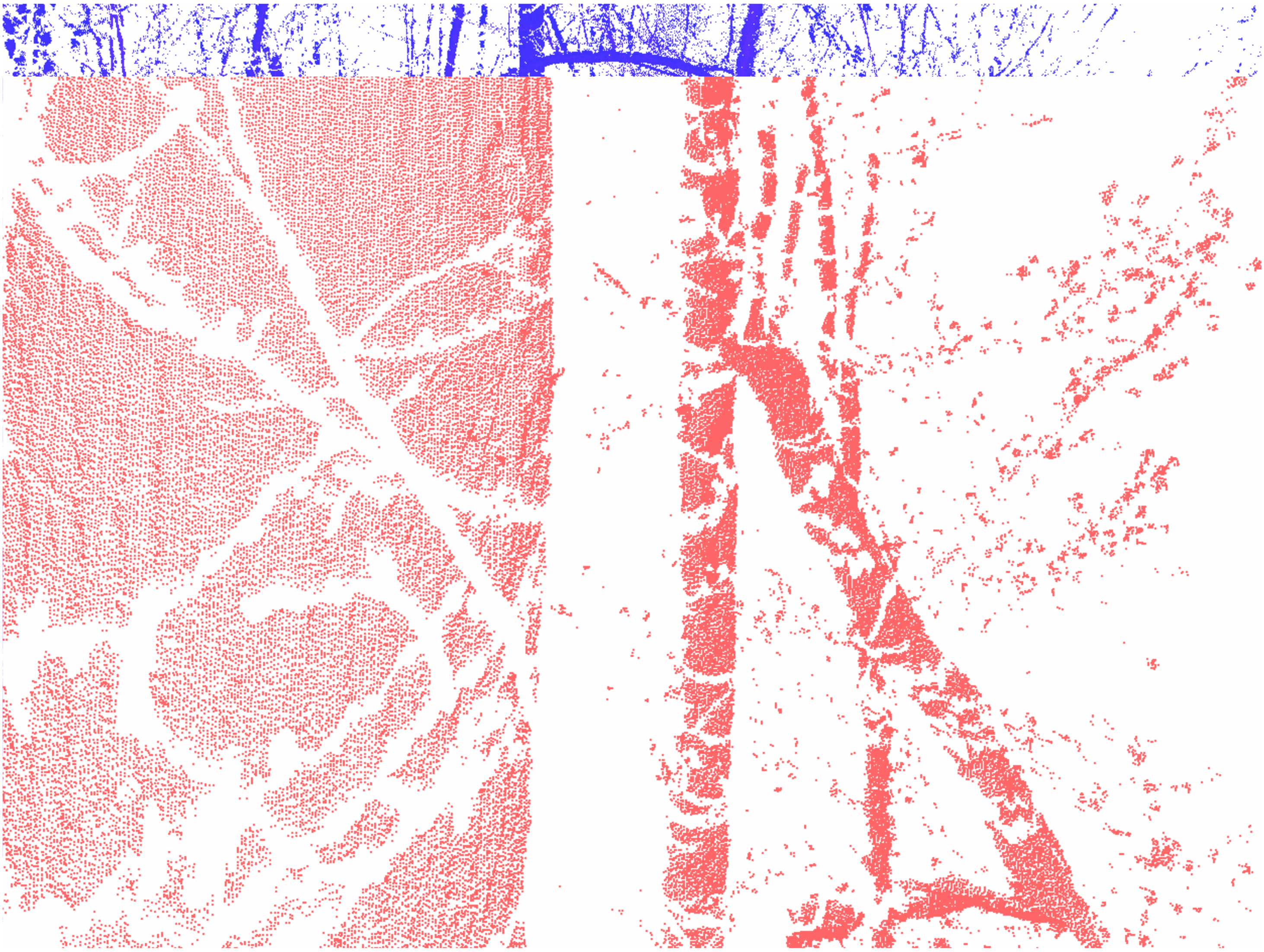


Comparison

suited for measuring / terrestrial	Satellite Positioning	CMM	Total Stations	Laser Scanning	Photo-grammetry
Points			x		
Edges			—		
Surfaces			—		
Range	global				
Precision					scale dependent
Speed					
Costs		very high			
Problems with/at Requirements					

Point cloud: primary result of one laser scan



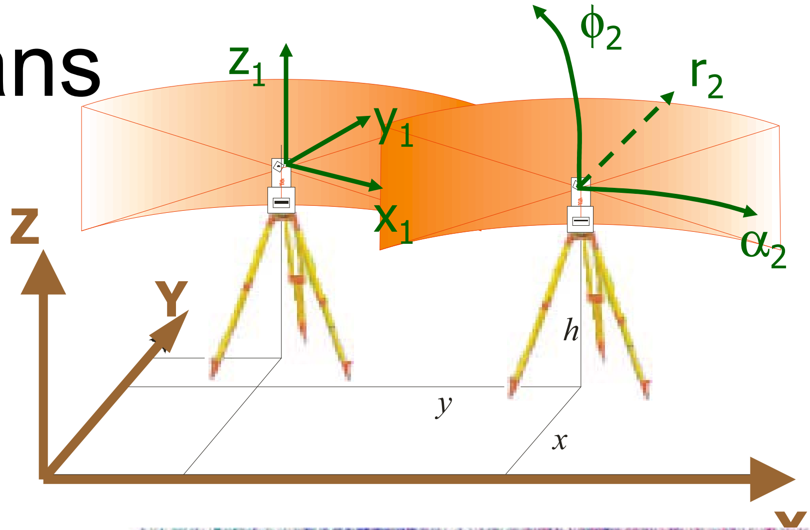


Registration

- 1. Object is visible only from one side in one scan
- 2. Multiple objects to be measured
- Different scans required to capture the entire scene
- Relative orientation (registration) required to have all points in one coordinate system
- Methods for Registration
  - Targets (like photogrammetry)
  - Iterative closest point (ICP)
  - Object based (corresponding features, e.g. planes, cylinders, …)
  - Direct georeferencing

  - Fine vs. coarse orientation

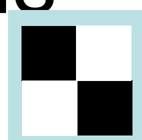
Combining scans

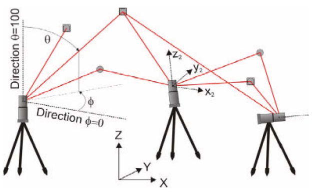


= relative orientation
= registration
= consolidation
= alignment
= co-registration

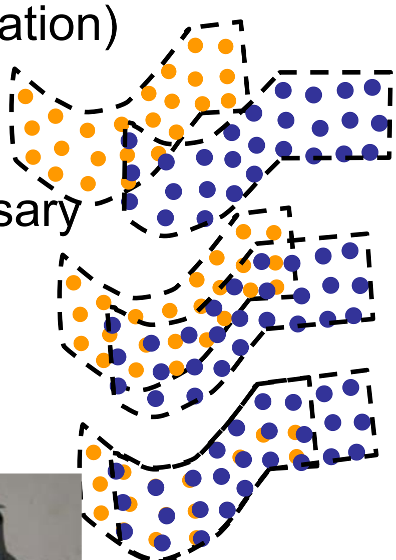
Transform each local device co-ordinate system into one superior system.

Registration methods





- Tie points
  - –) extra effort, only close to ground (extrapolation)
  - +) applicable in almost all circumstances
- ICP (iterative closest point)
  - –) overlap and manual approximation necessary
  - +) uses entire point cloud
- Object based: parametric "Features"
  - –) found only in special scenes (e.g. boxes, cylinders)
- Direct georeferencing
  - –) low cost devices: insufficient precision
  - +) highest degree of automation

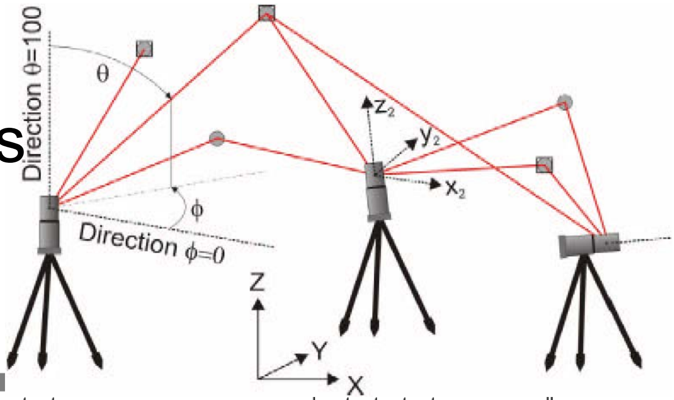


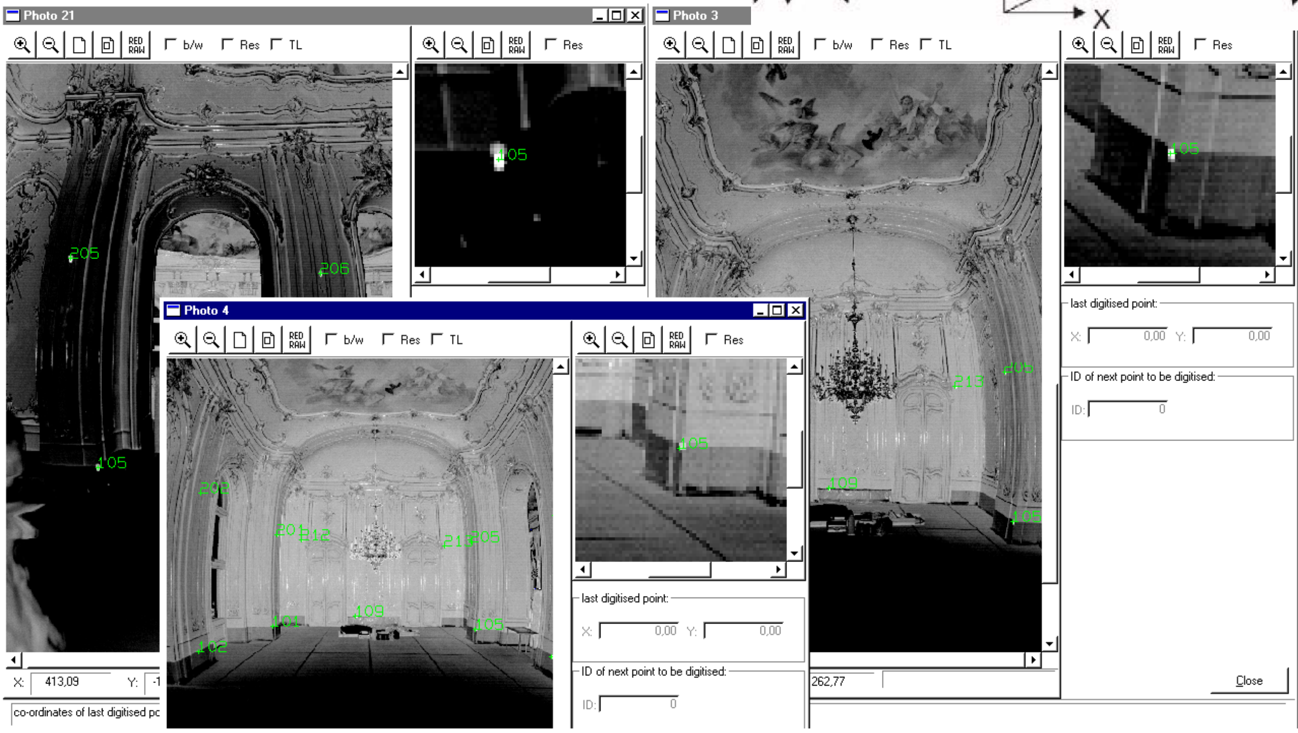
Böhm, Haala: EFFICIENT INTEGRATION OF AERIAL AND TERRESTRIAL LASER DATA FOR VIRTUAL CITY MODELING USING LASERMAPS. ISPRS WG III/3, III/4, V/3 Workshop "Laser scanning 2005", Enschede, the Netherlands, September 12-14, 2005

Registration via tie points

Example: 3 scans

retro-reflective targets (2cm)

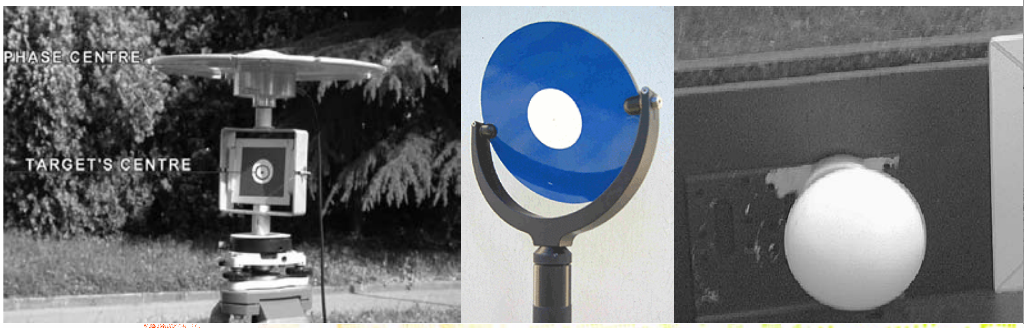


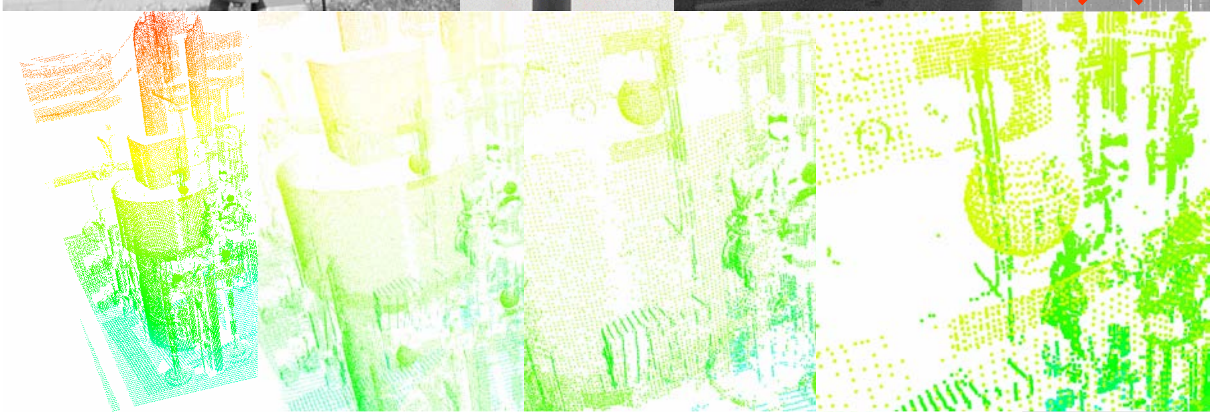


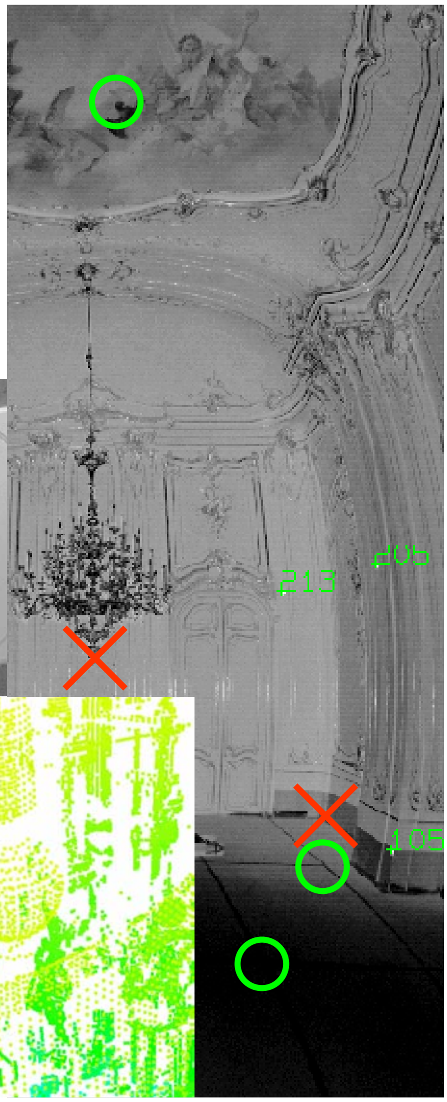
Registration via tie points

- Signalized vs. natural points
- Identify in

Intensity image OR Range image OR Point cloud

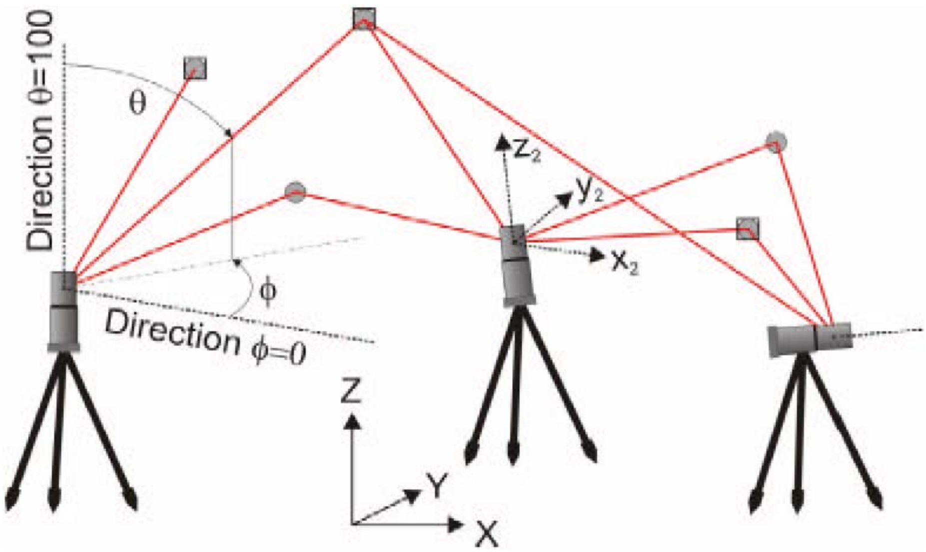






Registration via tie points

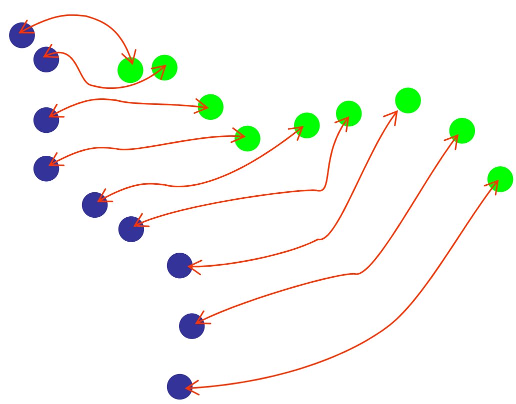
- Identify with sub-pixel accuracy
- Can be observed in photos or by tacheometry
- How many tie points required to register 2 scans?



Registration with ICP

- Given: 2 point clouds
  - on the same surface
  - in different local coord.sys.
- Simple case

  correspondences between points
  - exist
  - are known
- Solution



$$\sum_{i=1}^{n} \left\| q_i - (t + \mathbf{R} p_i) \right\|^2 \rightarrow \text{Minimum}$$

How to?

Registration with ICP

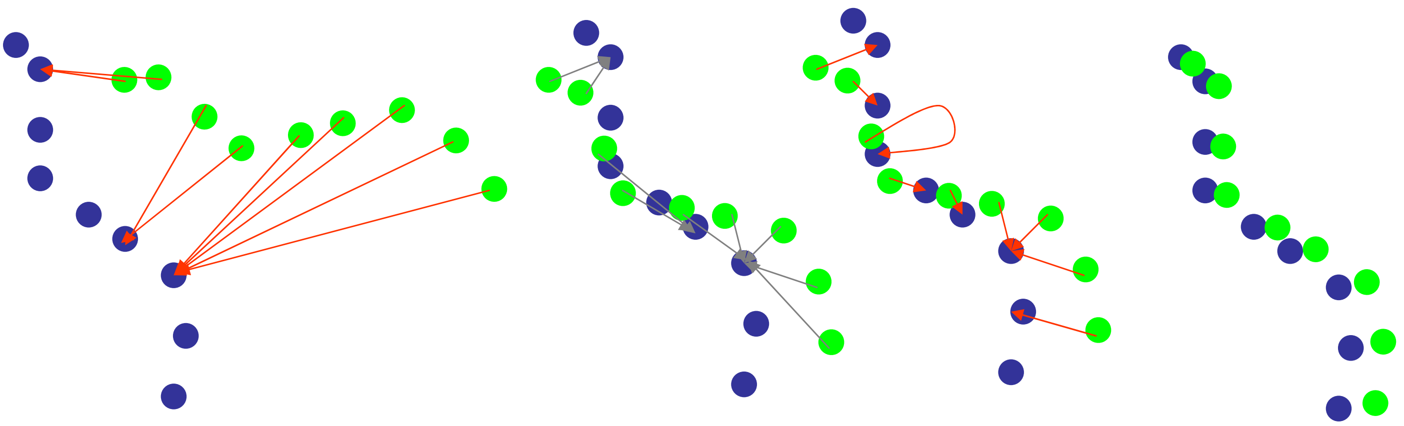
Problems

- Correspondences are generally not know
- Point-to-point correspondences do NOT exist

Solution

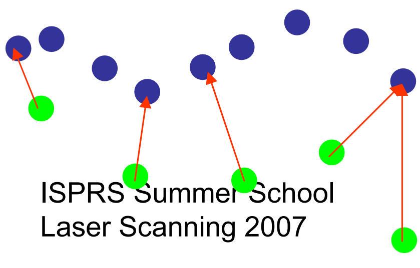
- Replace: Corresponding point → closest point
- Solve for transformation parameters
- Iterate

Registration with ICP



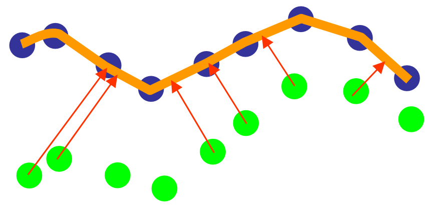
Find for each p_i closest point in $Q=\{q_1, \dots q_m\}$

Solve for and apply t and $\mathbf{R}$ to minimize offsets



Find for each p_i closest point in $Q=\{q_1, \dots q_m\}$

…



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Laser Scanning 2007

Registration with ICP

- num. pts. in Q $\neq$ num. pts. in P
- Rough alignment required (manual)
- Needs many iterations
- Works bad for flat surfaces
- Requires many iterations
- But! No tie points required!

Additional Notes

All points or only short distances (10% of all distances)

Alternative approaches:

1. Subsample one point set
2. Distance to triangulation
3. Distance to estimated tangent planes

Registration via objects

- (Points)
- Planes
- Lines
- Advantages / disadvanages

Coarse registration

- Esp.: generate approx. values for ICP
- Comparable to automatic relative orientation of an image pair
- Extraction of features
- Correspondence hypothesis
- Evaluation

Current ressearch topic !

Model reconstruction

- Point cloud
  - Many points
  - Without semantic information („meaning“)
  - Quality
- Model
  - Captures relevant aspects of reality
- Types of models
  - Meshes/Tiangulation
  - Boundary representation
  - Primitive instancing

Object size	Accuracy
1-5m	±0.2mm
5-50m	±1mm
50-1000m	±1-10cm
Airborne	
100-300m	±5cm
up to 2000m	±20cm

Modeling

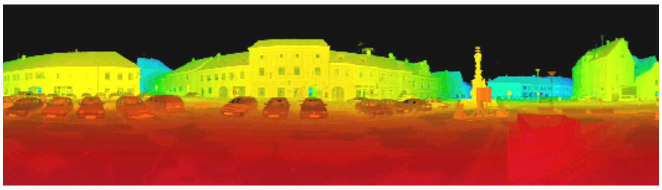
Measurement → Registration → Set of point clouds in one co-ordinate system

Modeling strategies

1. Point cloud is final product
   or extract information directly from point cloud
2. Generate mesh (triangulation)
   – Triangulate visible parts
   – Generate water tight model
3. Make parametric models (primitive instancing)
4. B-Rep model generation
5. Generate free form surfaces (NURBS, …)

Point Cloud as Final Product

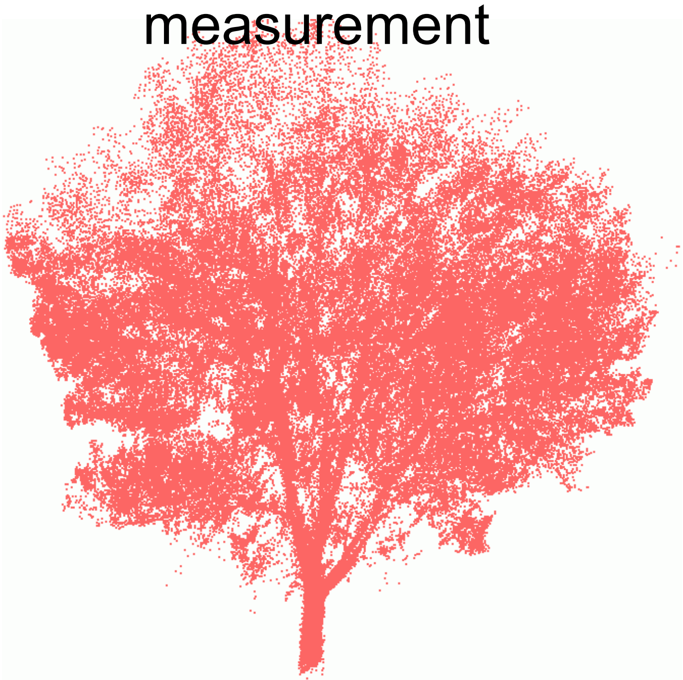
- Visualization
  – Give points a size
    e.g. 2 pixel or 2cm
  – Texture from photo
- Interface checking
- Simple measurements

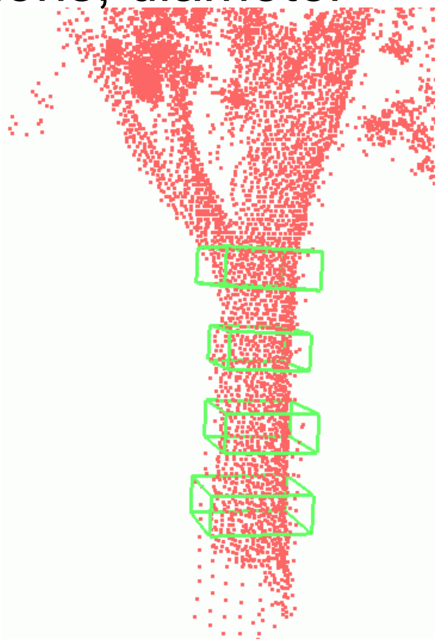


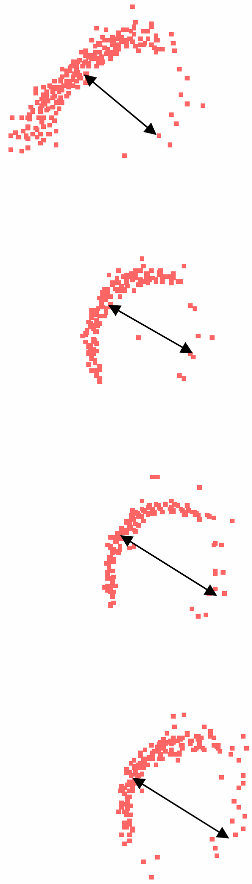
Yellow: point cloud,
gray: planned installation

Products extracted from point clouds

Example: tree cross sections, diameter measurement







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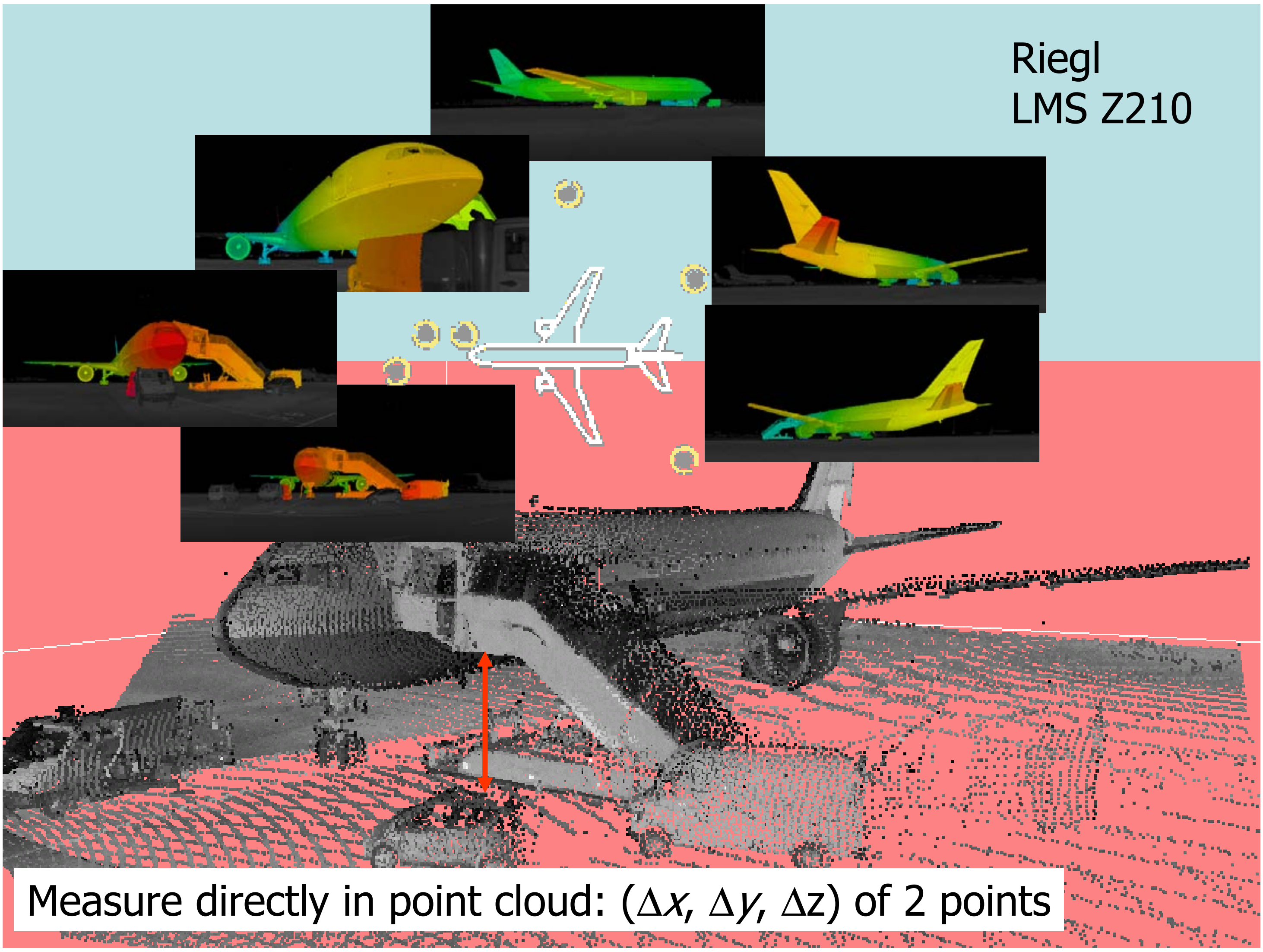


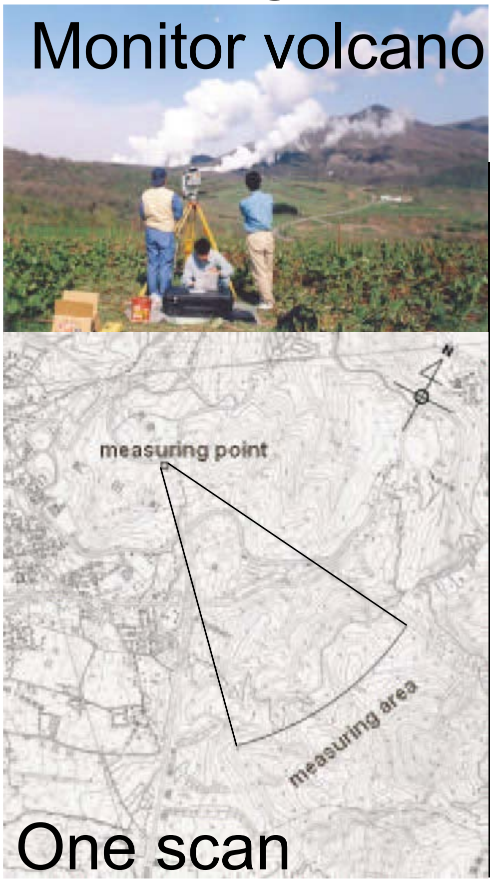
Triangulation / Meshing

Triangulation **adds surface** to point cloud

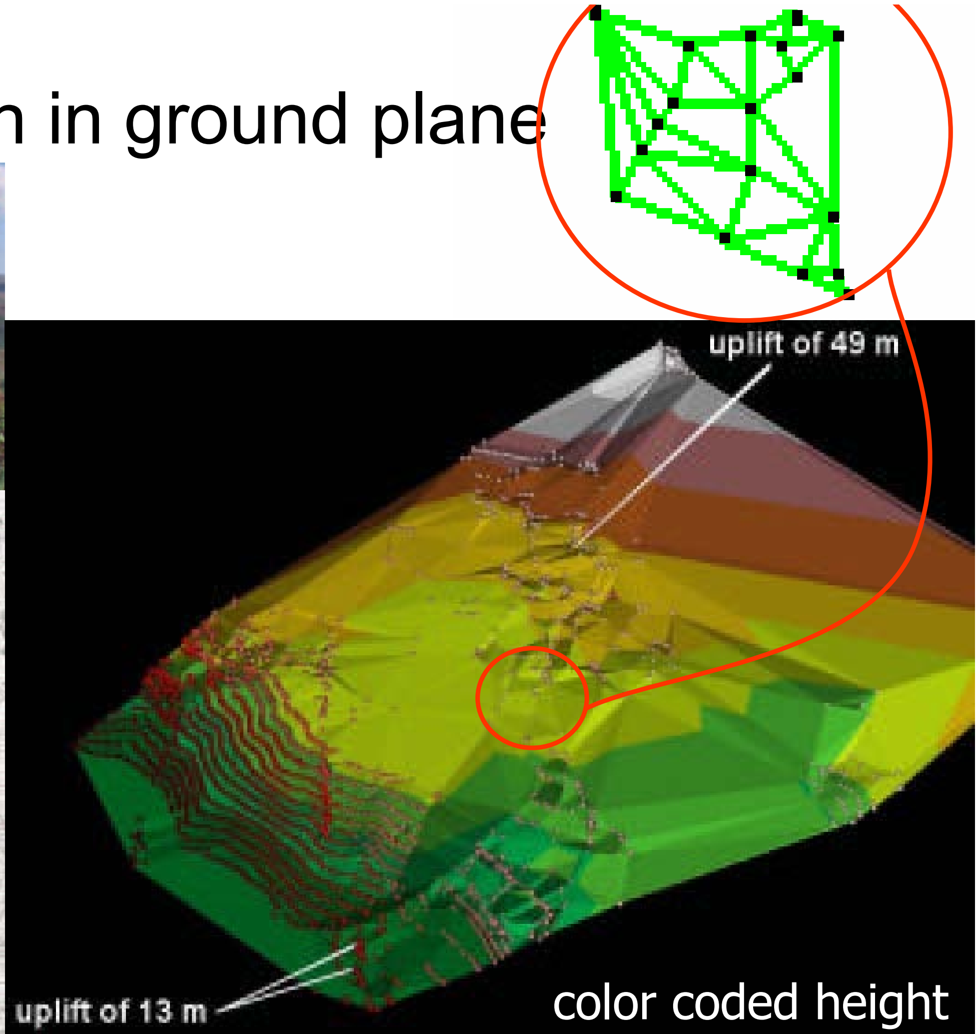
- Surface area computation
- Interpolation between points
- Computation of surface properties
  tangent plane, curvature, …
- Intersection with other surfaces
  e.g. with planes for cross sections
- Triangulate in
  - ground plan
  - parameterization domain
  - 3D
- Basis for freeform surface modelling
- Better combination with texture from images

Triangulation in ground plane

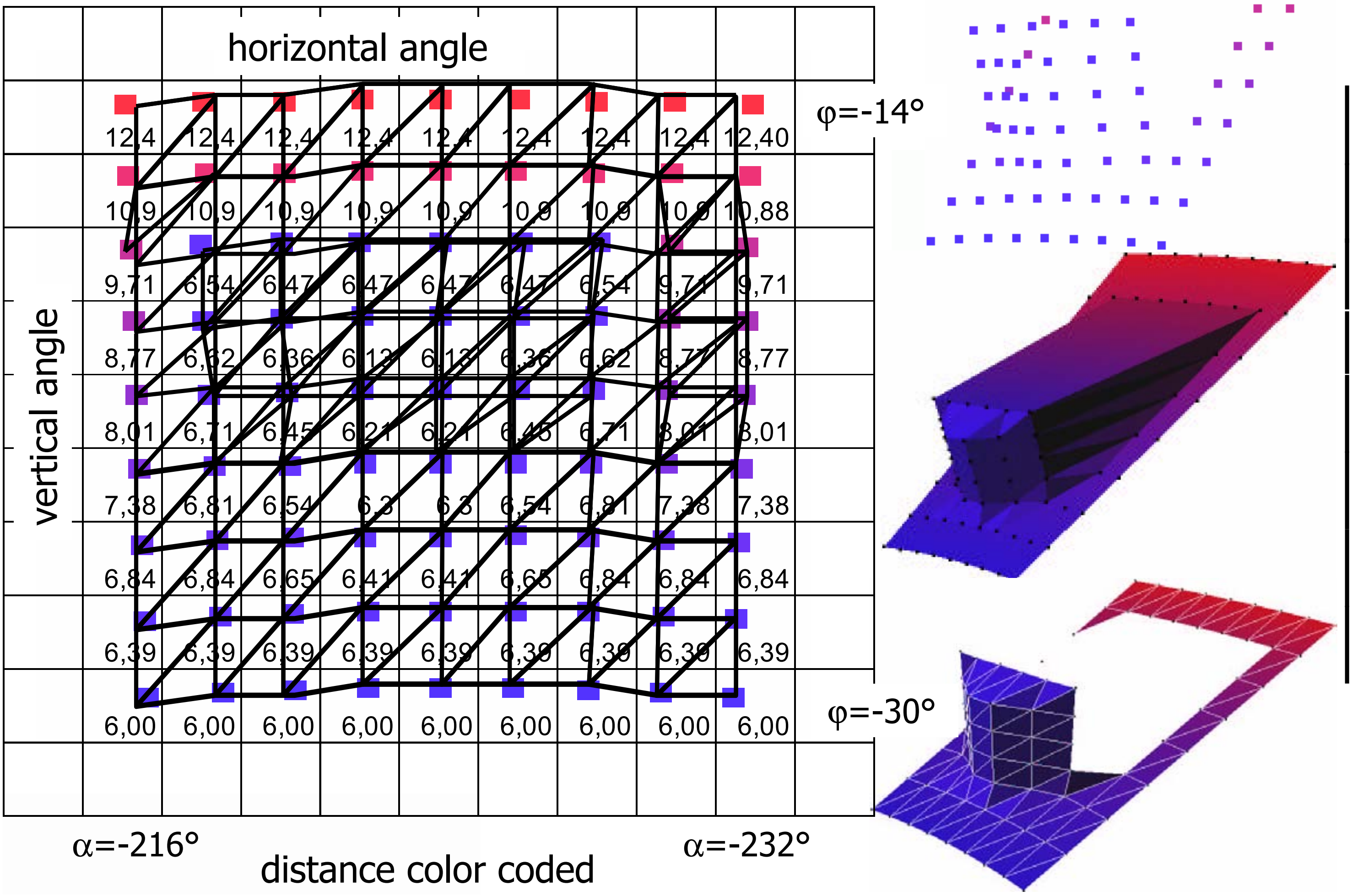
Monitor volcano



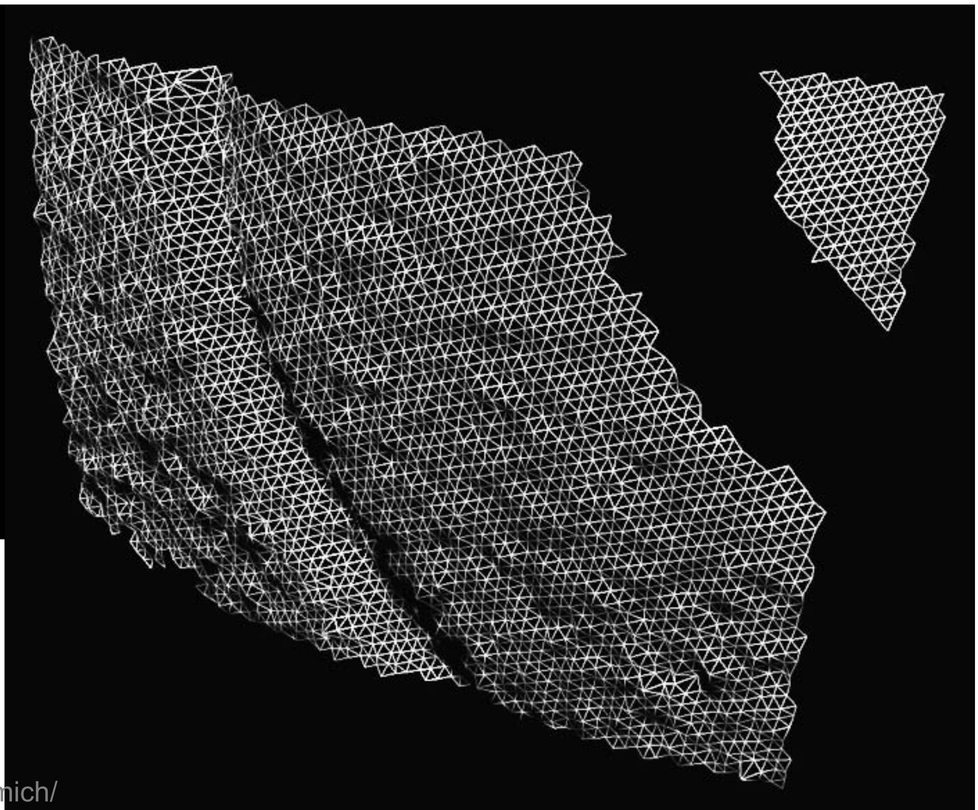
One scan



Triangulation in scanner domain



Triangulation in scanner domain



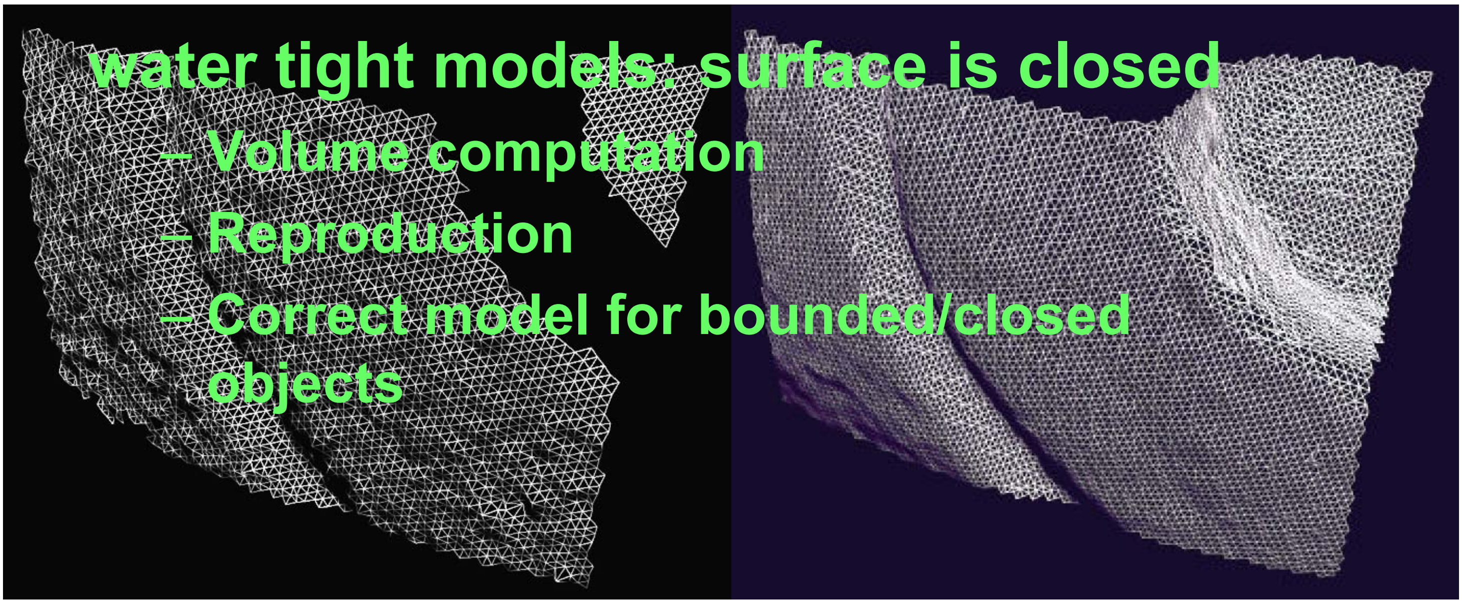
Digital Michelangelo

http://graphics.stanford.edu/projects/mich/

Triangulation

Complex objects require more scans: different sides & occlusions

1. Combine triangulations of individual scans
   → real 3D triangulation
2. Fill holes
   no holes → water tight model

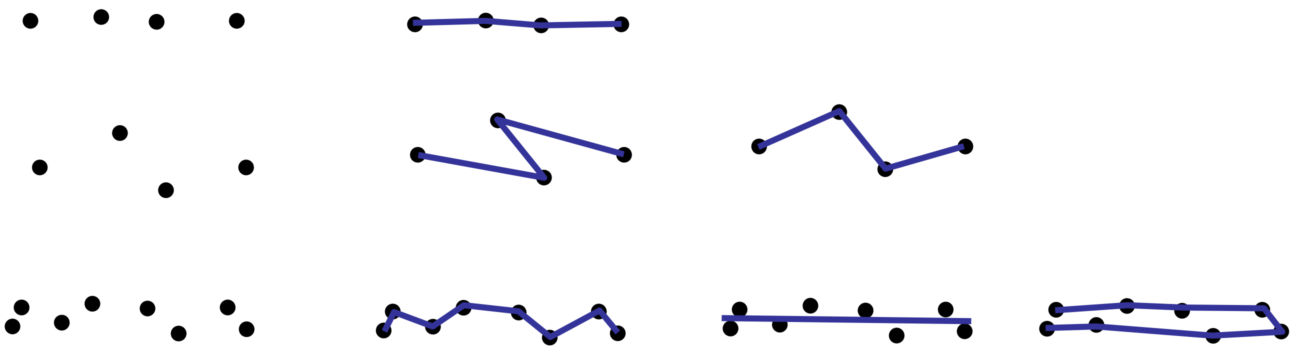


water tight models: surface is closed

- **Volume computation**
- **Reproduction**
- **Correct model for bounded/closed objects**

Triangulation in 3D

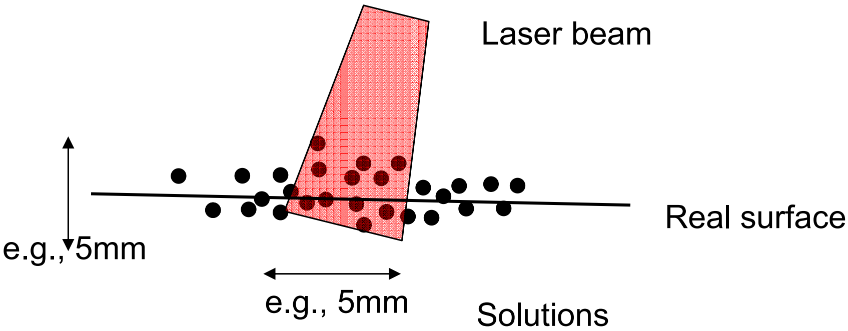
- Problem: which points are neighbors ?



Schematic 2D view

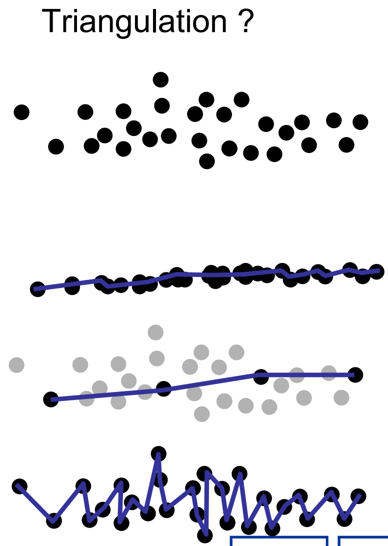
Triangulation and Noise

Random measurement errors and measurement density

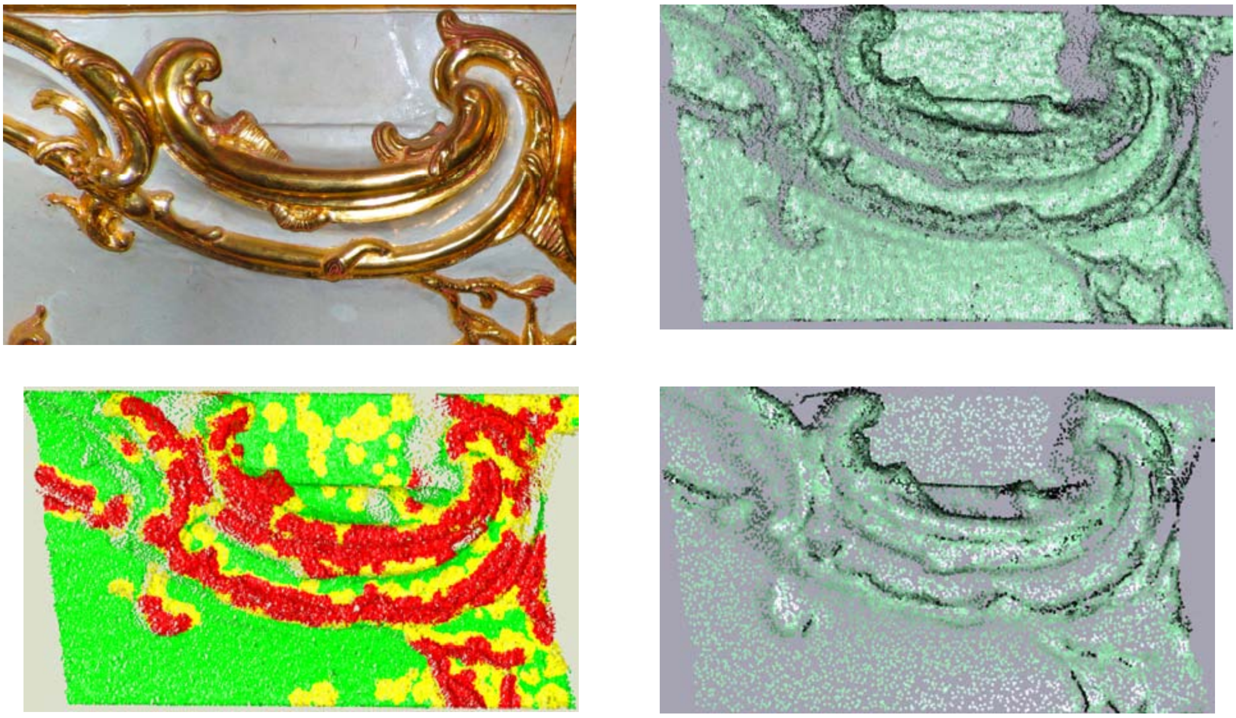


Solutions

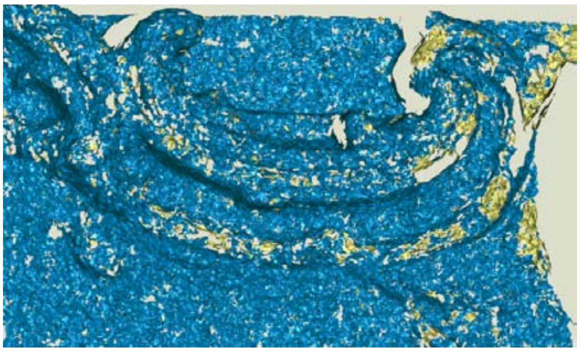
- Remove noise: low pass filter
- Thin out point cloud
- Robust methods

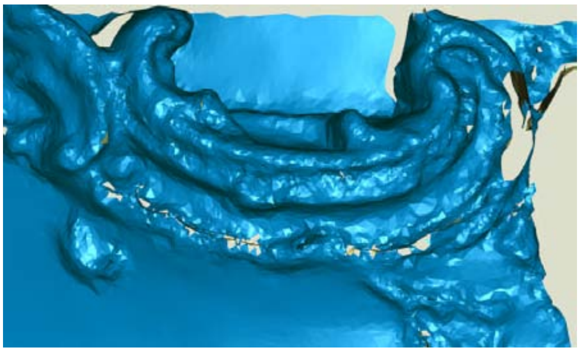


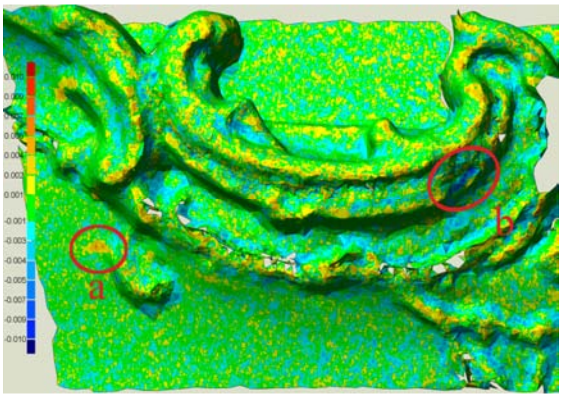
Triangulation and Noise



Triangulation and Noise







Triangulation Example

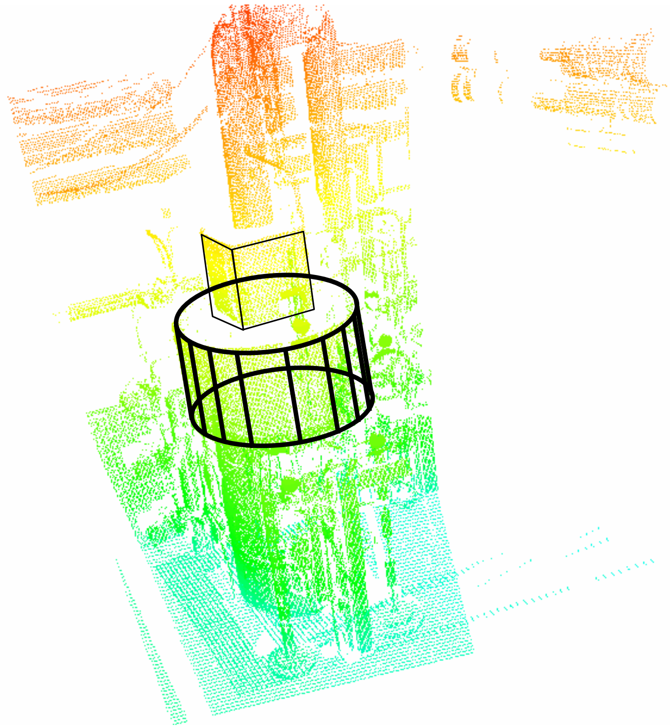
Parametric Primitives

Man-made structures

planes, cylinders, spheres, tori, cones, …

- Select points manually/automated
- Select primitive type
- Least squares fit determines primitive parameters

  How to? derivation of plane …



Parametric Primitives

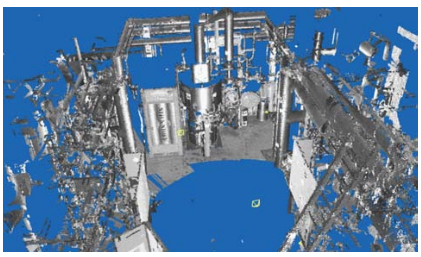
Automation through

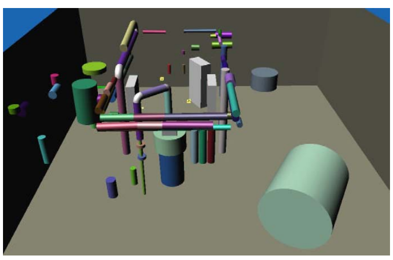
- Segmentation of point cloud

  e.g. region growing based on normal vector similarity
- Identification of surface type

  e.g. Gaussian image (normal vector image)

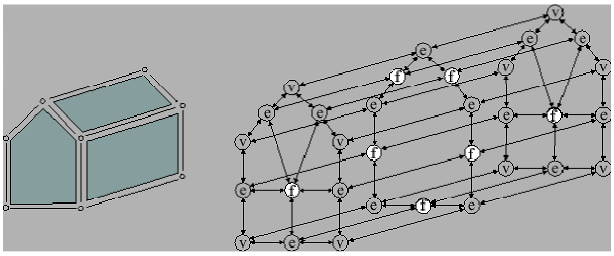
Point cloud → Model



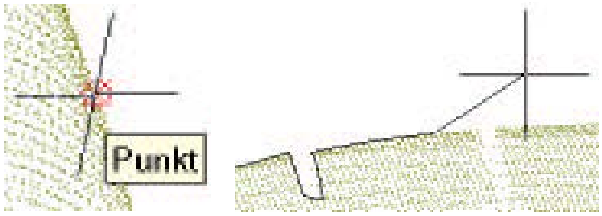


Boundary representation models
Generating B-Reps

- Digitizing in point cloud / mesh
  point identification
  edge = connect of 2 *points*
  face = enclose by *edges*



- Similar to photogrammetry,
  but !!!: digitizing in one scan is sufficient
- Example: AutoCAD plugin
  digitizing a point and a line



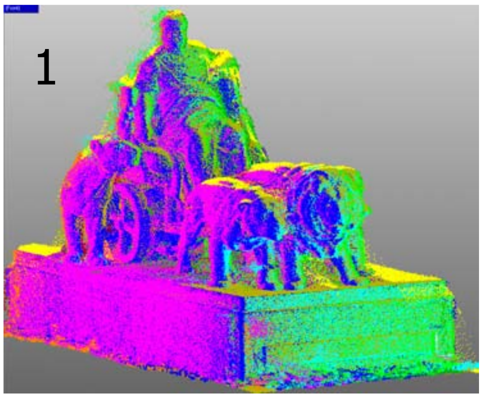
Free form surfaces

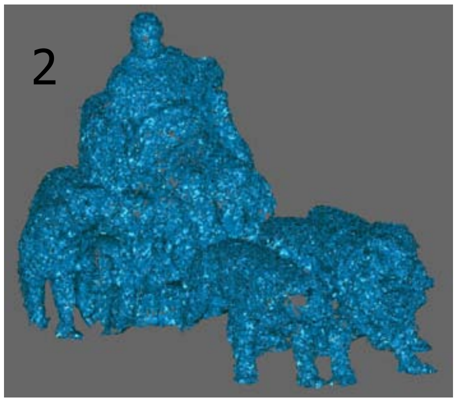
Modeling with free form surfaces

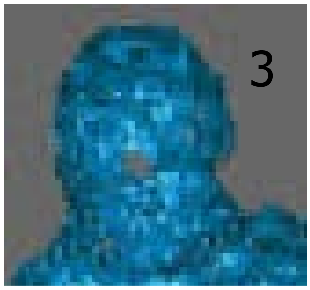
- What are free form surfaces?
  = splines, but bivariate
- Surfaces controlled by a (low) number of parameters, with continuity constraints (e.g. C1, tangent plane continuity) between adjacent surface patches
- NURBS = Non-uniform rational B-splines

Free Form Surfaces Example

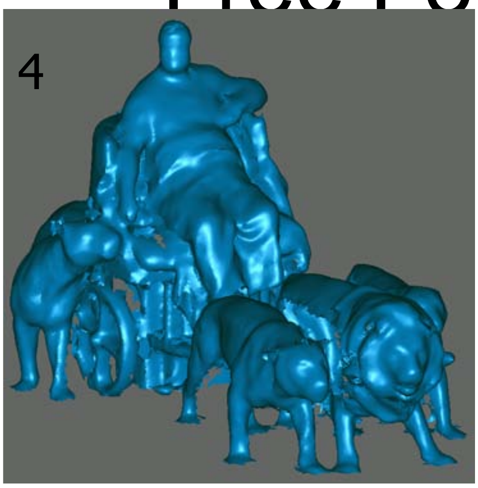
1. Original point cloud (~10 scans)
2. Triangulation (very rough surface)
3. Detail of triangulation (head)
4. Smoothed triangulation
5. Irregular boundaries of surfaces
6. Smoothed boundaries, hole-filling
7. Patch layout
8. Detail of patch layout
9. NURBS fitted to patches (i.e. point sets)

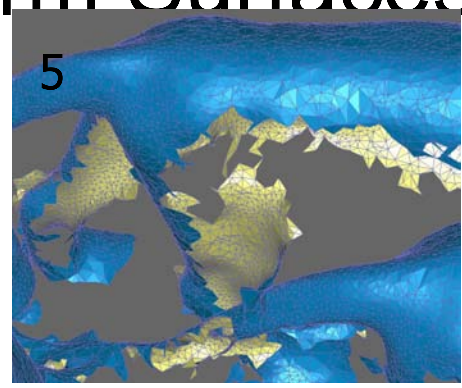


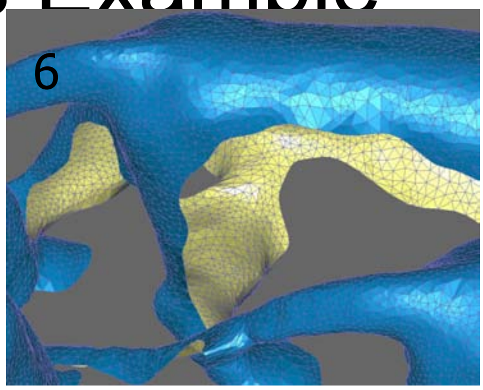


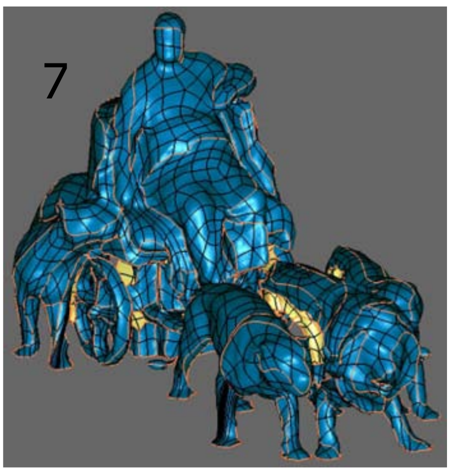


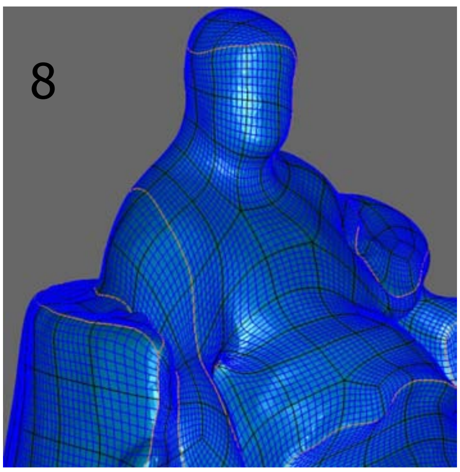
Free Form Surfaces Example

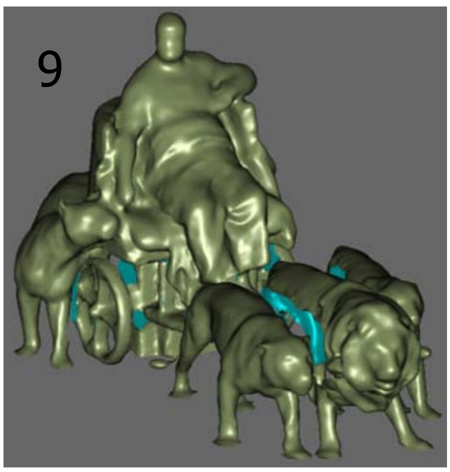












Applications

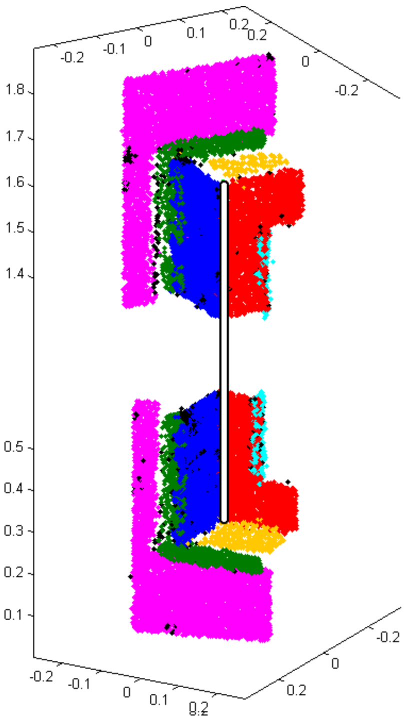
- 3D Visualization
- Archeology
- Architecture and Façade Measurement
- Archiving: Historical, Legal
- As-built Surveying
- City Modeling
- Digital Factory
- Forest Management
- Forensics
- Infrastructure
- Interface checking
- Medical Imaging/Medical Applications
- Mining/Open Pit Mining
- Movie Industry
- Monitoring and Civil Engineering
- Power Line + Poles Measurement
- Preservation
- Process Automation and Robotics
- Profiles, Volumes, Area calculations
- Quality Control/Quality Assurance
- Rapid Prototyping
- Reverse Engineering
- Rock Face Analysis
- Topography
- Tunnel Surveying
- Urban Planning
- Virtual Reality

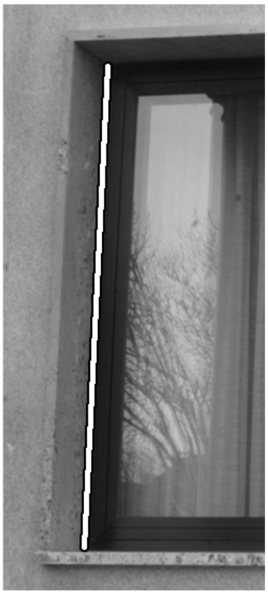
Taken from Riegl, Optech, Z+F, Leica

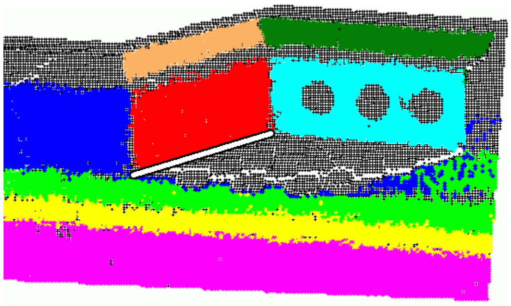
Applications

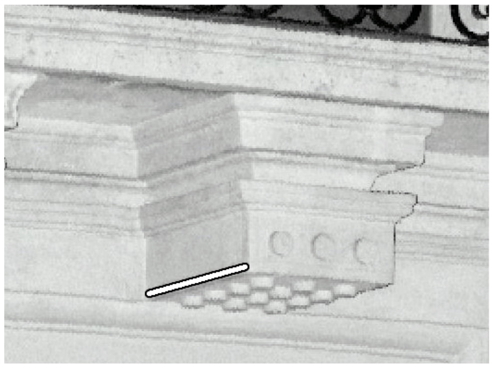
In the following slides example applications will be presented

Measurement in Models





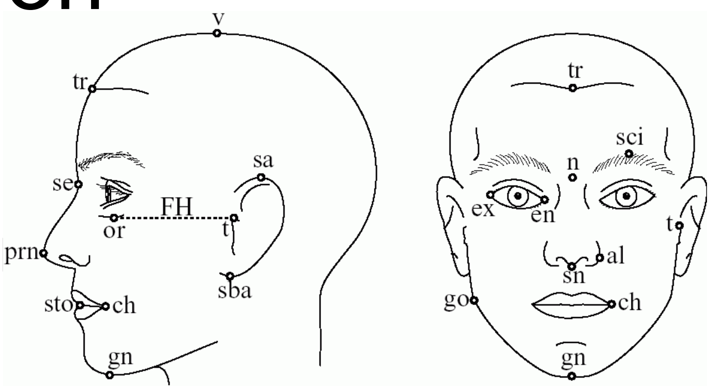




Window height: reference = 1447mm ; measured: 1444mm

Base: ref. = meas. = 518mm

Medical Application



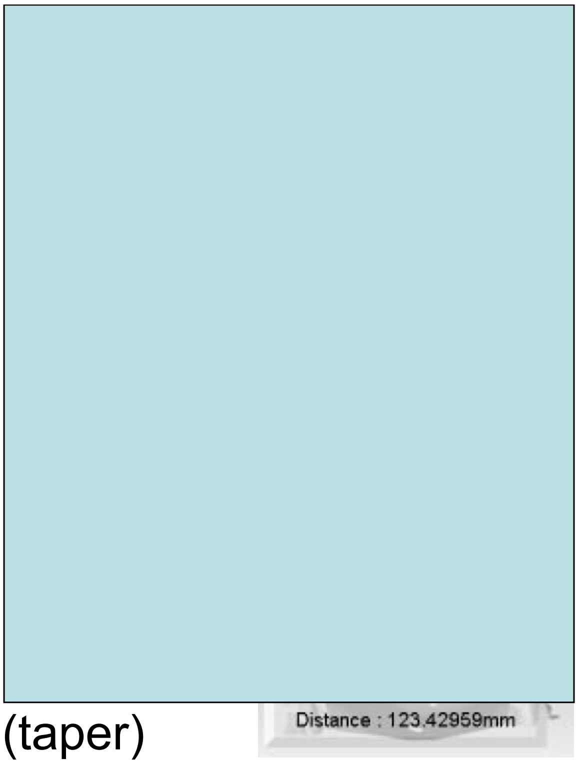
Measurement of anthropometric landma in the (human) face

- Comparison pre/post operation
- Monitor change during evolution
- Guarantee identity of persons
- …

Medical Application

- Which type of scanner? Why?

- Processing of data:
  use point cloud or simple mesh
- Degree of automation:
  manual selection of landmarks
- Problems:



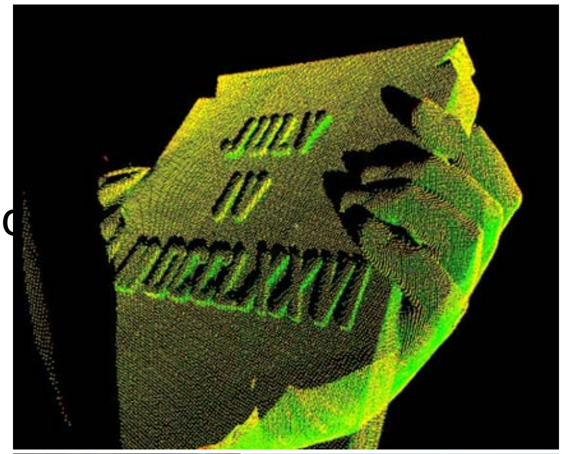
- Advantage over current method (taper)
  Scan once → Points → measure any landmark anytime
  non contact method

Heritage Application

DSOL (http://www.arch.ttu.edu/digital_liberty/)

- Preservation
  digital statue is “eternal”
- Simple measurements,
  e.g. crown diameter
- Investigation of corrugation, analysis of structural, mechanical problems
- Available everywhere,
  make (small scale) models

Heritage Application

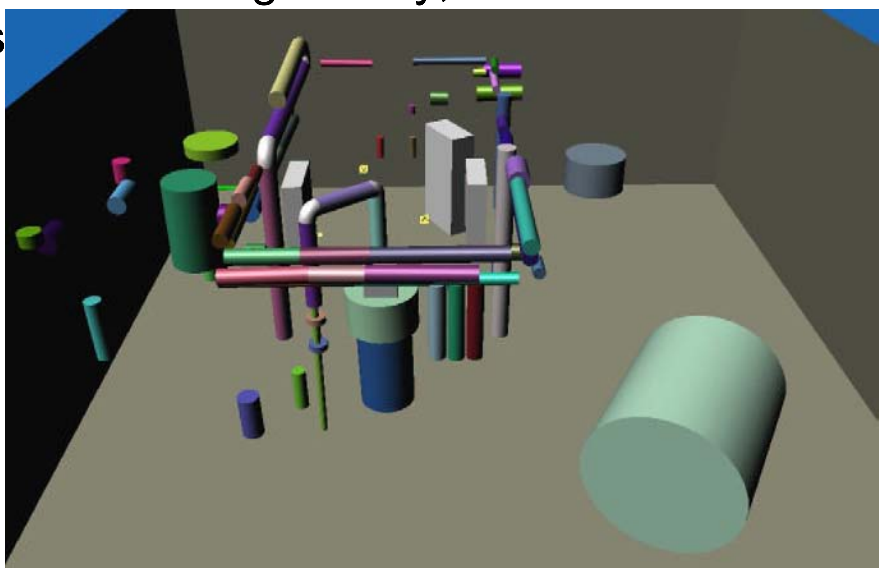


- Which type of scanner? Why?
- More than one positioning needed
- Problems:
- Modeling
  combine different scans
  make TIN model
  texture:
- Alternative methods:

Factory Reconstruction

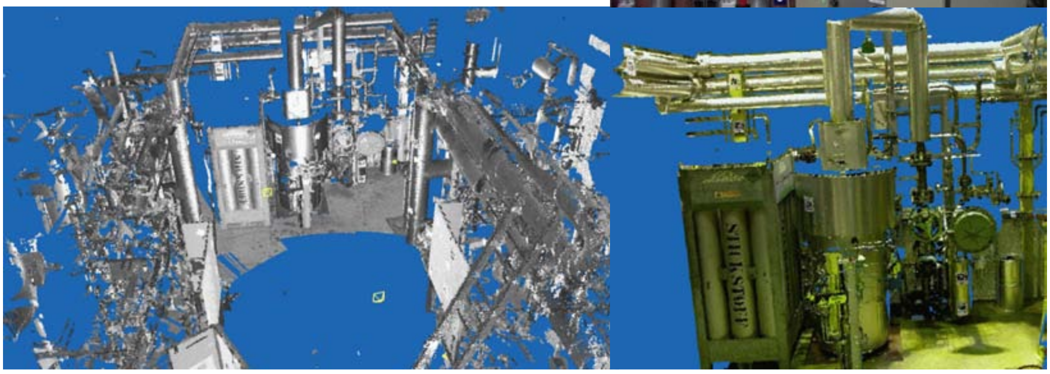
Reconstruction of industrial installations

- Make homogenous plan of existing factory, built in multiple stages
- Test fit of new planned installations
- Model production process digitally (e.g. liquid flow)



Factory Reconstruction

- Which type of scanner? Why?
- Problems:
- Automation: fitting of cylinders, planes
- Alternative methods:



Forestry application

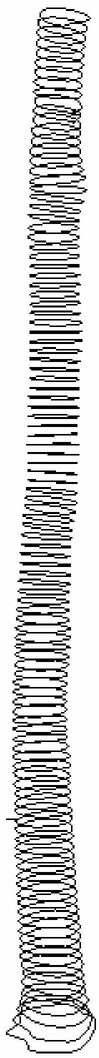
Reconstruction of single trees with precise stem cross sections

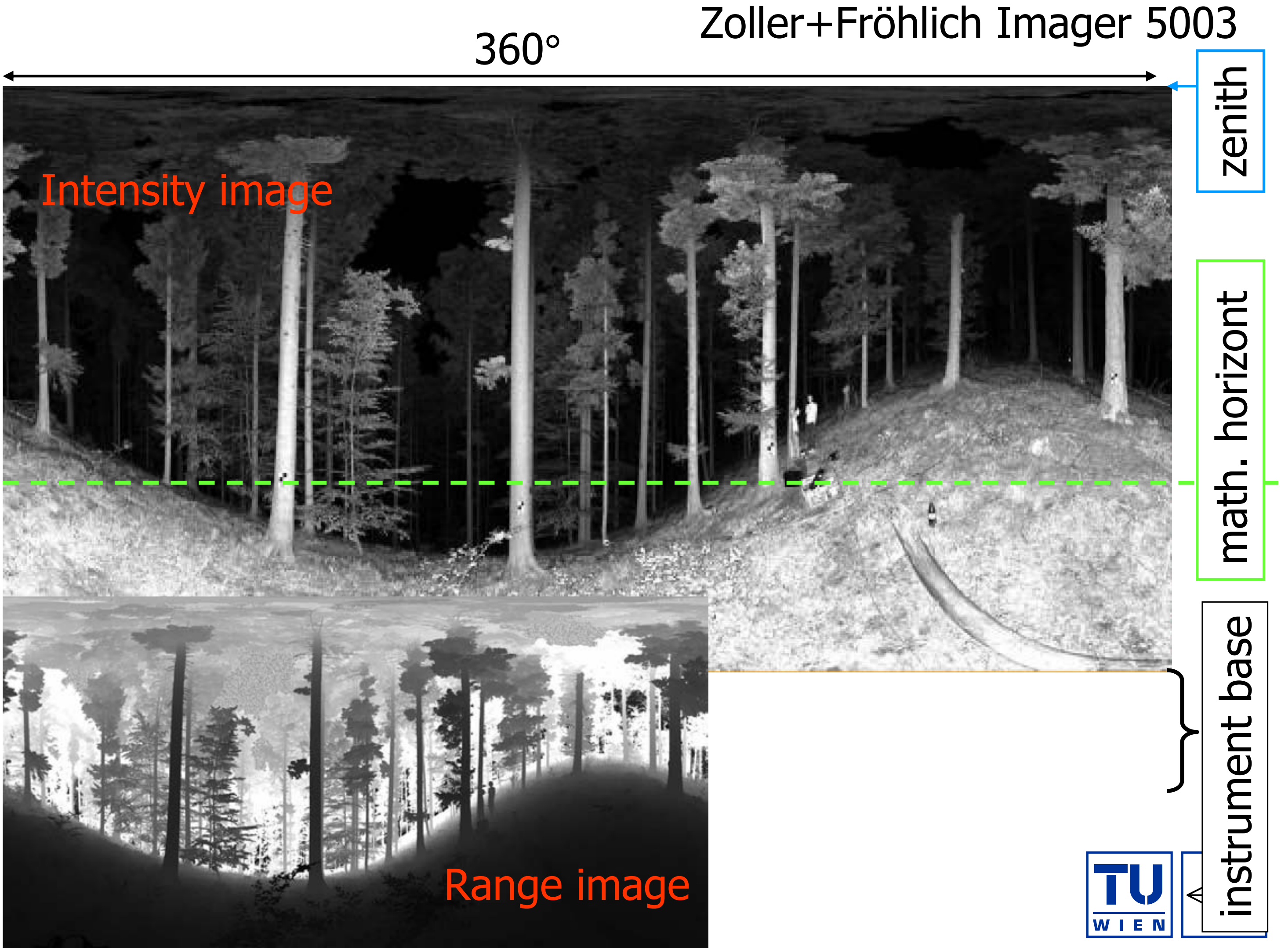
Point cloud of different scans

Cross sections along the stem

Next slide: data from one scan

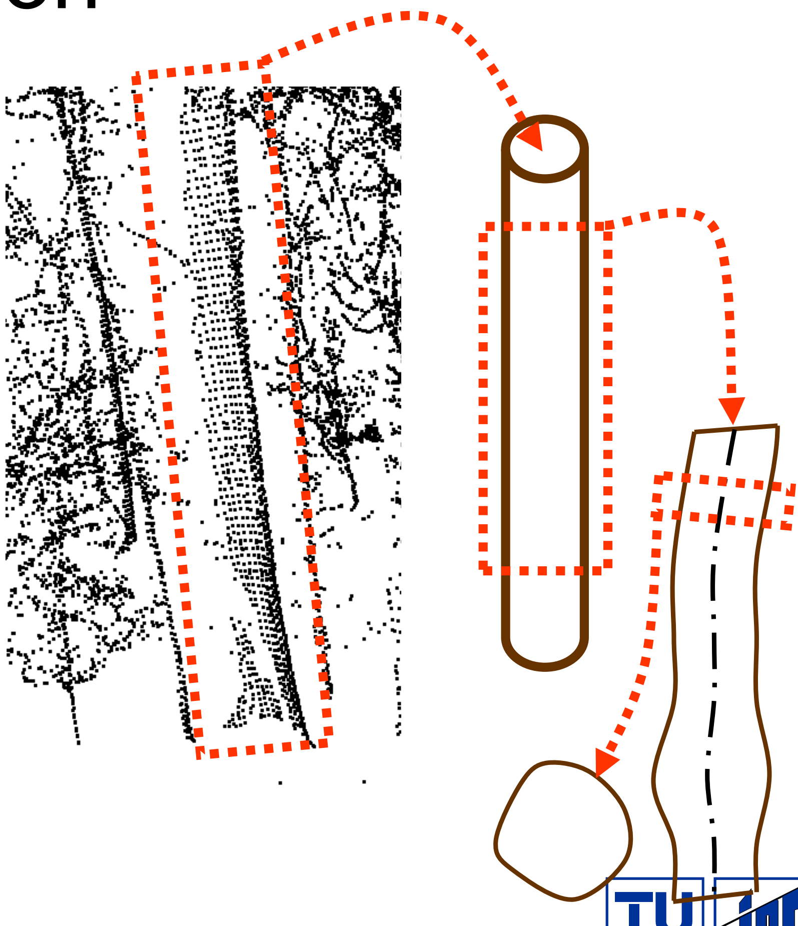
Still in research state !





Reconstruction steps

- Measurement ✓
- Registration ✓
- Coarse models
- Smooth branch models
- Cross sections



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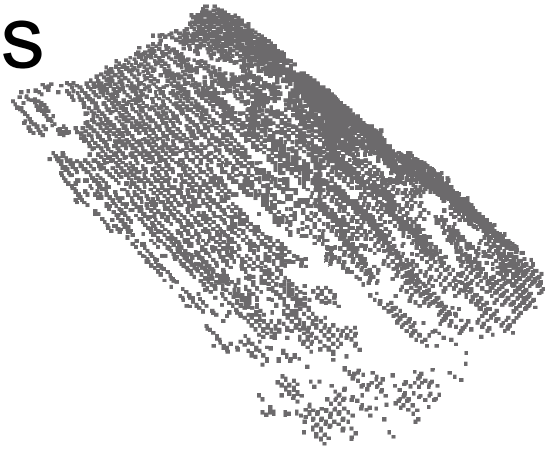
Coarse branch models

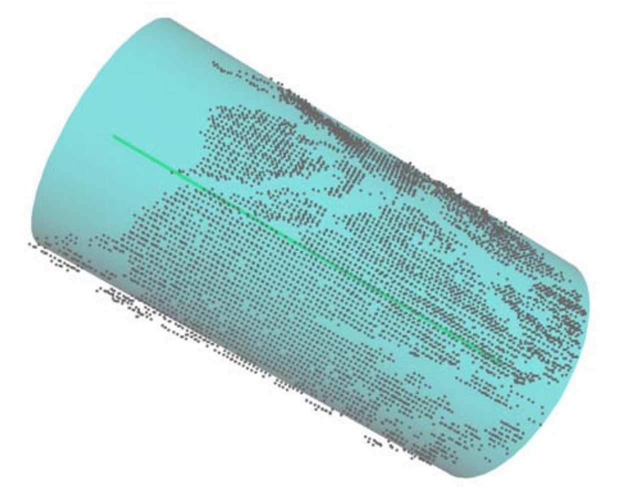


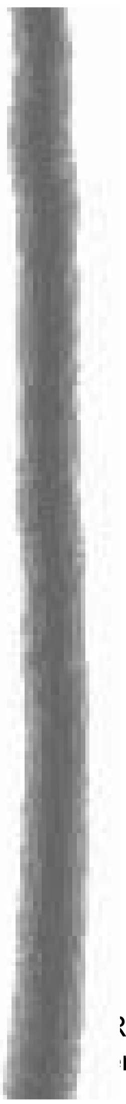
- Main parameters: radius, length
- Right circular cylinder

$$\left\| (\mathbf{Q_i} - \mathbf{P}) \times \mathbf{a} \right\| - r = 0$$

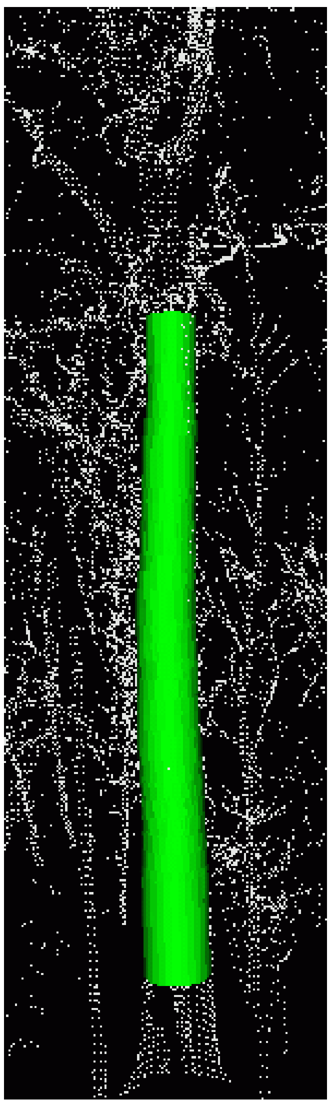
- parameters $\mathbf{a}$, r, $\mathbf{P}$
  observed points $\mathbf{Q_i}$
- Random measurement errors
  Systematic deviation from model

$$\left\| (\mathbf{Q_i} - \mathbf{P}) \times \mathbf{a} \right\| - r = v_i$$





Variation in radius and



- Real trees don't grow straight
- Real branches become thinner/thicker

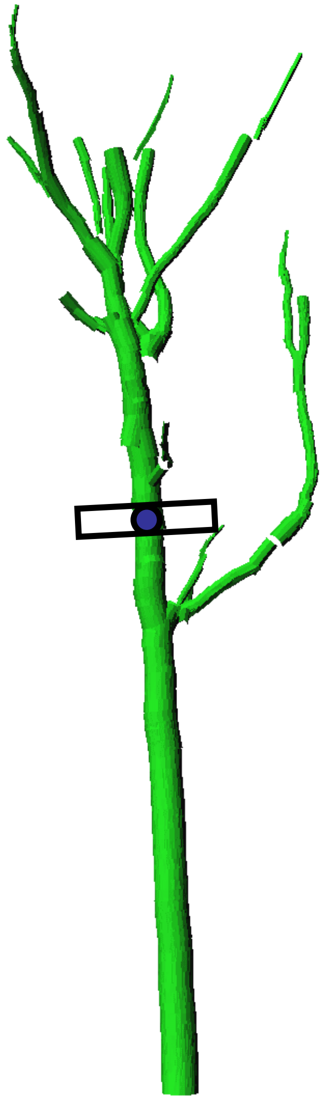
$\rightarrow$ Model only piecewise valid

$\rightarrow$ Cylinder sequence

- Accuracy

$$\sigma_0 = \sqrt{\sum_i v_i^2 \Big/ (n-5)} \cong \pm 2\text{cm}$$

Cross sections



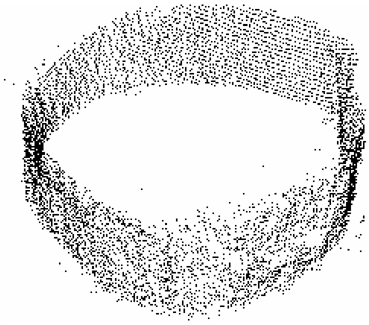
- Real branches don't have circular cross sections

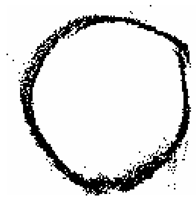
→ select point on axis

→ cross section plane
orthogonal to axis

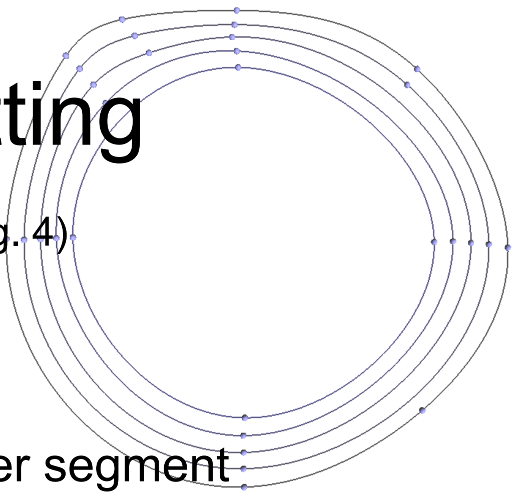
→ select points in cross section plane
tolerance Δh e.g. 20cm

→ project points onto plane
… 2D problem

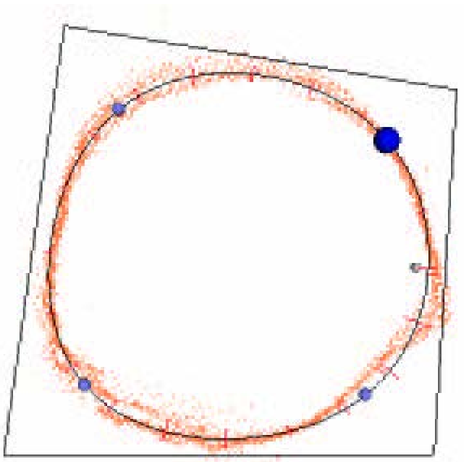


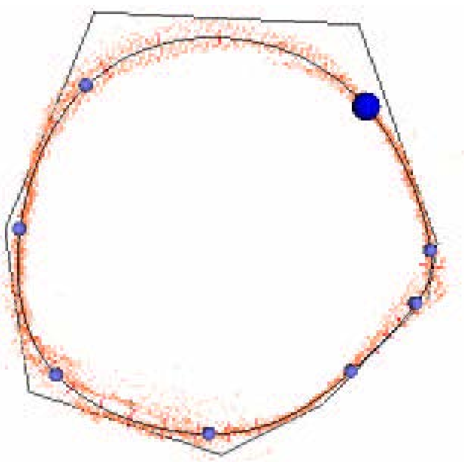


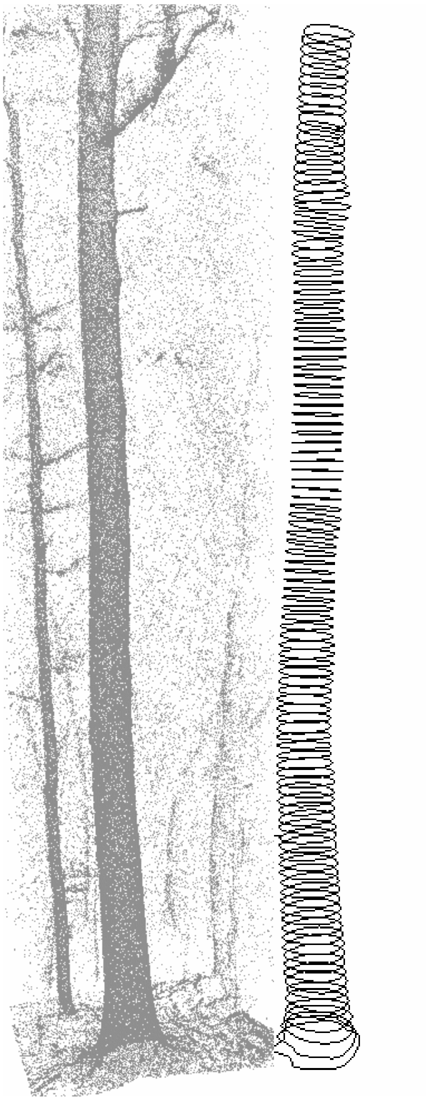
Spline curve fitting



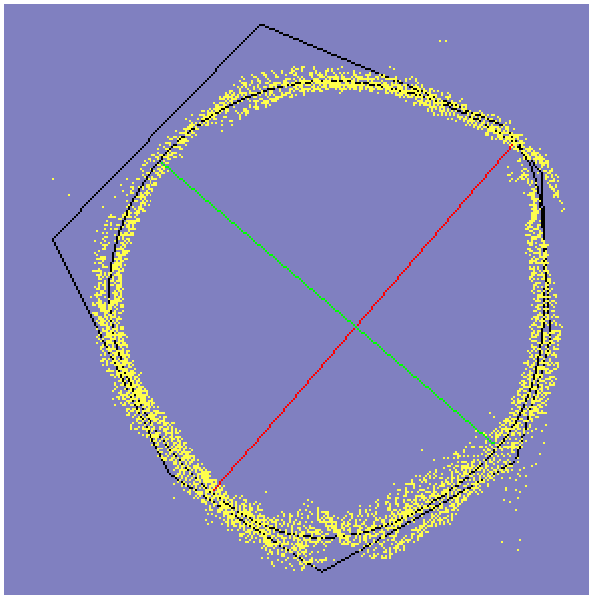
- Choose number of segments (e.g. 4)
- Systematic deviations
- Insert vertices selectively
  - Measure systematic deviation δ_i per segment
  - Insert vertex at segment with highest δ_i







Usage



Relative measure
Minimum diameter / Maximum diameter
= wood quality
= economic revenue

Conclusions

Terrestrial laser scanning

- Is a method for the acquisition of points on surfaces (no edges, no corners)
- Featuring different systems with different performance

Conclusions

Terrestrial laser scanning is

- fast,
- accurate,
- a combination of photogrammetry, total stations and coordinate measurement machines,
- easy to use,
- and finally a method that is developing (commercially available since ~1990s).

It is becoming a standard method for surveying tasks, excluding: